IFC (Industry Foundation Classes) -based Integration of Architectural Design and Structural Design

Submitted by

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Abstract

The success of a building design process is highly dependent upon effective coordination among the diverse design teams involved, such as architects, structural and service engineers, project managers and other specialists. The traditional 'human-interpreted' communication system is very time consuming and requires extensive effort in coordination. The aim of this research is to develop an IFC-compliant information model for building design processes and an integrated building design system to improve the capability of interoperation and the efficiency of information communication.

In this research, the process-oriented information modeling (PoIM) methodology is developed as a creative way to analyze information requirements and develop IFC extension models. Through the integration of the IDEFO process models and the enhanced IDEFI information models, the information requirements can be easily identified and derived from the process models. The information derived from the PolM is process-related, and is a general one which intends to characterize the flow of design information. It is not tied to any specific design process model. It provides a comprehensive view of the information and makes communication more effective and efficient. In addition, a set of standard transformation procedures and mapping tables is also designed to help the modeller quickly and easily identify elements, corresponding information, and relationships. Furthermore, the new process for IFC extension development based on the methodology is also proposed in this research.

The proposed PoIM methodology is used to build the generic information model for structural analysis and design domain. The model captures important aspects and essence of structural analysis. The gaps between the information requirements and existing IFC models are identified, and the usefulness of IFC to meet the needs. of structural analysis is assessed. The assessment is conducted from two levels and perspectives: 1) a generic and conceptual level from the knowledge gathered from structural engineering professionals; 2) the detailed requirements of structural analysis applications by investigating into the relevant softwares. The necessary IFC extensions for these information gaps are then developed. The proposed extensions improve the ability of the integrated system to provide better services on the integration of architectural design and structural analysis.

Finally, an IFC-based web-enabled integrated building design (IWIBD) system is developed, which provides a collaborative environment whereby the participants can perform online collaboration via the web. In this system, a model server is utilized to support both IFC-based data integration and transaction-based interoperation between architectural design and structural analysis processes by taking advantage of the Internet, distributed computing and other advanced network technologies. The overview of requirements, the framework of architecture and modular design for this integrated system are provided in the research.

A prototype system has been implemented to demonstrate its validity and feasibility. The prototype implements the developed process and data models in the context of distributed, model-based, integrated system architecture. Two case studies are carried out to demonstrate the capabilities of generating and exchanging information with IFC extensions and providing online services to maximize the interoperability and re-usability of design objects. The first case tests the interoperability with architectural design, as well as the approach on how to extract the information in architectural design and to deduce structural information. The second demonstrates the data transfer to, and interoperability with structural analysis and design software. The data exchange and sharing between two different disciplines and different applications based on IFC models is successfully executed. This research thus shows the feasibility and practicability of the collaboration between architects and structural engineering. It is hoped that with the services provided by this integrated system, the performance and productivity of architectural and structural design activities can be significantly improved.

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List of Abbreviations

Abbreviation	Term
AEC/FM	Architecture, Engineering, Construction/ Facility Management
AECO	Architecture, Engineering, Construction and Operation
API	Application Programming Interface
APs	Application Protocols
ARMs	Application Reference Models
BCCM	Building Construction Core Model
BLIS	Building Lifecycle Interoperable Solutions
BSI	British Standard Institute
C.I.B.	International Council for Research and Innovation in Building and Construction
CAD	Computer Aided Design
CAFE	Computer-Aided Fabrication Environment
CASE	Computer-Aided Software Engineering
CGI	Common Gateway Interface
CIFE	Center for Integrated facility for Engineering, Stanford University
CIM	Computers in Manufacturing
COMBI	Computer-Integrated Object-Oriented Product Modeling Framework for the Building Industry

Abbreviation	Term
COMBINE	COmputer Models for the Building Industry in Europe
	computer-based Integrated Building Design System (IBDS)
CPM	Critical Path Method
CSCW	Computer-supported Collaborative Working
CSI	Computers and Structures, inc.
DFDs	Data Flow Diagrams
DTD	Document Type Definition
DWF	Drawing Web Format
eCAADe	Education in Computer Aided Architectural Design in Europe
ELSEWISE	European Large Scale Engineering Wide Integration Support Effort
FFDB	Functional Flow Block Diagrams
FIPS	Federal Information Processing Standards
GAN	Generalized Activity Network
GARM	General Architecture, Engineering, and Construction (AEC) Reference Model
HTML	HyperText Markup Language
HTTP	HyperTexxt Transmission Protocol
IAARC	International Association for Automation and Robotics in Construction
IAI	International Alliance for Interoperability
ICAM	Integrated Computer-Aided Manufacturing
ICOMs	inputs, outputs, controls, and mechanisms
ICT	Information and Communication Technology
IDEF	Integrated Computer-Aided Manufacturing (ICAM) definition
IDEF0	Integration Definition for Function Modeling

Abbreviation	Term
IFC	Industrial Foundation Classes
ISO	International Organization for Standardization
ISS	Integrated Structural Software
ISSI	International Software Systems, Inc.
IT	Information Technology
JSP	Java Server Pages
LPM	Logical Product Model
LSE	Large Scale Engineering
MVC	Model-view-controller
NIAM	Nijssen's Information Analysis Method / Nijssen's Information Analysis Modeling
NIST	National Institute of Standards and Technology
OMG	Object Management Group
PAR	Product-Activity-Resource Model
PDES	Product Data Exchange using STEP
PDT	Product data technology
PERT	Program Evaluation and Review Technique
PFR	Process Flow Representation
PMBOK	Project Management Body of Knowledge
PoIM	Process-oriented Information Modeling
PRS	Procedural Reasoning System
REI	Research Engineers International
RISA	Rapid Interactive Structural Analysis
SABLE	Simple Access to the Building Lifecycle Exchange
SADT	Structured Analysis and Design Technique

Abbreviation	Term
SAMM	Systematic Activity Modeling Method
SAX	Simple API for XML
SIPE-2	System for Interactive Planning and Execution Monitoring
SRC	Steel Reinforced Concrete
STEP	Standards for the Exchange of Product data
ToCEE	Towards a Concurrent Engineering Environment in the Building and Engineering Structures Industry
UML	Unified Modeling Language
URI	Uniform Resource Identifier
URL	Uniform Resource Locators
VEGA	Virtual Enterprises using Groupware tools and distibuted Architecture
Vera	Information Networking in the Construction Process
VPML	Visual Process Modeling language
VRML	Virtual Reality Modeling Language
WISPER	Web-based IFC Shared Project EnviRonment
WWW	World Wide Web
XML	Extensible Markup Language

Chapter 1 Introduction

Design for the built environment is probably the most multidisciplinary practice in all of the design professions. Now, more than ever before, architects, structural and building services engineers, quantity surveyors, construction managers, landscape architects, and other specialists are required to work with a high level of integration during the design and development of schemes. The success of this process is highly dependent upon effective coordination among the diverse design teams involved. To a greater or lesser extent, these various professions are experiencing a number of pressures. There are pressures to reduce lead-time, to reduce costs, to reduce defects, to lower environmental impact, and to increase client satisfaction. In addition, there are pressures to improve communication with colleagues and to establish consistency in tools and procedures. Simultaneously, Architecture, Engineering, Construction, and Facilities Management (AEC/FM) are information intensive industries, and are increasingly dependant upon effective information technologies (IT) (Froese, 2003). Therefore, there are pressures to adopt computer-based working — partly so as to address the above issues (Garner and Mann, 2003).

There are various computer tools that are used to support building design tasks (Froese, 2003), such as CAD, Structure Computing software, etc. Under such circumstances, the traditional cross-discipline communication is increasingly manifested as an issue of data exchange and data sharing between different software applications.

In recent years, IFC (Industry Foundation Classes) has become the most popular and most promisingly accepted standard data model by AEC/FM industry. As an evolving international information exchange standard, the model for structural analysis and design domain was just completed last year. Even with much combined effort being put into the implementation of IFC by Scherer (2000), Liebich (2003), Froese and Hassanain etc. (2001 and 2003), the integration for the whole building design life cycle is not complete, at least for the case of architectural design and structural analysis. And most of projects only implement data interoperability, but not integrated system. Interoperability represents the ability for tools to exchange data. The data exchange through interoperability alone does not support the ability to manage the collective body of information since each tool works with only a limited view. The "business logic" associated with each view resides in different tools and can't interact. Under this circumstance, this research has been initialised in order to explore the integration and interoperability among the building design processes based on the IFC standards and product models. This research is a part of collaborative research project (CRP), Feasibility Study and Concept Proof of IFC-Compliant Building Information Modeling and Model Server Technologies, carried out by Nanyang Technological University and Singapore Institute of Manufacturing Technology (SIMTech).

1.1 Background

1.1.1 Limitations of Current Information Exchange Mechanism in Building Design Processes

Information represents the meaning that a human assigns to data by means of the known conventions used in their representation. It expresses facts, data, or instructions in any medium or form. Information exchange has been a major problem area in building design system. The increased complexity of buildings and of the organization of construction process has made the transmission and sharing of information more difficult as there is a growing amount of information to be consolidated, distributed, and exchanged (Jägbeck, 1998). Unfortunately, most of the software tools used to generate this information cannot interoperate.

In the whole building design, the processes of architectural design and structural design are most important. They are the base of all the following works in the whole life cycle of building. And the workload for this part is the biggest.

Presently, the work of architect and structural engineer is basically separated. The main communication between them is by documents and email. Although most of structural analysis software has the function of importing DXF file which can be exported by CAD (Computer Aided Design) software during architectural design, most of structural engineers do not use this function because of its inconvenience. First, the DXF files should be generated according to certain rules so as to be imported by structural analysis software. Secondly the accuracy of importing cannot be assured. If the engineer chooses to import the files directly, it still will incur additional work. Practically, engineer would rather do all the work by himself, starting from basics of structural analysis and design software.

During the building design process, the information is passed from one software forward to the next person via paper-based or electronic documents, who must re-enter relevant information into the next computer software. This manual data re-interpretation and entry is a non-value adding activity. It can often introduce errors into the project which may dramatically hamper the duration, quality and cost of the building process, and inhibits the use of better computational tools (Froese, 2003). Furthermore, in the future this situation will quickly get worse when more and more computer support becomes available and more electronic information is produced. Garner and Mann (2003) carried out a study into the current exploitation of computer-supported collaborative working (CSCW) in design for the built environment in the UK. The survey confirms that team working is increasing, and there are very real pressures to increase team efficiency and team output quality. The findings also confirm that in this field of design for the built environment, teams now involve a wider range of specialist, and communication between these specialists has increased. Therefore, the capability of software applications to interoperate has become increasingly important.

The main pitfalls existing in traditional "human-interpreted" communication system include:

1. Different views of the same objects. The same data has different meanings or semantics for different participants. Each participant re-translates the data in his own point of view, which results in non-integrity of data, work adding and time wasting.

2. Information lost or misunderstood during transfer. Problems of reworking may occur due to conflicting information and information not received in time to the parties concerned.

3. Less collaboration and low integration of design with software. A high percentage of the IT system solutions (software) that are available today focus on specific tasks such as architectural design, structural analysis, beam design, etc. These isolated applications have resulted in a broad spread of stand-alone applications packages with no or "fixed" communication links.

The major reason which causes these pitfalls is the lack of consistency in the flow of information between the different parties involved in the building design. First, a standardised platform for information exchange is lacking. The incompatibility between different data formats has raised serious "technical" problems, which have prevented design participants to easily access and exchange the information. These problems are caused by the lack of standardisation of information that can facilitate the flow of information between incompatible formats. In addition, the industry lacks an integrated comprehensive system, which facilitates the smooth flow of information between the various stages of the building design.

As a conclusion, an integrated system, which provides a standardized platform and supports exchange of information without human interference, can cater to this need. This system changes human-interpreted communication to computer-interpreted communication. All data are stored in their most essential meaning no matter how they are viewed by any user.

1.1.2 Collaborative Efforts in AEC/FM Industry

Some of the general characteristics of integrated systems are that they cluster many functional views around an overall task of building and adopting a model-based approach. Generally, the product model (the physical components of the built facility) plays a central role (Froese, 2003). Product modeling has been recognized as a basis for computer integrated engineering since the late 1980s. Product modeling standards seek to facilitate effective communication and seamless inter-working between disparate professionals by providing common terminologies, technologies, and ways of expressing and communicating information. They utilise an open data model, which provides common data representations to enable external programs to read and manipulate data. These models form the basis for automation, customisation, rich searching, and alternative interfaces (Myers, 1998). Standardization enables integration not only throughout a single computer system, but also throughout the industry in general. This provides the motivation and the justification for adopting an industry-wide product-modeling standard (Owolabi et al, 2003).

In this decade many product models have been designed and proposed. Eastman (1999) divided current building product modeling efforts into two categories: aspect models that address a specific domain in the building industry, and framework models that address the whole structure of a building. Some building aspect models that make use of several STEP technologies, such as the Logical Product Model (LPM) in CIMsteel project (Watson and Crowley, 1995), the central building model (IDM) in COMBINE (Dubois and Flynn, 1995) and Part 225, the STEP AP that describes the building elements using explicit shape representation (ISO, 1999). The framework model is like Part 106, the STEP Building Core Construction Model (BCCM) (Wix, ISO, 1996).

Various prototype product model environments have also been developed to prove the validity and effectiveness of these approaches, including ATLAS, CIMSteel, COMBI, and COMBINE etc. The COMBI (Computer-Integrated Object-Oriented Product Modeling Framework for the Building Industry) (Scherer, 1995) carried out the exchange of data between the different product representations used by the separate design tools. The objective of COMBINE was the development of future intelligent integrated building design systems (IIBDS) through which the energy, services and other performance characteristics of a planned building can be analysed. CIMsteel project aims to facilitate the sharing and the management of engineering information relating to steel building frames.

However, as listed above, different product models were developed and only adopted in the early stage of these projects. In this point, this kind of integration is just implemented and limited in the scope of projects. Out of the projects, the problem of incompatibilities between applications still exists. Starting from a set of model that is widely used and accepted is a good solution to improve the extensibility and compatibilities of integrated systems, which should be at industry-wide level, not at the level of individual firms.

As the world's largest developer of standards, the International Standards Organization's (ISO) STandard for the Exchange of Product model data (STEP) effort is undoubtedly a major international effort to establish standards for communicating product data (Warthen, 1988). STEP (ISO 10303) is a large, complex standard that was designed to support the needs of many different industries and disciplines to exchange product data. The US equivalent of STEP is called Product Data Exchange using STEP (PDES), which is the project within American National Standards Institute (ANSI) (Mitchell, 1996). Three major classes of products are defined: mechanical products, Electrical & Electronical products, and products of the AEC industries (Gielingh 1988a and 1988b, Gielingh et al. 1991).

On 8 November 2002, ISO announced acceptance of the Industry Foundation Classes (IFC) standard - used as a common language and an international standard in construction - as an ISO/PAS 16739 (IAI-NA, 2002). The IFC is an effort of International Alliance for Interoperability (IAI) to provide data structures for the AEC/FM industry shared project model and seeks to enable data sharing across heterogeneous applications by representing building products and their information requirements in a neutral computer language - the EXPRESS modeling language (IAI, 2003). IFC is consistent with and adopts a number of specifications from STEP (Daley et al., 1999).

Currently, IFC is the most widely accepted and supported standard data model by the AEC/FM industry. From the point of view of the basic technical ability to exchange AEC/FM information, it can be said that the IFCs have now been established as a viable interoperability technology. Significant portions of the IFCs are now mature, stable standards and numerous prototype and early commercial systems have demonstrated their extensive information exchange capabilities (Froese, 2003). De facto standards are quite as important and the IFCs are the best hope for modeling buildings at present, with the BLIS (1999) project for software interoperability showing how many firms are producing software (Howard and Andresen, 2001).

Even though standardization addresses the problem of incompatibility of data formats by providing industry-wide syntax and semantic, it is still unavoidable that some people may doubt that standardisation limits design freedom. For example, Stouffs and Krishnamurti (2001) argued that standardisation is not the solution to data exchange, particularly in the design process, because it attempts to impose a common semantic model for all to adhere to with attendant restriction to possibly better solutions and impedance to creative new approaches to specific problems. However, it is just like what Howard and Andresen (2001) likening the notion to saying the alphabet limits literary expression. Adopting Stouffs and Krishnamurti (2001)'s propositions would do little to improve the existing complicated, highly-fragmented communication among the project team members with the accompanying omissions, repetitions, confusions, misunderstandings, errors, delays and litigations.

1.2 Challenges Faced When Using IFC Models

The IFCs, initiated in 1994, have now undergone four major releases. The latest version IFC 2x Edition 2 and its addendum has been released whose domain coverage includes Architecture, HVAC (Heating, Ventilation & Air Conditioning), FM, Construction Management, Building Controls, Plumbing Fire Protection, Structural Elements, Structural Analysis and Electrical Domain (IAI, 2003, 2004).

As the substantial progress of IFC, many design software companies have implemented file exchange capabilities of IFC-based product models (such as Autodesk's Architectural Desktop, Graphisoft's ArchiCAD, Nemetschek's Allplan, Microsoft's Visio, and Timberline Precision Estimator). Simultaneously, there are a large number of finished or ongoing research projects related to IFC models in recent years. Some extended the IFC models or developed IFC-compliant models for different domains (Weise et al. 2000, Kim et al. 2003, Hassanain et al. 2001). Also many studies have been carried out with the aim of integrating the various building life-cycle phases based on IFC models, such as the information exchange between architects and precast concrete designers (Ronneblad and Olofsson, 2003), the integrated asset management system (Hassanain, Froese and Vanier, 2003), the Building Lifecycle Interoperable Software (BLIS, 1999), ToCEE (Towards a Concurrent Engineering Environment) (Scherer, 2000), and Vera (Information Networking in the Construction Process) (Froese, 2002).

However, IFC is still in its early stage of development. Only recently have IFC-compatible software applications started to become commercially available, and, as yet, IFC has almost no actual use in industry (Froese, 2003). There are still some challenges and problems facing the current implementation of IFC models.

1.2.1 Lack of Assessment to the Capability of IFC Models for Structural Analysis and Design

Most of above projects and almost every paper on IFC modeling deal with either the development of domain extensions or the application of IFC models in a certain domain. There has been virtually no assessment and validation of how well the IFC can support various domains' requirements, such as structural analysis and design. The information requirements of architectural design and structural design are different. Therefore the gaps as well as the reasoning mechanisms and the transformation between them need to be analyzed in order to integrate these two processes. So far IFC gives a very comprehensive expression for architectural design domain and many general architectural design softwares provide the support for IFC models (ArchiCAD, ADT, Bently, etc.). However, the IFC extensions for structural analysis domain is formally just released in 2003 in the version 2x Edition 2. It is seldom that a project would involve the integration of architectural design and structural analysis and it is also seldom for commercial structural analysis and design application to provide the support of IFC. Very little work has been done on specifying a mapping from the IFC into structural analysis and design tools.

In addition, since a number of programs are required for engineering design, the absence of standardization and the lack of coordination among software developers can result in difficulty in data communication from one program to another. Therefore, a good representation which is easily communicated within a project must not only cover the requirements of industry professionals, but also cover the requirements of the wide range of design tools and CAD systems utilized in the industry (Amor et al., 2002a). Thus, the assessment need to be conducted both from the view of professionals and from the perspective of analysis and design tools in order to give the comprehensive evaluation on the usefulness of IFC models.

1.2.2 Lack of Effective Methodology for Information Modeling and IFC Extensions Development

Product and process modeling paradigms as well as many models have been developed over the last decade for specific sub-processes. The traditional process of IFC extensions development is based on an iterative process. However, the efforts on IFC are still on-going and evolving. The changing modeling base and environment increase the needs for more effective modeling methodology. There are few published papers or guides that cover the detailed methodology of developing IFC extensions. Therefore, there is a strong thread arguing for the need for flexible and extensible models in contrast to the traditional product modeling approach. An advanced information analysis and modeling method for modeling the requirements is an essential requirement to achieve the ultimate goal of a full scale integrated building design system.

In past years, quite a few process and information modeling methods have been developed, such as the generic process description methods like IDEF (ICAM Definition language) and PetriNets, the information models like EXPRESS data specification language, and other process activity or functional models, simulation model, etc (Karstila et al. , 2000). These information modeling languages provide various ways of formally representing an information model. However, there has been a noticeable lack of development on integrated models and integrated project databases with the preferred approach for all possible mappings. Currently these modeling methods are independent. Each one describes or models a system from its own perspective and concentrates on a relatively narrow set of relationships and system characteristics comprising a particular viewpoint of the overall system. The methodologies/tools are not completely integrated to each other, thus causing inefficiencies in the development process. None of the methodologies or tools provides a comprehensive environment that can be used for the information system design from start to finish. The methodologies and tools are incomplete, and are inconsistent with each other. Usually a system should be pictured by different models in order to get a full picture of the system. In this case the modeling process may be very time-consuming and involves a tremendous amount of wasteful effort because essentially they capture the same data. Open questions seem to centre around how to use them more effectively and efficiently and how to get a flexible and extensible models. That is, developing a generic integrated methodology has become one of most important areas which would be considered in this research. The study of methodology for information modeling to support the standard model development is proposed in order to help improve the effectiveness and efficiency of model development and avoid any duplicate work during the future model development.

1.2.3 Trends and Future Directions of IFC-based Interoperability

There are currently two major trends in IT for AEC/FM: the model-based systems and web-based collaboration, which is also the future direction for IFC-based interoperability. Model-based integrated systems are central to the next generation of IT support for the AEC/FM industry. Web-based collaboration is another major IT trend. It is important that these vital technologies should not be developed in isolation of each other. Model-based systems and interoperability should be integrated with important web-based technologies such as document management, workflow management, knowledge management, and e-commerce applications (Froese, 2003).

In 2000, Faraj developed a web and IFC-based distributed computer integrated environment, namely Web-based IFC Shared Project EnviRonment (WISPER), within the construction domain. Abidemi Owolabi et al. (2003) identified key requirement for IFC-based online product libraries and presented an architecture, which is aimed at supporting present and emerging industry practices in the production and consumption of product information. An Internet-based distributed building simulation quality control system was developed by Robert Amor et al. (2002b). An experimental Internet-enabled system that integrates Building and Facilities Management Systems has been development and tested (Shengwei Wang et al., 2002). To date, web applications have proven their value for promoting communication and publishing. The open standards and wide accessibility of the Internet mean that it is fast evolving into a powerful environment for supporting distributed and collaborative group work (Faraj, 2000).

Thus, it can be summarized that generally in current changing environment several mechanisms need to be developed to meet the practical needs for an integrated building design system. Firstly, the system should follow an industry-wide standard data exchange format (IAI/IFC), namely a model-based integrated system. It is estimated that the technology of standard-base approach could bring about up to 30% cost savings in AEC project development (Drogemuller, 2000). In design, it is estimated that reduction of 10%-35% of design time and cost are achievable (Liebich and Wix, 1998a). Secondly, the system should be integrated with web-based technologies in order to provide a much powerful, flexible and extendible integrated environment. The online services maximize the interoperability and re-usability of design objects, and in exchanging and sharing the extended models data among life-cycle processes. Consequently, an IFC based web server for the collaborative building design system is developed in this research.

1.3 Scope and Objectives of Research

The main focus of this research is to develop the integrated methodology for information requirements analysis, assess the capability of IFC to support the integration of structural analysis and architectural design and to develop the prototype implementation of the interoperation between these two domains. The research has the following objectives:

a. To select and develop appropriate modeling methodology to support industry needs and requirements for the integrated building design system, which aims to improve the efficiency of modeling and make it easier for users to understand and use.

b. To introduce the new process of IFC extensions development based on the proposed modeling methodology and develop a generic information model for the structural analysis and design process. The model should also capture important aspects of the essence of structural analysis from the conceptual level to the detailed practical level.

c. To assess the usefulness of IFC to meet the practical needs of structural analysis, not only from professionals' knowledge but also from software's point of view, through the analyzing of the information gaps by the mapping and comparison between the information requirements and IFC models.

d. To develop the IFC extensions through appropriate approaches based on generality study of the information gaps so as to give a supplement for the standard product model to structural analysis domain. This building product model will provide an infrastructure for structural analysis information and be used as a basic information structure for the use of IT within structural design.

e. To propose the framework and architecture design of an integrated system, and to develop an IFC-based web-enabled integrated building design (IWIBD) system for the integration and interoperability of architectural design and structural design.

f. To develop a prototype implementation for the system and demonstrate the functionality of the integrated system's architecture by using two cases.

Building design is a complex multi-disciplinary process. As shown in Figure 1.1, only the processes in the shadowed box are included in this research. Since the architecture information has been defined in IFC and most of architectural design softwares have been provided the support for IFC, the scope of the modeling focuses on the portion of the structural analysis and design process. However, the initial planning, including the specification of design requirements, is assumed to occur prior to conceptual design and is outside the scope of the study. A user scenario is adopted by assuming that the work process of a structural engineer starts with examining existing architectural information.

In this research, the modeling is confined to static structural analysis and design for reinforced concrete structure. In prototype implementation, the structural analysis and design is carried out by using SAP2000 software. For architectural design, the supporting software used is ArchiCAD 7.0, which is one of the most popular softwares used in the architectural design.

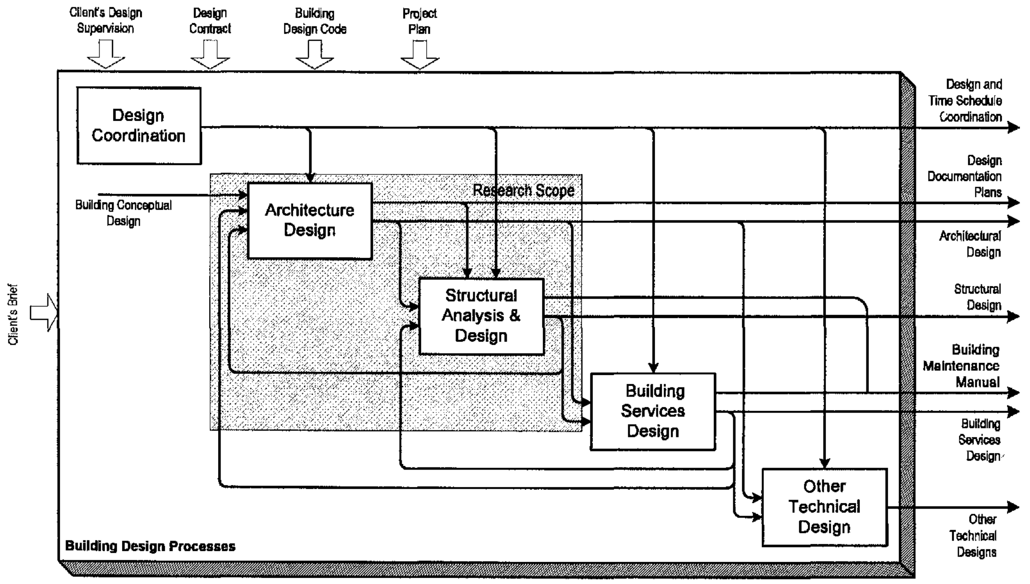

Figure 1.1 The Research Scope: Integration of Architectural Design and Structural Analysis

1.4 Relationships with Other ST Projects

The modeling emphasis of the research is based on structural analysis and design process. There are four IFC projects which are related to the structural field, the steel frame constructions model development project ST-1, ST-2 (Yasaka and Furukawa, 2002) for the basic structural design and structural execution design, the precast concrete structural model project ST-3 (Karstila, 2002) and ST-4 (Liebich et al., 2002) for the structural analysis and model of steel constructions. Figure 1.2 illustrates the relationships between this collaborative research project and these four IFC projects.

Basically, this research project is completely different from ST-1, ST-2 and ST-3 projects. Firstly, the focus is on different domains. This project's focus is mainly on the process from architectural design to structural analysis and design, while ST-3 project is mainly concerned with the whole life cycle of precast concrete construction, from design, manufacture to installation. Secondly, the research covers different types of structure and different types of material. Precast concrete construction was mainly involved in ST-3 project and steel frame structure was studied in ST-1, while reinforced concrete for in-situ construction is the primary study subject of this project. Last but not least, different processes are studied. ST-2 involved structure design and structural execution design. The primary aim of this project is to integrate structural analysis with architectural design. Therefore, this project will not duplicate the work of ST-1, ST-2 and ST-3 projects and there is no direct relationship between them. It will however use the IFC extensions developed by these three projects.

The most relevant project to this research is the ST-4 project. They both cover the modeling for structural analysis domain. The only difference lies on the final level of implementation. The IFC models of ST-4 are developed much more from experts' perspective rather than from the actual software operation. There should be some deficiencies existed in the current models for the real application. Among the 10 specific scenarios listed in Vol. 0 of ST-4 project documentations (Horenbaum, 2002), the data sharing between architect and structural engineer is not included. This is just the reason of producing the assessment of IFC models for structural analysis domain in this research. To some extent, it can be said that this research project gives a real meaning to the integration of architectural design and structural design.

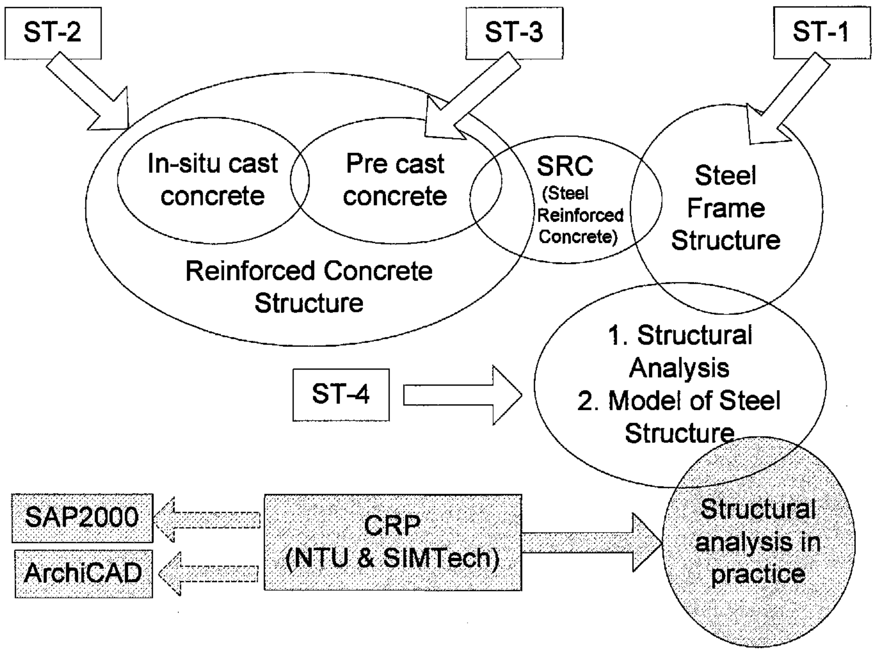

Figure 1.2 Relationships with Other IFC Structural Projects

1.5 Research Methodology

Except for the literature review and the background study (covered in Chapter 1 and 2), the main approaches used in the research include interview with experts, modeling development, software development and prototyping etc.

In order to develop appropriate modeling methodology, which guides the information modeling in the research, the existing process and information modeling techniques should be reviewed first. After comparison, the IDEF0 and augmented IDEF1 are selected as most suitable modeling tools. And the integrated modeling method, Process-oriented Information Modeling (PoIM) Methodology is developed in order to improve the effectiveness of information requirement analysis and modeling.

Through the proposed PoIM methodology, information modeling is carried out to identify the information requirements of structural analysis domain. This model attempts to give a comprehensive understanding of the structural analysis process.

Then, the capability of current IFC models supporting structural analysis is assessed by identifying the information gaps through the mapping and comparison of the proposed information model with the existing IFC models. And new extensions to current IFC models are developed to complete model of structural analysis domain.

Following the software development lifecycle, the architecture of the integrated building design (IWIBD) system is developed and designed. Prototyping is used to develop and implement a prototype system as a test model to prove and implement the concept of the integration of architectural design and structural analysis design.

Finally, two case studies are used to validate and test the prototype system. One case illustrates the information exchange and sharing between architect and engineer through the integrated system's server. The other case demonstrates the communication with engineers.

1.6 Organization of The Thesis

This thesis consists of nine chapters and is organized as follows:

Chapter 1 Introduction provides an introduction to the thesis by describing the current building design situation, its general context and highlighting the problems and challenges faced. It also describes the scope and the phases of this research. The objectives and the methodology used in the research are also included.

Chapter 2 Literature Review reviews existing research trends in related fields. It includes an introduction to information modeling and product models. The previous studies on information model and standards for AEC industry, especially STEP and IFC related efforts are presented. The existing process modeling and information modeling methods would also be reviewed as the basis of proposed methodology.

Chapter 3 Research Methodology and Processes describes the methodologies used to develop the research results. The steps and procedures of the model development are presented. In addition, literature review, information modeling and software development are presented in detail in this chapter.

Chapter 4 Process-oriented Information Modeling (PoIM) proposes an integrated method for information analysis, Process-oriented Information Modeling (PoIM) methodology. It is a new methodology to model process-related information through integrating IDEF0 process models and enhanced IDEF1 information models. The new process and procedures for developing IFC extensions based on this methodology are described in this Chapter. Some rules for IFC extension development are also specified so as to minimize conflict and confusion for organizations that will implement the extension model.

Chapter 5 Information Modeling for Structural Analysis presents the general information model for structural analysis domain developed in this research. Currently the information is collected from professionals' literatures and the modeling is constructed through using the PoIM methodology. The relationships between architectural design and structural design are also discussed to prove the necessity and feasibility of their integration. Then the capability of current IFC models to support structural analysis is assessed. It is found that in a conceptual level most of the information for structural analysis can be explicitly supported by current IFC models.

Chapter 6 IFC Extension Development for Structural Analysis Process focuses on analyzing the detailed information requirements for structural analysis domain from the software's point of view. After the comparison with current IFC extensions, the usefulness of IFC models and standards to support practical structural analysis is assessed. It is found that most of the information for structural analysis can be explicitly supported by current IFC. However there is still some information missing. Some may be inferred from the data existing in IFC. Therefore, the necessary extensions for the missing information are developed.

Chapter 7 IFC-based Web-enabled Integrated Building Design System presents a description of the architecture design for this internet-enabled open software framework. By taking advantage of the Internet, Model-view-controller (MVC) architecture, and other advanced computer technologies, such as J2EE, the modular design of system and interactions among the modules are investigated. The implemented of a prototype system is also described.

Chapter 8 Prototype Application and Case Studies uses two case studies to illustrate and validate the functionality of the system architecture which demonstrates how design information can be integrated and communicated between architect and engineers.

Chapter 9 Conclusion and Recommendations summarizes the works finished and primary contributions of this research, as well as the limitations currently existed. The recommendations on the area for future research work are also proposed.

Chapter 2 Literature Review

2.1 Organization of Literature Review

Design standards together with process and information modeling, has been active research areas for several decades. This chapter begins with a review of the basics of information modeling and product models, followed by an overview of existing information modeling and product models in the AEC industry. The STEP and IFC related efforts are especially reviewed, as they lay the foundation for this research. After reviewing the current efforts from different perspectives, the needs for an integrated building design system can be distinguished in section 2.7. Section 2.8 and section 2.9 then give brief descriptions on process modeling and information modeling methods which are utilized to analyze their characteristics for the developing of the process-oriented information modeling (PoIM) methodology. Finally, section 2.10 concludes in a summary.

2.2 Basics of Information Modeling and Product Model

Models have existed for a long time and have been used in many different ways. The purpose of a model is to depict something existing or planned in a simplified way. Information modeling is a technique for specifying the data requirements that are needed within the application domain (Lee, 1999). It is a way to formulate concise descriptions of real world artefacts and ideas so that they may be processed and communicated efficiently (Zamanian and Pittman, 1999). Product data technology (PDT) is a unified perspective for information modeling of products and all associated life cycle processes, with the aim to share that information within and across engineering disciplines (Eastman and Augenbroe, 1998). A product model is a digital representation of a real world object held to facilitate the unambiguous transfer of the information between computer systems and to support information sharing (Eastman, 1999). Turk (2004) defined product model as "Totality of all information required of product through its entire life cycle".

The goal of product modeling and data exchange is to make the exchange and sharing of information among multiple applications easy and an everyday occurrence (Eastman and Augenbroe, 1998). Product models have become a common information technology artefact. They define the vocabulary and semantic structure of the engineering and design products within particular business domains, allowing this information to be unambiguously exchanged, communicated and sometimes generated electronically. Product models facilitate automation of activities, electronic communication and reengineering of engineering processes (Eastman and Sacks, 2002). Product modeling has been recognised as a basis for computer integrated engineering since the late 1980s.

2.3 Efforts of Information Modeling and Product Models for AEC Industry

During the past twenty years, there have been numerous efforts in the area of information modeling and information sharing protocols for the AEC domain (Gielingh 1988a, Turner 1990, Eastman etc. 1991, Powell and Abdalla 1991, Howard et al. 1992, Björk 1992, Zamanian 1992, Hakim 1994, Wix 1996, Arnold et al. 1996). These researches seek to facilitate effective communication and seamless inter-working between disparate professionals of the AEC domain by providing common terminologies, technologies, and ways of expressing and communicating information.

Early efforts to apply the data exchange technology include the General AEC Reference Model (GARM) (Gielingh, 1988), RATAS (Björk, 1989 and 1992) and Engineering Data Model (EDM) (Eastman, 1991), Semantic Modeling Extension (SME) (Clayton, Kunz and Fischer, 1996).

The GARM methodology viewed the product model as functional units associated with a functional requirement, and a matching set of one or more technical solutions. Furthermore, a technical solution can be decomposed into a set of lower order functional units, and the decomposition can be repeated for a technical solution associated with a functional unit as necessary.

The RATAS building product model was developed as part of a large effort by the Technical Research Center of Finland (VTT) to establish a standard CAD environment for the Finnish national construction industry. The organization of entities in this model was modelled via an abstraction hierarchy with five levels: (1) building, (2) system, (3) sub-system, (4) part, and (5) detail.

Developed by Eastman et al. (1991), EDM was perhaps the most formal data model for the representation of engineering information. The major focus of EDM has been on the design stage of the product model lifecycle and the development of appropriate data modeling concepts and tools for this task. A major contribution of Eastman's work was the generalization of the concept of instantiation to design refinement (Zamanian and Pittman, 1999).

In contrast to many other AEC information models, Clayton et al. (1996) referred to SME as a “virtual product model” since it arose dynamically as a result of the user’s actions while designing a building. SME was intended to capture functional and behavioural information about the building components in addition to the traditional geometry-centered, physical information, thus providing richer content for information sharing by various AEC disciplines across different phases of a project.

RATAS, EDM, and SME created a general framework for modeling various abstractions of an evolving AEC project. They tended to offer more flexible approaches for dealing with evolving, less-structured information pertaining to more general abstractions used in AEC projects. After twenty years of product modeling development -- first in the area of building modeling and in the last ten years primarily centred around the ISO-STEP efforts (ISO, 1994), but more recently augmented by the IAI, therefore the following section would like to review the primary efforts related to STEP and IFC.

2.4 Standard Exchange of Product Model Data (STEP) and Collaborative Efforts

STEP is an international product modeling standardization effort. The objectives of STEP include the incorporation of object-oriented programming concepts and formal specifications of the defined structures, separation of the data model and the physical file format, supporting subsets of the total model, and the sharing of reference models among these subsets.

The STEP Committee defines the Application Protocols (APs) (the subsets) first, and the APs are later incorporated into the total model. An AP has two parts:

- The Application Reference Model (ARM) that represents the requirements of an application using the IDEF1X (IDEF1X, 1985), NIAM (Nijssen's Information Analysis Method) (Nijssen and Halpin, 1989), and EXPRESS-G models (Schenk and Wilson, 1994)

- The Application Interpreted Model (AIM) that uses EXPRESS (ISO, 1994) to specify the structure of the ARM data

Building-industry related APs include Part 225 (building elements), Part 228 (HVAC), and Part 230 (steelwork). Interpreted (shared) Resources include Part 41, the application context, and Part 42, geometric representation.

Many of current product modeling projects use the concepts from the International Standards Organization (ISO) Standard for the Exchange of Product Model Data (STEP) effort. Numerous organizations worldwide are developing STEP to provide a computer-interpretable representation and exchange of model data in the AEC industry.

2.4.1 CIMsteel Integration Standards

The central objective of CIMsteel project was to facilitate the sharing and the management of engineering information relating to steel building frames (Waston and Crowley, 1995). It has provided the first stable implemented AEC industrial strength model: CIMsteel Integration Standards (CIS). It aimed to establish open standards for the management and exchange of product data which address all types of steel frames and which are coincident with STEP standards. The LPM (Logical Product Model) for the steel frame of building was developed and has been validated progressively through a sequence of demonstrator prototypes.

CIS/2 (CIMsteel Integration Standards Release 2) is an extended and enhanced second-generation release of the CIMsteel Integration Standards (CIS). CIS/2 substantially extends the engineering scope of CIS/1, and introduces advanced data management capabilities to enable data sharing. CIS/2 is intended to create a seamless and integrated flow of information among all parties of the steel supply chain involved in the construction of steel framed structures. It has been adopted by the American Institute of Steel Construction as their format for Electronic Data Interchange (EDI).

2.4.2 Architecture Methodologies and Tools for Computer Integrated Large Scale Engineering (ATLAS)

The ATLAS project aimed at the development, demonstration, evaluation and dissemination of architectures, methodologies, and tools for computer-integrated large-scale engineering (Tolman et al., 1994). This model formed three layers on general STEP resource models and can be specialized for different engineering sectors such as buildings or process plants. The model is also intended for specialization of different views, i.e., for use by different project participants such as the architect, project managers, etc. (Froese, 1996).

2.4.3 Computer-Integrated Object-oriented product Modeling Framework for the Building Industry (COMBI)

The European Union ESPRI III research and development project, COMBI (Scherer, 1995), carried out an exchange of data between different design tools by a common communication medium. This common communication medium consists of a set of product model schemata (the generic product model), a project context data base (the instantiated product model) and a control mechanism (the design process model).

2.4.4 COmputer Models for the Building Industry in Europe (COMBINE)

This projects were among the first international projects with relevance for the building industry to adopt the then emerging ISO STEP standard for data exchange of product model data. COMBINE was a major EC funded research project, which was a multiple-participant integrated AEC systems project based on common project models (http://erg.ucd.ie/combine.html and Augenbroe 1995). Its objective was the development of future intelligent integrated building design systems (IIBDS) through which the energy, services and other performance characteristics of a planned building can be analysed.

COMBINE's integrated data model (IDM) provided the standard STEP interface for six performance tools covering HVAC, internal space planning, thermal simulation, energy analysis, energy-economic design, geometric modeling, and designing external building elements. However, IDM focuses on building design tasks and does not emphasize the construction process portion of the project scope (Froese, 1996).

2.4.5 Building Construction Core Model (BCCM)

As the proposed ISO-10303 Part 106 standard in the STEP initiative, BCCM was an international effort to define a "lowest common denominator" information model for the building industry (Wix, 1996). In addition to its main objective for enabling information exchange across different AEC disciplines, BCCM was intended to facilitate the creation of consistent Application Reference Models (ARMs) and provided the basis for the interoperability of Application Protocols (APs) in this industry. The primary information modeling constructs used in BCCM included: (1)

products as tangible items, (2) processes as activities resulting in products, (3) resources enabling the processes, and (4) controls for constraining the products, processes and resources.

2.4.6 Industry Foundation Classes (IFC)

Currently, there is an effort by the International Alliance of Interoperability (IAI), to develop standards for a three-dimensional project model that enables interoperability between applications by different software vendors. The IAI's effort includes defining a set of objects called Industry Foundation Classes (IFC) that conform to current object-oriented philosophy (IAI, 1997). The IFC model adopts terminology from the British Standard Institute (BSI) and external sources from STEP. IFC is a high-level, object-oriented data model for the AEC/FM industry. The IFC models all types of AEC/FM project information such as parts of a building, the geometry and material properties of building products, project costs, schedules, and organizations, etc.

2.4.7 Conclusion

As mentioned in Chapter 1, the building aspect models, such as CIMsteel, COMBINE, only addressed a specific domain in the building industry. Even though a significant amount of work has been done in these areas, most of the efforts have been performed independently and for specific objectives. The framework models, such as BCCM and IFC models, address the whole structure of a building. They captured various levels of content and organization of a completed AEC project created by multiple disciplines. They are useful for well-established information content and organizations in routine AEC projects, such as manufacturers parts libraries and parameterized design entities. Recently IFC has become the leading standard within the domain of product models for AEC/FM industry. IFC is the most widely accepted and supported standard data model by the AEC/FM industry. To improve the extensibility and compatibilities of integrated systems, IFC based is a much more appropriate solution to the consequent collaborative efforts. Therefore, IFC is separately described in Section 2.5.

2.5 IFC Models and Structural Engineering

2.5.1 IFC Model Architecture

Figure 2.1 illustrates the decomposition of the IFC model architecture. The IFC model architecture provides a modular structure for the development of model components, the 'model schemas'. There are four conceptual layers within the architecture, which use a strict referencing hierarchy. Within each conceptual layer a set of model schemas is defined. The lowest layer, the Resource Layer, defines resources such as units of measure, geometric representation, and other fundamental types. These classes are used by classes in the higher levels. The second conceptual layer provides a Core project model, containing the Kernel and several Core Extensions. The Kernel contains objects that are not AEC/FM-specific such as the `IfcProduct`, `IfcProcess`, `IfcModelingAid`, and `IfcDocument` objects. The Core Extensions include AEC/FM-specific extensions to the Kernel objects. The third conceptual layer is the Interoperability Layer and provides a set of modules defining concepts or objects common across multiple application types or AEC industry domains. Finally, the fourth and highest layer is the Domain/Application Layer. It provides further detail in specific domains such as Architecture and Facilities Management.

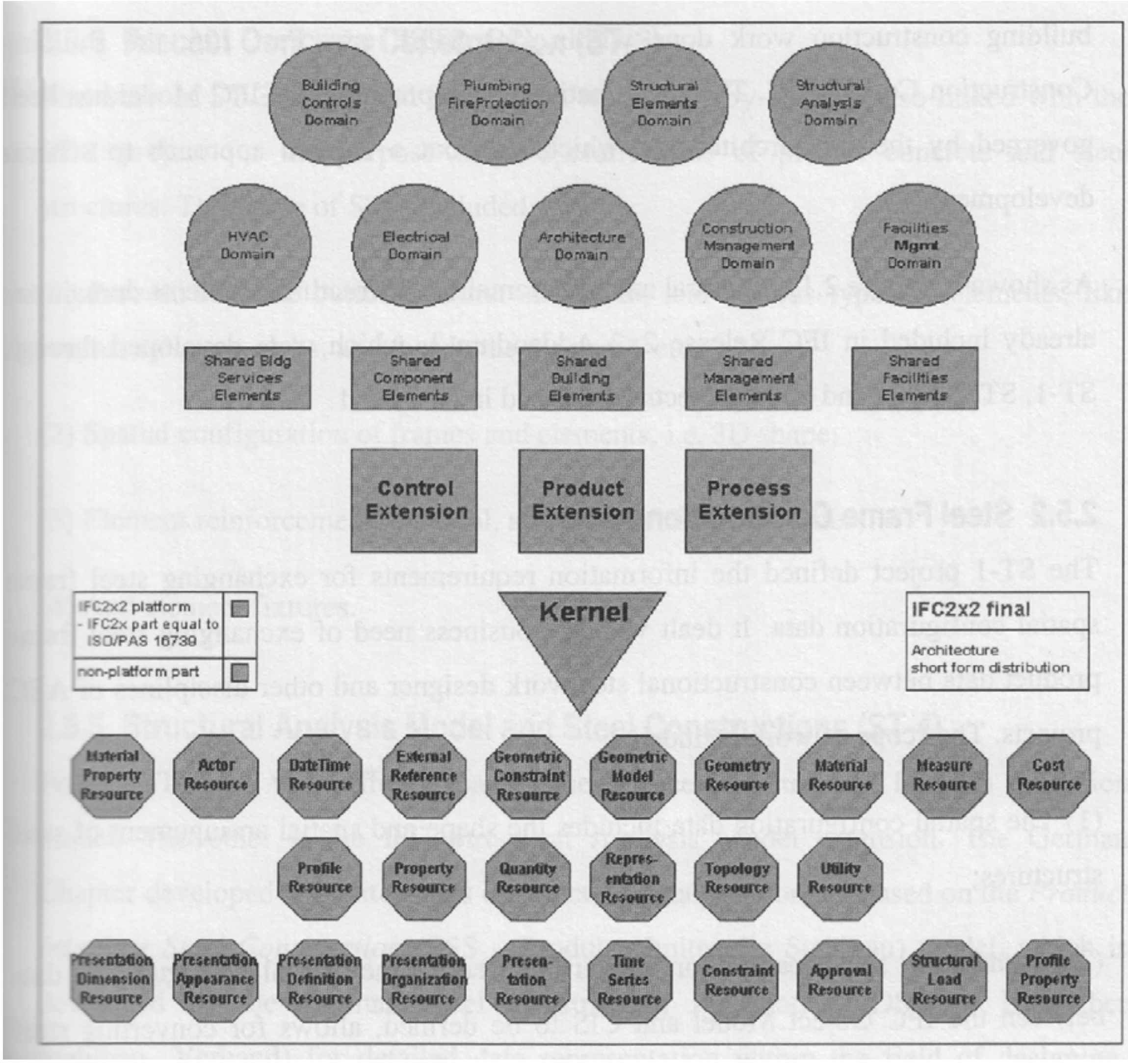

Figure 2.1 IFC Release 2X2 Addendum 1 Model Architecture (IAI, 2004)

(Source: http://www.iai-international.org/iai_international/Technical_Documents/R2x2_add1/index.html)

The IFC architecture provides the backbone of the integration process that leads into a new release. The schemas of the resource, core and interoperability layer define the platform layer, which is required to remain unchanged (at least on the level of STEP physical file exchange). The schemas on the domain layer are extensible and new schemas can be defined on top of the platform.

IFC builds on earlier work from ISO STEP: 1. uses STEP technology such as the EXPRESS language and STEP Part 21 file exchange formats; 2. follows from building construction work done within ISO STEP e.g., Part 106, the Building Construction Core Model. The specification development of the IFC Model has been governed by the IFC architecture, which lays out a layered approach to schema development.

As shown in Figure 2.1, structural analysis domain and structural elements domain are already included in IFC Release 2x2 Addendum 1, which were developed through ST-1, ST-2, ST-3 and ST-4 projects mentioned in Chapter 1.

2.5.2 Steel Frame Constructions (ST-1)

The ST-1 project defined the information requirements for exchanging steel frame spatial configuration data. It dealt with the business need of exchanging steel frame product data between constructional steelwork designer and other disciplines of AEC projects. The scope of work included:

(1) The spatial configuration data includes the shape and spatial arrangement of steel structures;

(2) A mapping specification for converting steel frame spatial configuration data between the IFC Object Model and CIS to be defined, allows for converting steel design baseline from building designers from the IFC form, into CIS form for steel designer;

(3) And steel design from steel designer from the CIS form to be converted back into the IFC form for building design coordination and visualization.

2.5.3 Reinforced Concrete Structures and Foundation Structures (ST-2)

ST-2 emphasized modeling the basic structural design and structural execution design. The scope of the work included:

(1) Structural design scheme, Structural execution, Allowable stress;

(2) Decision of member shape, and Ultimate strength design.

2.5.4 Precast Concrete Construction (ST-3)

The work of ST-3 linked and expand the work done by ST-2. It also linked with the ST-1 project for the purpose of co-operative use of precast concrete and steel structures. The scope of ST-3 included:

(1) Precast conctere building frame structures, and various types of elements, like beams, columns, slabs, and facade the elements, etc;

(2) Spatial configuration of frames and elements, i.e. 3D shape;

(3) Element reinforcement, material, and other quality properties;

(4) And element fixtures.

2.5.5 Structural Analysis Model and Steel Constructions (ST-4)

Project ST-4 has two different parts. One is Steel Construction Domain extension model. The other is the IFC Structural Analysis Model extension. The German Chapter developed IFC extensions on structural analysis domain based on the *Product Interface Steel Construction* (PSS – Produktschnittstelle Stahlbau) model, which is developed by the German Steel Construction Association (DStV – Deutscher Stahlbau- Verband) for detailed data representation within the field of designing, dimensioning and manufacturing steel constructions in 2000. In ST-4 project, many new entities and data types were proposed to be included in IFC 2x2 for structural analysis domain. They are mainly made from following four respects:

(1) Defining planar and spatial structural analysis models;

(2) Specification of loadings including point, line planar and temperature loads and the assignment to load groups, load cases and load combinations;

(3) Specification of different structural analysis models;

(4) Description of analysis result by force and displacement.

2.6 IFC Related Efforts

IFC is getting popular as a standard product data model. Information integration based on IFC models with other computer-based tools, such as the Internet, database technologies, is today the focus for many research projects on a national level (VERA 1997, Froese 2002) and on an international level (BLIS 2002, SABLE 2002).

2.6.1 Towards a Concurrent Engineering Environment in the Building and Engineering Structures Industry (ToCEE) *

The goal of ToCEE (Amor et al., 1997), an EC-ESPRIT funded project, running from 1996 until December 1998, was the development of systems of information exchange in support of a concurrent engineering environment.

A client multi-tier server system for concurrent engineering, considering the specific needs of the construction industry, has been developed. It was designed to support any kind of distributed, extended or virtual enterprises for design, construction planning, construction management and facility management. It followed the STEP methodology and is based on IFC-V1.5. One of the advantages of the system was that technical, business; product and process models are considered together and integrated by a common object oriented meta model.

2.6.2 Virtual Enterprises using Groupware tools and distributed Architectures (VEGA)

The VEGA project aimed to integrate business and technical processes (http://cic.sop.cstb.fr/ILC/ecprojec/vega). It targeted the Large Scale Engineering (LSE) industry, particularly in communication and information supply. In these sectors, distributed teams carry out concurrent activities. VEGA will contribute towards solving some of the problems by developing models and tools within a Computer Integrated Construction (CIC) environment. To implement CIC in virtual enterprises, distribution and workflow technologies are required for information sharing and to manage the sharing process. The VEGA Platform is designed to support any data model/specification defined in EXPRESS and is thus a schema-independent (late bound) implementation. The applications that have been integrated into the VEGA Platform support the IFC release 1.5. Mappings to other application schemas such as AP225 and the VABI schema have also been made.

2.6.3 Building Lifecycle Interoperable Software (BLIS)

BLIS is a coordination project -- coordinating the implementation efforts of vendors seeking to support IFC R2.0 in applications that shipped in 2001. Its goals include: (1) delivering increasing levels of application interoperability through semantic model sharing and implementation collaboration by sub-groups working to support specific BLIS 'views', (2) 'Jump start' IFC support in shipping applications and IFC based interoperability, and (3) validating any proposed extensions to IFC through software implementation.

Currently the end user 'use cases' supported by the BLIS model 'Views' of IFC included: Design ⟷ Design (geometry view); Client briefing/space planning → Architectural design; Architectural design ⟷ HVAC design; Arch/HVAC Design → Quantities take off / cost estimating; Arch/HVAC Design →Thermal load calculations / HVAC system design; and Arch/HVAC Design → Construction management/scheduling. The BLIS project is growing quite rapidly now. The BLIS project concept has proved to be quite successful in transforming the concept of IFC into real interoperable software for the AEC industry.

2.6.4 Intelligent Services and Tools for Concurrent Engineering (ISTforCE) †

ISTforCE, was a European 5th Framework Information Society Technologies project (2001-2003). In ISTforCE a novel, user-centred services platform for concurrent engineering has been developed. The substantial novelties in ISTforCE were that (1) it provided a personalised human-centred environment, enhancing current, less flexible project-centred approaches, (2) it set up an open collaboration platform where

* Available at: http://wwwcib.bau.tu-dresden.de/tocee/
† Available at: http://www.istforce.com/

new services and tools may be easily integrated as long as these servers fulfill some specifications developed in the project, and where providers of engineering information, services and tools meet project managers, engineers and architects, (3) it made flexible and customisable object-level data exchange possible, and (4) it provided an infrastructure for on-line e-business by integrating seamlessly legal and financial transactions, at all system levels.

2.6.5 Information Networking in the Construction Process (Vera) *

Vera is a technology programme of Tekes, the National Technology Agency of Finland. In the Vera technology programme construction processes and information systems are being developed simultaneously. The vision of the Vera Technology Programme was management of information through the entire life cycle of the built environment. The four central goals identified to achieve the vision of the Programme were: (1) integrated information management among all participants in the construction project, (2) efficient use of information networks, (3) efficient and wide utilization of information and communication technology (ICT), and (4) development of design, construction and FM processes to provide efficient and flexible support for client needs, sustainable development and value networks.

2.6.6 Simple Access to the Building Lifecycle Exchange (SABLE)†

This project aims to deal with the definition, the development and the implementation of a simple AEC-domain specific language to communicate with IFC model servers. This language, called interface, aims to be AEC-domain specific, to be defined using standard technology, to be free to use and to facilitate the access to IFC model servers from a client application whatever the technology used by this application. Figure 2.2 shows the architecture of the SABLE framework.

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* Available at: http://cic.vtt.fi/vera/english.htm

† Available at: http://www.blis-project.org/~sable/

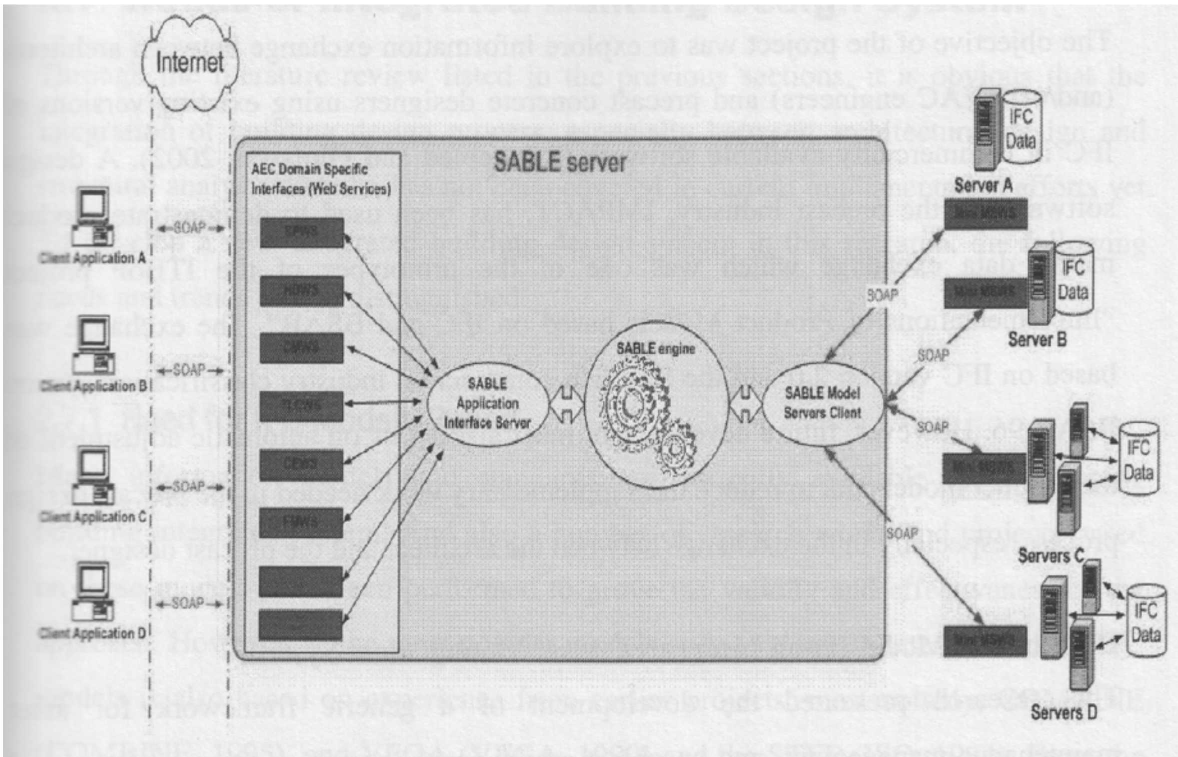

Figure 2.2 The SABLE Framework Proposed Architecture

(Source: http://www.blis-project.org/~sable/)

2.6.7 Other IFC-based Computer Integrated System

WISPER

In this project, a Web and Industry Foundation Classes-based (IFC-based) distributed computer integrated environment for the construction domain was developed and implemented which was known as Web-based IFC Shared Project EnviRonment (WISPER) (Faraj, 2000). This environment is based on a three tier architecture, where user interfaces, business logic and database were kept separate. This environment supported design (CAD), visualization (VR and Drawing Web Format-DWF), estimating, planning, specifications and supplier information. WISPER enabled project information to be exchanged through s STEP Part 21 file and shared through the IFC database. Meanwhile, a set of Web pages allowed for remote interaction, as well as access to and the distribution of application.

Product Model for Precast Concrete Constructions (IMPACT)

The objective of the project was to explore information exchange between architects (and/or HVAC engineers) and precast concrete designers using existing versions of IFC in commercially available software (Rönneblad and Olofsson, 2002). A design software for the precast industry, IMPACT, has been used to demonstrate product model data exchange which was one of the prototypes of the ITBoF project "Implementations of Product Models based on IFC and BSAB". The exchange was based on IFC version 2.0 and the Swedish construction industry classification system BSAB 96. However, future development must also focus on automatic adjustment of the product model data to reduce the supplementary work needed in the precast design process, especially in the exchange between the architect and the precast designer.

Distributed, Model-based Integrated Asset Management System

This research presented the development of a generic framework for asset maintenance management, and an object model for the maintenance management of roofing systems as a case study to demonstrate the applicability of the framework (Hassanain et al., 2003). The model built upon the IFC to define object requirements and relationships for the exchange and sharing of maintenance information between applications. A distributed, model-based integrated system was developed to explore the implementation of the developed maintenance management models. A three-tiered reference architecture was proposed for integrated distributed systems and the Jigsaw Distributed System (JDS) was developed as the implementation environment of the reference architecture, which aimed at creating tools to support both project model-based data integration and transaction-based application interoperability. Finally Asset Management Tool (AMT), a prototype integrated application that can initiate data exchanges with a number of data servers (including MicroROOFER, Microsoft Project, and files that can be used by several other applications), was used to demonstrate software interoperability in the Facilities Management (FM) domain.

2.7 Needs of Integrated Building Design System

Through the literature review listed in the previous sections, it is obvious that the integration of building design process, especially between architectural design and structural analysis domain, has not been covered in current implementation efforts yet. To develop a new integrated building design system in this research, the following needs and trends can be distinguished.

2.7.1 Need for IFC Models Based

Many information models and standards are currently available for developing building integrated system. And also a number of research works and projects based on these models have been performed to prove the validity and effectiveness of the approach. However, as the most popular models and standards in latest years, the IFC models is also based on experience from earlier projects, most notably, COMBINE (COMBINE, 1995), and VEGA (VEGA, 1999) and the STEP (ISO, 1994). From the point of view of the basic technical ability to exchange AEC/FM information, it can be said that the IFCs have now been established as a viable interoperability technology. Significant portions of the IFCs are now mature, stable standards and numerous prototype and early commercial systems have demonstrated their extensive information exchange capabilities (Froese, 2003). As more and more IFC-compatible software applications become commercially available, any efforts on developing new building design integrated system had better be based on IFC models.

2.7.2 Need for Assessment of the Capability of IFC Models for Structural Analysis and Design

Most of above mentioned projects related IFC models deal with either the development of domain extensions or the application of IFC models in a certain domain. There has been virtually no assessment and validation of how well the IFC can support various domains' requirements, especially for structural analysis and design domain. That is because the IFC models for structural engineering domain were just started in 2000 by ST series projects (Horenbaum etc., 2002) and formally released in IFC 2x Edition 2 (IAI, 2003). Currently even no any structural analysis and design software provides the full and native support for IFC models. In order to enable not only the different participants but also different application software to communicate, the assessment needs to be conducted from these two perspectives respectively.

2.7.3 Need for Better Information Modeling Methodology

Being knowledgeable about design is the precondition for assessing IFC models. That is, information requirements of structural analysis and design are needed. Therefore it is further needed for an advanced modeling methodology. In the past years, many existing modeling techniques are developed to modeling the design processes, and each technique is of its own disadvantages and advantages for this specific situation. Their current forms seem to have matured and be in fairly widespread use. However, recently there has been a noticeable lack of presentation on integrated models and integrated project databases with the preferred approach seemingly being to utilize bespoke translators for all possible mappings (Amor et al, 2002a).

The following sections would like to review the existing process and information modeling representations, which lays the foundation for the development of integrated modeling methodology in Chapter 4. All of these modeling techniques have similarities in that they have successfully been used within organizations the world over. However with all of the elements that these models have in common, they also have a great number of differences. It is these differences which make all of the stated process both unique and potential methods for the use of modeling at this research.

2.8 Existing Process Modeling Representations

Here the term “representation” is used as an all-encompassing term to include languages, methodologies, tools, standards, etc. In general, a representation is an approach to specifying process models. This may include semantic definitions, methods, and/or syntax (which may be textual, graphical, or both).

This review is not intended to be an exhaustive list of every process representation currently available. It does, however, represent a sample of representations that provide some insight into different ways of representing process information.

ACT *

ACT (Wilkens & Myers, 1995) was created at the SRI International Artificial Intelligence Center as part of research into systems that select and execute appropriate actions for achieving goals in dynamic and uncertain environments. The ACT formalism is a language for representing the knowledge required to support both the generation of complex plans and reactive execution of those plans in dynamic environments. ACT has been used as the interchange language in an implemented system that links a previously implemented planner (System for Interactive Planning and Execution Monitoring (SIPE-2) (Georgeff & Ingrand, 1989)) with a previously implemented executor (Procedural Reasoning System (PRS) (Wilkens, 1984)).

The basic unit of representation is an Act, which can be used to encode both plan fragments and standard operating procedures (SOPs). An Act describes a set of actions that can be taken to fulfill some designated purpose under certain conditions. Action specifications are called the plot, and consist of a partially ordered set of actions and sub-goals. The environmental conditions and plots are specified using goal expressions, each of which consists of one of a predefined set of meta-predicates applied to a logical formula. The meta-predicates permit the specification of many different modes of activity, including goals of achievement, maintenance, and testing. ACT can be used to build a very strong model of the relationships between actions, temporal requirements, and resources.

ACT is intended to serve as a general-purpose representation language that could be used to share knowledge between many different execution and planning systems. The representational and computational adequacy of ACT has been validated by implementing the Cypress system (Wilkens and Myers, 1995), which uses ACT as an interlingua to enable runtime interactions between planning and execution subsystems.

* Available at: http://www.ai.sri.com/~act/act-formalism.html

ACT focuses on a practical, yet sufficiently expressive representation that can address a variety of needs.

Data Flow Diagrams (DFDs)

Data Flow Diagrams (Orr & Gane et al., 1989) provide a view of the data flows in a system and the various data stores and processes/functions to/from which they flow. This is a popular method in software and information system design, and appears often in Computer-Aided Software Engineering (CASE) tools (Grady 1993, Scotti 1994). It is generally used to determine the information contained within a system. It can be decomposed hierarchically as in IDEF0, with the attendant benefits, but does not clearly show the process flow in a manufacturing system. It does not incorporate any constraints in the data and data relationships. They are primarily used as a tool for performing structured systems analyses to explore the relationships between processes and the data that they transform or create.

DFDs represent the flow of data throughout a process or between processes, depicting a system from a *data perspective* (of those who use the data), as opposed to a control perspective (of those who act upon the data), or a resource perspective (what is needed by whom and why, to do what). DFDs include specifications of the boundaries of a system, sources and destinations of data, flows of data, transformation processes, and stores of data for later use. DFDs are a graphical/diagrammatic representation with processes rendered as circles, or "bubbles." Directed arcs indicate that data move from one process to another with the name of the data labeling the arc. For each process element (bubble) in a DFD, an engineer must identify all of the inputs required, all of the outputs that the bubble must produce, and the data stores the bubble must access.

Functional Flow Block Diagrams (FFBD)

Functional Flow Block Diagrams (FFBDs) (DSMC 1986, Grady 1993, Scotti 1994) are a fundamental representational tool within the systems engineering community. It is used to define and illustrate graphically the functions that must be performed by a system as well as the sequential relationships among the functions. They are used in functional analysis to gain, in an organized way, insight into what a system (or system element) is required to do and in what sequence it must be done. Systems engineers have traditionally used FFBDs to provide a graphical view of system behavior as sequences, selections, and concurrences of functions. An FFBD is perceived as an analog of actual system operation where a function is performed by a set of system resources that are not yet fully specified.

The primary benefit of FFBDs is their ability to support analyses of the process flow or behavior of a system with respect to time. However, while they do show all the possible sequences of system behavior, they ignore data flows, including those that trigger a transition from one behavior state to another. As well, FFBDs are like IDEF0 diagrams (Wisnosky & Batteau, 1990) in that they are not intended to show the time duration of activities/functions, nor do they convey the time between functions. Equally importantly, from a process modeling perspective, FFBDs are not, by definition, resource- or equipment- oriented. That is, they identify "what" must happen and do not assume a particular answer to "how" a function will be performed.

Behavior Diagrams

Behavior Diagrams (Ballard 1989, Alford 1990) combine the features of Functional Flow Block Diagrams and Data Flow Diagrams, capturing data flows (functional interfaces) as well as control transitions and sequences. These diagrams are used to describe the functional behavior of a system design with a time sequence of functions indicating functional inputs and outputs, strict precedence relationships, control flow and data flow, as well as completion conditions for purposes of time-based simulation and analysis.

Behavior diagramming provides a number of basic constructs and features that can be used to model functional behavior. As is the case with many other process-related representations, Behavior Diagrams are hierarchically decomposable. The elements of the diagrams (particularly function blocks) can also be linked to related textual documents that contain detailed information about such things as performance requirements, requirements traceability, and so on.

Behavior Diagrams were designed, and best suited, for the behavioral modeling of physical artifacts (i.e., the operational behaviors of well-defined physical systems) as oppose to capturing the more abstract and complex programmatic elements (such as nonmachine, human activities like design) that are seen in the product realization process modeling and workflow domains.

Gantt Charts

Named for its developer, Henry Laurence Gantt, the Gantt chart (also known as a bar chart) (Avallone & Baumeister 1987, PMI 1996) provides a graphic display of schedule related information, including the relative and absolute durations and start/finish of activities. They can be used to schedule resources as well as activities. In the typical Gantt chart, activities or other project elements are listed down the left side and dates or other suitable time intervals are shown across the top. In the area formed between these two axes, individual activities or project elements are shown as bars. Each bar has a length corresponding to the duration of its corresponding activity, and is placed on the diagram in a location consistent with its designated start or finish time.

Gantt charts are a simple but effective means to convey schedule-related information graphically. They allow a recognition of the tasks that must be performed sequentially and those that may be performed in parallel. They also provide an easily understandable description of the workflow throughout an entire project.

IDEF0

The ICAM (Integrated Computer-Aided Manufacturing) Definition (IDEF) Language was developed in the U.S. Air Force ICAM Program during the 1976 to 1982 timeframe. The IDEF0 described in this section and the following IDEF2, IDEF3, IDEF1 are all included in this language.

IDEF0 (Wisnosky & Batteau, 1990) is a standard for functional modeling derived from the Structured Analysis and Design Technique (SADT) (SofTech, 1981). The IDEF0 methodology (Bravoco et al., 1985a) is a top-down hierarchical method which provides a description of functions and processes in manufacturing. It has similarities to flow-charting in that there is a series of processes/functions arranged sequentially. The hierarchical breakdown allows for defining the system in any number of levels of detail, down to the level required for analysis. This makes it easier to understand complex manufacturing systems. It does have a capacity to incorporate constraints.

Today, IDEF0 is being used in both the public and private sectors for the modeling of a wide range of enterprises and application domains, and has been formally standardized in *Federal Information Processing Standards 183* (NIST, 1993). FIPS 183 describes the IDEF0 modeling language (semantics and syntax) and associated rules and techniques for developing structured graphical representations of a system or enterprise.

As described in an analysis of the strengths and weaknesses of IDEF0 by Knowledge Based Systems, Incorporated: "The primary strength of IDEF0 is that the method has proven effective in detailing the system activities for function modeling, the original structured analysis communication goal for IDEF0. Activities can be described by their inputs, outputs, controls, and mechanisms (ICOMs). Additionally, the description of the activities of a system can be easily refined into greater and greater detail until the model is as descriptive as necessary for the decision-making task at hand. In fact, one of the observed problems with IDEF0 models is that they often are so concise that they are understandable only if the reader is a domain expert or has participated in the model development."

IDEF2

The IDEF2 methodology (Bravoco et al., 1985b) provides a description of the dynamic aspects of a system--the resources used to produce a product (e.g. factory facilities), the paths an entity can take and the resources needed along that path (e.g. the path of an automobile through a factory); status of resources (machine use, forklifts, etc.), depending on system status; and controls on activities.

IDEF3

The IDEF3 methodology (Mayer et al., 1995) is designed to capture the knowledge of the area expert about how a particular process, event, or system works. The IDEF3 methodology is capable of providing different user views of temporal precedence and causality relationships via two main diagram types, or "description modes." One, the Process Flow Network (PFN), provides a process-centered view of a system, while the other, the Object State Transition Network (OSTN), allows an object-centered view.

It is more of a description of what a system is doing than a model, a language for the organization and expression of process descriptions. This has the intended effect of enabling a domain expert to intuitively express his knowledge of the operation of a particular system or organization. It incorporates constraints in the processes, and it does have a hierarchical decomposition similar to IDEF0. The resulting descriptions that are captured by the IDEF3 can then be used to facilitate the construction of analytical and design models. The methodology stops short of providing the ability to construct predictive simulation-based *models*; rather, it is a method to obtain structured *descriptions* of what a system actually can or will do in practice.

OZONE

OZONE (Smith & Becker, 1997) is a toolkit for configuring constraint-based scheduling systems developed at The Robotics Institute, Carnegie Mellon University. A central component of OZONE is its scheduling ontology, which defines a reusable and extensible base of concepts for describing and representing scheduling problems, domains and constraints. The OZONE ontology provides a framework for analyzing the information requirements of a given target domain, and a structural foundation for constructing an appropriate domain model. Through direct association of software component capabilities with concepts in the ontology, the ontology promotes rapid configuration of executable systems and allows concentration of modeling efforts on those idiosyncratic aspects of the target domain. The OZONE ontology and toolkit represent a synthesis of extensive prior work in developing constraint-based scheduling models for a range of applications in manufacturing, space and transportation logistics.

OZONE adopts an activity-centered modeling viewpoint. There are five basic concepts of the ontology - Demand, Activity, Resource, Product, and Constraint. The ontology also defines specific inter-relationships and properties for these entities. Scheduling is defined as a process of feasibly synchronizing the use of resources by activities to satisfy demands over time, and application problems are described in terms of this abstract domain model. OZONE has a powerful architecture that permits a domain modeler to focus on those items that are special for a specific instance. The use of constraint managers assists in rapid identification of aspects to consider.

PAR2

PAR2 (Product-Activity-Resource Model for Realization of Electro-Mechanical Assemblies: Version 2) was developed by M.R. Duffey and J.R. Dixon in the late 1980s (Duffey, 1993) at the Mechanical Design Automation Laboratory of the University of Massachusetts as a proof-of-concept object-based implementation designed to explore representational issues related to the interdependencies of product, process, and resource representations within the domain of electro-mechanical design. Additionally, PAR2 was designed to explore the modeling of cash flow uncertainty for the product realization process for electro-mechanical assemblies using activity network simulation. PAR2's process representation includes an activity-on-arc representation based on the Generalized Activity Network (GAN) model of Salah Elmaghraby that allows stochastic branching and other features that enable iteration. According to Duffey, "the implementation of PAR2 uses crude but effective object-based representations and an associated simulation engine written in common lisp. It included a (now extinct) SunView graphical interface for 1) hierarchical decomposition of product instance, activity class, and resource class representations, 2) relational matrices for product-activity and activity-resource relationships, 3) a Gantt-type chart of activity subgroups that could be manipulated to explore effects of overlapping/concurrency alternatives, and 4) a cash flow diagram dynamically created during the process simulation."

Duffey contends that "PAR2 is not meant to be a robust language, but was a doctoral research experiment. It is quite ad-hoc in its modeling of stochastic networks and lacks rigorous grounding in mathematical formalisms." Nonetheless, it features a number of important elements that can be of use in future modeling of the relationships between products, processes, resources, and even requirements.

Part 49

Part 49 (Process structure and properties) is an integrated generic resource of STEP (Standard for the Exchange of Product model data) (ISO, 1995). An integrated generic resource is a group of context independent resource constructs used as the basis for future information. Part 49 includes the information necessary to specify the actions or potential actions to realize a process. This includes the relationships between the actions or potential actions in the process and the relationships between the processes that are used to realize a product. This part does not specify any particular process, but defines the elements to exchange process information. This part is applicable to all types of process definitions that can be represented in a discrete manner.

The constructs define the structure for specifying: relationships between processes, when a process is used, the properties of a process, the resources required for the process, the properties of the resource, the representation of process, the representation of the resource, and the relationship of the process to the product. Together, these constructs can be combined to create a process plan.

Part 49 is captured in the EXPRESS language (ISO, 1994). EXPRESS is a formal data specification language that provides the mechanism for the normative description of information while allowing a complete description of the data and constraints applicable to that information. EXPRESS permits the definition of resource constructs from data elements, constraints, relationships, rules, and functions.

Process Flow Representation (PFR)

PFR was designed as an extensible, computer- and human-readable language for describing semiconductor processing. It was created at the Massachusetts Institute of Technology to be used with the Computer-Aided Fabrication Environment (CAFE) (Boning & McIlrath et al., 1992). PFR was developed to explore some ideas about process modeling, design synthesis, and manufacturing. The PFR language is a text language with a parenthesis grammar adapted from Lisp and is intended to be read and possibly interpreted (executed) by various programs for the purpose of simulation, manufacturing, or analysis. In most cases today, such programs run in CAFE, which is used to operate the MIT semiconductor fabrication facilities and includes an object oriented database. PFR includes a turing-complete programming language (adapted loosely from scheme). It also includes an extension language for accessing the environment of the executing program (e.g., the CAFE database).

Visual Process Modeling Language (VPML)

VPML is the underlying language for the ProSLCETM Process Editor and the Process Simulator. ProSLCSETM is a software package developed by ISSI (International Software Systems, Inc.). Its goal is to help a company perform process engineering, which is defined as a long-term, whole system approach to help identify, analyze, and improve a business's key processes. The hopeful result is a streamlined organization able to respond quickly and effectively to the changing business environment. This will entail a totally integrated, process-driven environment composed of tools and services to support process capture, analysis, refinement, enforcement/enactment, and improvement.

VPML is a graphical language for defining process. Within VPML, a process is defined as a set of partially ordered steps toward meeting a goal. The components of a process diagram are activities, products, resources, and the connections between them. Activities represent work that is performed in a process and is the central focus of VPML. Products represent items (information) that are used, created, modified, and transferred among activities in a process. Resources are real-world resources that are required to perform an activity. Connections are used to establish relationships between constructs, pass product information between activities, and coordinate the scheduling of activities.

Systematic Activity Modeling Method (SAMM)

The SAMM modeling methodology (NASA, 1977) is similar to IDEF0 in that it is a top down hierarchical method. It uses a system of nodes and branches, each node being represented by an activity diagram. This method represents both the activity flows as well as data flows along with the amount of data being exchanged. The relations between the activity diagrams are the data flows (and quantities of data). This method was applied to modeling the design process in the IPAD studies.

2.9 Existing Information Modeling Techniques

Quite a few information modeling languages have been developed or are under development. These information modeling languages provide various ways of formally representing an information model. In general, the languages are presented in two forms: graphical form and textual form. The former uses diagrams that are formed by graphic symbols. The latter uses a specific context-free grammar that includes formal language syntax and semantics. The graphical form is designed primarily for humans, while the textual form is for both humans and computers. This research concentrates on six modeling languages: Entity-Relationship Model, the Integrated Computer Aided Manufacturing (ICAM) Definition Language 1 (IDEF1) (Mayer, 1992), Nijssen's Information Analysis Modeling (NIAM), Semantic Nets and the EXPRESS Language (ISO, 1994), and the Unified Modeling Language (UML) (Harmon and Watson, 1998). The reason these languages are chosen is three-fold: they are formal languages, they are either standardized or in the public domain, and they are the most frequently used in current manufacturing areas.

Entity Relationship Model (E-R)

The Entity-Relationship model was originally proposed by P. Chen in 1976 as a way to unify the network and relational database views. Entity Relationship diagram provides a view of data entities and their associated relationships. This model allows one to model information and data that may be conceptualized as having components that are inter-related. Moreover, the relations among components are captured as well as their respective components and attributes. In the E-R model, data components are represented as entities. These entities may have relationships with other entities. Furthermore, the mapping cardinalities of these relationships may be one-to-one, one-to-many, many-to-one, and many-to-many. Entities can be denoted weak or strong. A weak entity is one whose existence is solely dependent on a strong entity that has a relationship with the weak entity. This construct is particularly useful for consistency maintenance of a database. Attributes may be associated with each entity, usually representing the properties of the component represented by the entity. Furthermore, these attributes provide one with a mechanism to identify each of the entities uniquely.

The beauty of this method is its simplicity, and its representation of information entities in a "real world" way. Also, it is relatively straightforward to map ER diagrams into a relational database design. The E-R model has been widely used in information systems design, especially in systems involving relational databases

IDEF1

The IDEF1 method (Mayer, 1992) can be viewed as a method for both analysis and communication in establishing Computers in Manufacturing (CIM) requirements. However, IDEF1 is primarily focused on support of the task of establishing the requirements for what information is or should be managed by an enterprise. It is similar to ER conceptually, but are different graphically, and more complicated semantically, thus making them more difficult to use than entity-relationships. It is a graphical representation and is designed using the ER approach and the relational theory. It is used to represent the "real world" in terms of entities, attributes, and relationships between entities. Normalization, that eliminates redundancy and arranges a collection of data according to its inherent logical structure, is enforced by KEY Structures and KEY Migration. The language identifies property groupings to form complete entity definitions.

NIAM

The NIAM (Nijssen's Information Analysis Modeling) methodology (Bray, 1988) is another data modeling method, showing objects and their relationships; constraints, however, can be modeled in this method. It, like ER, is simple to learn and use, and can be mapped into a relational database design.

Semantic Nets

A semantic net is a formalism for representing facts and relations between facts with binary relations (Amble, 1987). Semantic nets are extensively used in artificial intelligence applications. Each object modeled is represented as a node in the network and these networks can become quite large. These can model data abstractions as IS-A and ISPART- OF relationships. Ternary relations are not supported.

EXPRESS

Express was created as ISO 10303-11 for formally specifying the information requirements of a product data model. The language is part of a suite of standards informally known as the STandard for the Exchange of Product model data (STEP) and was first introduced in the early 1990s (ISO, 1994, Schenk & Wilson, 1994). EXPRESS is a textual representation. In addition, a graphical subset of EXPRESS called EXPRESS-G is available. EXPRESS is based on programming languages and the O-O paradigm. EXPRESS consists of language elements that allow an unambiguous object definition and specification of constraints on the objects defined. It uses the SCHEMA declaration to provide model's partitioning, and it supports specification of data properties, constraints, and operations.

UML

The Unified Modeling Language (UML) is a relatively new modeling language for specifying, visualizing, constructing, and documenting the artifacts of software systems, as well as for business modeling and other non-software systems. The UML represents a collection of the best engineering practices that have proven successful in the modeling of large and complex systems (Hamilton, 1999). The UML formalism organizes models into logical packages. Each package groups a collection of classes or objects closely related to each other. It was conceived originally by Grady Booch, James Rumbaugh, and Ivar Jacobson (1999). UML was approved by the Object Management Group (OMG) as a standard in 1997. It could be argued that UML is the most successful standard from the OMG. It is the way the world models not only application structure, behavior, and architecture, but also business process and data structure.

It is a graphical representation. The language is based on the objected-oriented paradigm. UML contains notations and rules and is designed to represent data requirements in terms of O-O diagrams. UML organizes a model in a number of views that present different aspects of a system. The contents of a view are described in diagrams that are graphs with model elements. A diagram contains model elements that represent common O-O concepts such as classes, objects, messages, and relationships among these concepts (Harmon and Watson, 1998).

All above methods can be used to create a conceptual model, and each has its own characteristics. Although some may lead to a natural usage (e.g., implementation), one is not necessarily better than another. In practice, more than one language may be required to develop all information models when an application is complex. In fact, the modeling practice is often more important than the language chosen.

2.10 Summary

The literature review indicates that existing research falls short in providing an integrated model and system for managing the design information for architectural design and structural analysis. Some existing systems, however, are developed for specific uses and cover a narrow scope of the information system. The need for detailed analysis of current practices and the development of a framework are derived from the review.

Further, as is evident from this literature review, there are a number of different process and information modeling techniques in use in organizations and institutions all over the world. It must be realized that just because one process modeling technique was a success in one organization or institution similar to the one in question, it does not mean that the same modeling technique will work for the situation in this research. Therefore the task before to use these methods is to determine which one is the appropriate one to this research as well as how to use it effectively. The main motivation of chapter 4 is based on this. The literature review has been continuously performed in parallel to the development.

Chapter 3 Research Methodology and Processes

3.1 Selection of Research Methodology

In this thesis the research design aims to select appropriate methods for modeling data exchange between architectural design and structural analysis involved in structural engineering design and development. There are a number of research methods to do so. In choosing research methods, consideration was given to: (1) an ideal study is one that combines both processes as a whole; (2) it is a complex system; (3) the methodology should fit the issues to be studied, rather than structuring the issues to fit a preferred method; and (4) the methodology should reflect the environment in which the activities of architectural design and structural analysis are operated.

Based on above consideration, literature review, model developing, software development and prototyping, as well as case study are chosen as research methodology.

3.1.1 Literature Review

The literature review aims to build a theoretical foundation upon which the research is based. A good literature review will not only place the research into a scientific perspective, but also avoid duplication of effort, and identify conceptual and procedural problem, related to theories, research methods and data analyses (Dane, 1990).

Cooper (1988) argued that "... a literature review uses as its database reports of primary or original scholarship, and does not report new primary scholarship itself. The primary reports used in the literature may be verbal, but in the vast majority of cases reports are written documents. The types of scholarship may be empirical, theoretical, critical/analytic, or methodological in nature. Second a literature review seeks to describe, summarise, evaluate, clarify and/or integrate the content of primary reports." The review's purpose is to provide the background to and justification for the research undertaken (Bruce, 1994).

According to Bourner (1996) there are good reasons for spending time and effort on a review of the literature before embarking on a research project. These reasons include: to identify gaps in the literature, to avoid reinventing the wheel, to increase your breadth of knowledge of your subject area, to identify information, ideas and methods that may be relevant to your project, etc.

This inter-disciplinary research covers building standards, information model as well as the modeling methodologies. These thus form the scope of literature review conducted in this research. Together with the existing process and information modeling technologies, literature related to the subjects of information model and standards for AEC industry is reviewed. Especially the two most popular building product models (STEP and IFC), as well as their applications in projects, related collaborative efforts and web-based integration systems, are also reviewed.

3.1.2 Model Developing

As per the objectives listed in Chapter 1, one of tasks of this research is to assess the usefulness of IFC models to meet the practical needs of structural analysis. The pre-requisite is to analyze and model the information requirements which should be sufficiently detailed to describe the data needs of the application. In order to obtain an information model that is independent of any physical implementation, an integrated methodology, process-oriented information modeling (PoIM) methodology is developed to get the general information model as the basis to define standard product model. This generic information modeling technology and tools, aims to improve the efficiency of modeling, and supports industry need and requirements for the integrated building design system.

Based on the general information model and concept of IFC models, the information gaps can be identified and necessary extensions to current IFC models can be developed. A more completed IFC models for structural analysis domain will be proposed. This standard product model will be the role of integration between the architectural design and structural analysis.

3.1.3 Prototyping

Research can be classified into work which discovers and describes existing reality (explorative research) or which aims at creating a new reality (e.g. new technology or processes) which needs to be evaluated and justified (Svensson, 1998). The research in this thesis aims at developing appropriate information structures for architecture design and structure analysis, and using it to develop an integrated building design system for the information exchange and sharing between the above two processes. An important methodology used in this research is thus prototyping.

Prototyping is a research process which includes conceptualization. In this type of research prototyping is used as an approach for constructing and evaluating models and other information structures. Generally, prototyping could be defined as a design process for products. In the research, it includes four steps:

1. Defining a 'conceptual model'.
2. Identifying possible technical solutions.
3. Prototype development.
4. Testing.

3.2 Definition of Research Domain and Research Procedures

3.2.1 Definition of Research Domain

The initial phase for any research starts with the definition of the scope of research domain. The scope specifies the domain of discourse and the processes that are to be supported by the information model. It is a bounded collection of processes, information, and constraints that satisfy some industry need (Lee, 1999). A well-defined scope should be accurate, unambiguous, viable, and meet the industrial need. During the course of the modeling, the scope should be revisited and may be refined. Since the scope provides the boundaries of the application domain, it also serves as a guideline for evaluating the "completeness" of the information model.

This process is related to problem perception and formulation. The activity within this phase required initial observing and analyzing the area of interest, i.e. integrated building design system and the use of information within this work. The research question was formulated on the basis of literature review and interview with structural professionals (Maey Leow from T.Y. Lin International Pte. Ltd., et al.) and the aim and objectives were decided.

The research domain is data exchange and sharing within architecture design and structure analysis processes and the use of information technology (IT) within data exchange. This includes data requirements of different parts involved in architecture design and structure analysis processes, and the type, attribute and format of data. The hierarchy and relationship within data should also be investigated. The use of IT should strengthen the ability to accomplish the objective of data exchange.

3.2.2 Research Procedures

The procedures used in conducting this research are: (1) Literature Review, (2) Analysis of Current Practice, (3) Development of Information Model, (4) Development of System Architecture and Prototype to Verify the Concepts, and (5) Evaluation of the Prototype System. Figure 3.1 illustrates the procedures used in this research.

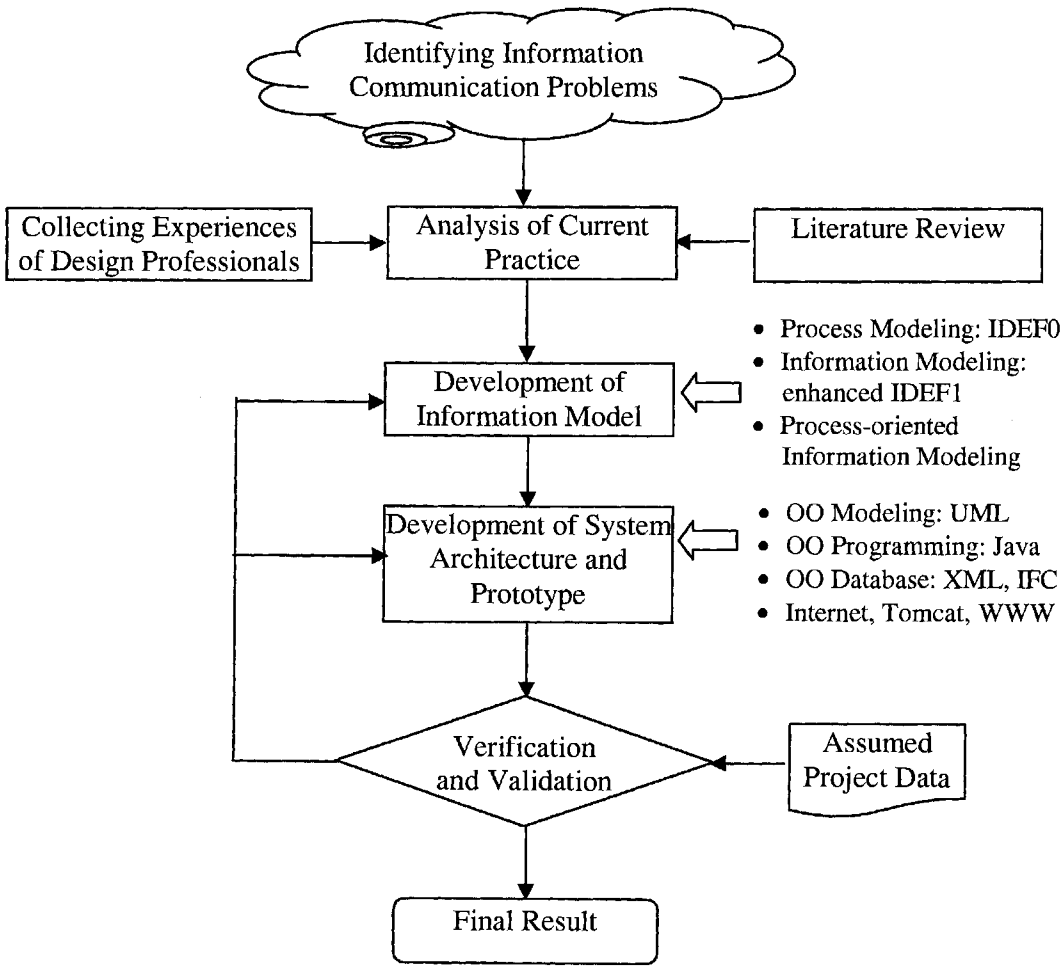

Figure 3.1 The Research Procedures

(1) Literature Review and Data Collection

By reviewing the relevant literature, the research issues, which are worthy of researching, have been identified. That is, the literature review is not an end in itself, but is a means to the end of indemnifying the worthy research issues (Chad, 1996). In this research literature related to the subjects of information modeling, the advanced information technologies, and integrated systems was reviewed.

(2) Analysis of Current Practice

Many research works fail to be developed and implemented as actual applications. The primary reason for this would be insufficient analysis of the actual practices of the industry. During this research, emphasis is placed upon attempting true and accurate investigations of current communication practice between architect and structural engineer. Constant feedback and updates from the industry practitioners should be observed until a complete picture is constructed.

(3) Development of Information Model

The development of information model is one of the most important outcomes of this research. Based on the results from the steps above, the process-oriented information modeling (PoIM) methodology would be developed. The methodology is used to model the information requirements of structural analysis process. The step is followed by the assessment of current IFC models to support structural analysis. Consequently the new IFC extensions for the information gaps are developed.

(4) Development of System Architecture and Prototype Implementation

In this phase of research the framework and architecture design of an IFC-based web-enabled integrated building design (IWIBD) system is proposed. An implementation prototype is also developed using object-oriented programming languages and network communication applications. A prototype means an experimental design of the whole or part of a product used for illustration or testing purposes (The Usability Company, 2004). A prototype could provide an operational model of the application system, a basis for further system development, and an evaluation (of the user interface) of the application system (Budde et al., 1992)

(5) Validation and Verification of System framework (Test of Prototype System)

Two case studies are used to test the prototype system developed based upon the proposed architecture, and to check whether it is capable of providing integrated exchange between architectural design and structural analysis. The performance of the model is also evaluated and assessed. The concept of software interoperability through the use of IFC models has been demonstrated.

3.3 Information Model Developing

The AEC industry is on the edge of the information society. The need for exchange of more and more complex information has successively grown. As identified by Amor (2002a), one of key current themes is the modeling of processes and products, as well as the integration of this with visualization and standardization of information life-cycles. This is concerned with the creation of a representation of buildings and projects which is easily communicated within a project. An information model is a representation of concepts, relationships, constraints, rules, and operations to specify data semantics for a chosen domain of discourse. The advantage of using an information model is that it can provide sharable, stable, and organized structure of information requirements for the domain context. IFC is selected as the basis of the research. Considering the challenges when using IFC models (as described in Chapter 1), the processes for model development are schematically described as an IDEF0 model in Figure 3.2. The detailed explanations on each process are given in the following paragraphs.

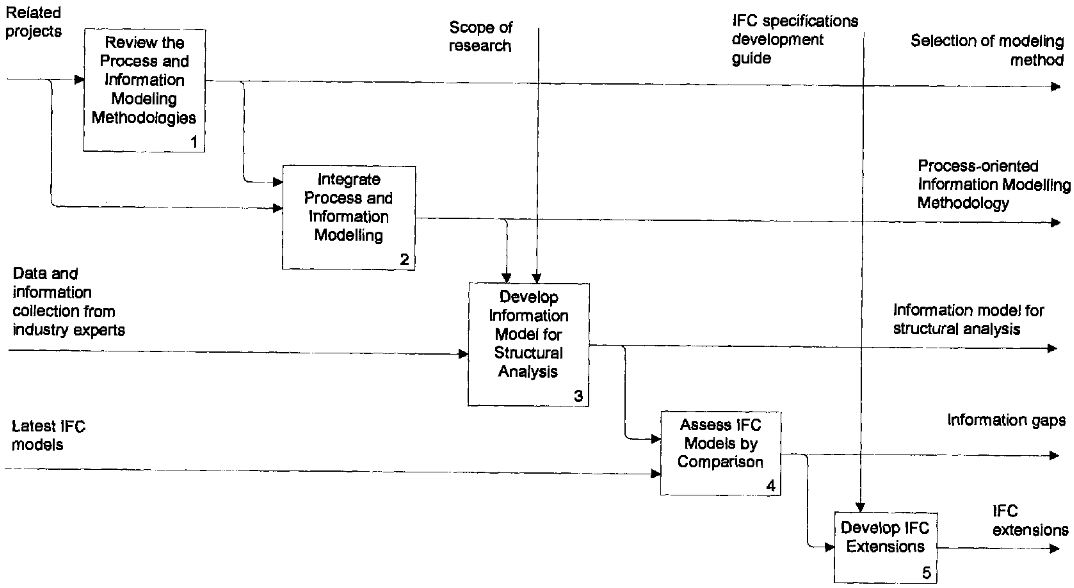

Figure 3.2 Processes for Information Model Development

3.3.1 Review of Existing Modeling Methodologies

In Chapter 2, the various modeling techniques such as the ACT, Gantt charts, PFR etc. for process modeling, and entity-relationship model, EXPRESS, NIAM and IDEF etc. for information modeling, have been discussed. Considering the possibility of integration and ease-of-use to end users, the IDEF0 and IDEF1 are selected as the process modeling and information modeling methods respectively.

3.3.2 Developing Process-oriented Information Modeling (PoIM) Methodology

Information models are needed in addition to process models to provide a comprehensive view of the information that makes effective and efficient communication possible. Therefore, the problem of how to model process-related information effectively is addressed. An integrated methodology, i.e. the process-oriented information modeling methodology, is developed to integrate the IDEF0 process model and enhanced IDEF1 information model so as to obtain the general information model as the basis to define standard product model. The methodology is explained in detail in Chapter 4.

3.3.3 Information Modeling for Structural Analysis Domain

There is no standard method for collecting information requirements. However, the information may be collected from the following sources: literature survey, standards surveys, domain experts' interviews, industrial data reviews, current industry practices, traditional practices, and near-future trends.

The information collected is then transformed into a conceptual model by using process-oriented information modeling (PoIM) methodology proposed in this research. The information model is independent of any physical implementation and should be sufficiently detailed to describe the data needs of the application.

3.3.4 Assessment of IFC Models

The information requirements in proposed information models would be mapped with latest IFC model and standards, IFC 2x Edition 2 and its addendum. The capability of IFC models to support structural analysis is assessed and the information gaps are identified.

3.3.5 Developing IFC Extensions

According to IFC 2x Extension Modeling Guide (IAI, 2001), different approaches of extension development can be applied to different scenarios. For the sake of classifying the scenarios for identified information gaps, their generalities are studied through generality study by investigating other ten versatile and most popular structural analysis and design software. Whereafter, the necessary extensions are developed.

3.4 System Development and Prototype Implementations

The term prototype is often referred to as a single application that is developed prior to developing a complete application. It is also referred as any of several approximations that is redeveloped in order to gradually expand and enhance a core application into a full-blown application (Harmon, 1998). In this research an IFC-based web-enabled integrated building design system would be developed. The prototyping part of the research work aims to implement the conceptual model and conceptual framework, to verify the integration of architectural design and structural analysis.

3.4.1 Development Process

It is important to choose appropriate development lifecycle process to the project at hand because all other activities are derived from the process. A more typical software life cycle includes at least five well defined stages:

- Requirements analysis
- System architecture and design
- Implementation
- Validation and verification
- Maintenance and deployment

The first activity, requirement definition, is the most important of the five in the development process. It affects and colors all the rest (Fox, 1982). Design here is the software design, not the system design of which the software is but a part. In this phase, the architecture of system and modules are developed. During the implementation, or coding stage of a software development project, software engineers complete detailed level designs. Testing or verification as it is now frequently being called is a critical and difficulty activity. Maintenance of service development and deployment is the last phase in the software lifecycle.

3.4.2 Requirements Analysis

This is where every software project starts. Requirements serve many purposes for a software development project. For starters, requirements define what the software is supposed to do. The requirement will become the basis for all the future architecture definition and design, coding, and testing that will be done on the project (Hamilton, 1999). Quality requirements are broken up into two kinds: functional and non-functional (Wiegers, 1999). Requirement engineering acts as the bridge between the real world needs of users, customers, and other constituencies affected by a software system, and the capabilities and opportunities afforded by software-intensive technologies. Typically, requirements start out as high-level general statements about the software's functionality as perceived by the users of the software. Non-functional requirements describe the performance and system characteristics of the application. It is important to gather them because they have a major impact on the application architecture, design, and performance.

3.4.3 System Architecture and Design

The architecture provides a high-level view of the system and its component parts make it possible for a large number of participants to evaluate the feasibility of the architecture. This workflow occurs at two levels. First, the top-level architecture is produced by using the software system engineering work products. Choosing the appropriate architecture for an application is key. Second, the subsystem-level analysis and design is performed to meet the specification from the top-level architecture. In addition, the subsystem-level effort will undoubtedly uncover problems or even mistakes in the top-level architecture.

Even with a good architecture it is still possible to have a bad design. Many applications are either over-designed or under-designed. The two basic principles here are "Keep it Simple" and information hiding (Perks, 2003). For many projects, it is important to perform Object-Oriented Analysis and Design using UML. Reuse is one of the great promises of OO, but it is often unrealized because of the additional effort required to create reusable assets.

3.4.4 Implementation

The top-level architecture and subsystem-level architectures are input to the implementation workflow. The tasks of implementation include writing the codes and combining, interconnecting parts of programs. Construction of the code is a fraction of the total project effort, but it is often the most visible. The process of writing a program is an iteration of write, run, and correct. Correct because the program is rarely without errors the first time (Fox, 1982). The software architect must ensure the resulting implementation matches the top-level and subsystem-level architecture for each of the iterations. Implementation will also uncover areas of the software architecture that need to be modified.

3.4.5 Verification and Test

Testing tells the state of what has already been built and shows where to go in and fix a problem. Verification helps to avoid having the error getting in there in the first place. An error in a program can be many things, from a miscoded statement that will cause the entire system to stop, to something as trivial as a column error on a printout. An error can be caused by misstatements in requirements, in design, or in coding. It can come from a mistake, an ambiguity, a void, or a confusion. Even state-of-the art development techniques cannot eliminate 100 percent of software bugs but proper software validation and testing can go a long way toward detecting most bugs before software is released to end users (Hamilton, 1999).

3.4.6 Maintenance and Deployment

The maintenance phase deals with changes that need to be made to the service over its lifetime because of new of changed requirements. Deployment is the process of releasing an application for users. The software architect at this point is involved in communicating the architecture to the end users, and potentially to the sales staff, so that the benefits of this architecture over others can be easily seen.

3.4.7 System Modeling Tools-UML

Today, a software architect almost always uses some sort of system modeling tool to graphically represent the architecture of a software system. Just as good blueprints are important for constructing an office building, have a model of your software system before you actually start writing code is equally important. Having a model helps you decompose complex software systems into individual pieces that are easier to comprehend (Hamilton, 1999).

Among many modeling techniques, the Unified Modeling Language (UML) is used for development of system model. As one of the most common modeling languages in use, UML is an industry-standard language for specifying, visualizing, constructing, and documenting a software system. With UML, a system architect creates a "blueprint" for construction (design and coding) of the system. UML represents a collection of "best engineering practices" that have proven successful in the modeling of large and complex systems (Hamilton, 1999). The detailed descriptions about UML are provided in Chapter 7.

3.5 Case Study

Case study research excels at bringing us to an understanding of a complex issue or object and can extend experience or add strength to what is already known through previous research. Case study, like experiment, is an alternative way for collecting primary data. They allow for the identification of variables that were not identified in archival analysis. It is a systematic way of looking at what is happening, collecting data, analyzing information, and reporting the results. The most important is that case study can be used for pattern-matching, time-series analysis, and their combination.

Program implementation case studies help discern whether implementation is in compliance with its intent. These case studies are also useful when concern exists about implementation problems. Extensive, longitudinal reports of what has happened over time can set a context for interpreting a finding of implementation variability (Webster Dictionary). Two case studies are carried out in this research which aims at testing the architecture and functionality of prototype system.

Chapter 4 Process-oriented Information Modeling (PoIM)*

4.1 Introduction

This chapter compares the existing methodologies used to develop process and information model with each other and explains the reason to choose the IDEF methodologies. The current research works deal mostly with how to use IDEF methods in different application areas. Each type of IDEF methods is a description of the same system from its own perspective. Therefore, they should have consistency, to a certain degree, with each other. But very little research has dealt with the integration of these methodologies. In this research a generic method, i.e. the process-oriented information modeling (PoIM) methodology, is developed. This method aims to improve the effectiveness and efficiency of information requirements analysis by integrating the IDEF0 and IDEF1.

Process-oriented information modeling (PoIM) methodology is an integration of process model and information model. This information model is obtained from process models and all the information is process related.

The chapter is organized as follows:

- Section 4.1 gives a brief description of the content and structure of the chapter.

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* Part of this chapter has been published in the paper "Augmented IDEF1-Based Process-Oriented Information Modeling" in November 2004 on the Journal of Automation in Construction, Vol. 13, No. 6, pp. 735-750, Elsevier Ltd, UK (Please see Publications (Page 308) for details).

- Section 4.2 explains the necessity to integrate process model and information model.
- Section 4.3 is a comparison of the existing process modeling methods and it explains how and why the IDEF0 methodology is finally selected.
- Section 4.4 does the comparison among the existing information modeling methods and the IDEF1 methodology is finally selected. Considering the nature of IDEF1 and current usage environment, this section proposes that some enhancements to IDEF1 are needed.
- Section 4.5 provides the basic concepts of selected methodologies as well as the enhancements to IDEF1 method.
- Section 4.6 provides the detailed description of the process-oriented information modeling methodology.
- Section 4.7 introduces the new processes for IFC extension development based on process-oriented information modeling methodology.
- Section 4.8 concludes with a summary for the chapter.

4.2 Necessity to Integrate Process Model and Information Model

Process models have many applications and have been used for several years to describe and manage enterprises. As the arguments issued by Eriksson and Penker (2000), the process model can give a better understanding of an existing business, and it can act as the basis for creating suitable information systems that support the business. The model facilitates improvement of the current structure and operation and an innovated structure can be presented by means of a process model.

Information modeling is a technique for specifying the form and content of information requirements that are needed within the application domain. An information model specifies how information is logically arranged. The model defines the information entities within a system or process and specifies the interrelationships among the entities.

Oliver et al. (1997) provided insight into the relationship between information models and process models. An information model is used to provide a greater understanding of the information needed by the engineering process. Thus, a process model, together with an information model, defines what is the "right" information. Information models are needed in addition to process models to provide a comprehensive view of the information that makes effective and efficient communication possible.

Therefore, defining an information model based on processes should be a necessary and effective way in the information analysis. However, organizations rarely create one. One reason is that there has been little published work on how to create an information model of a systems engineering process and what notations provide the best approach. This research addresses the problem by developing a generic methodology for modeling process-related information. The methodology will be used to build an information model for the benefit of the developing of integrated building design system.

In order to develop such kind of generic methodology, it is necessary to undertake an investigation into the different types of modeling techniques available, so as to enable the assessment of which techniques would be best for this specific situation, as described in Section 4.3 and Section 4.4. Based on these, the process-oriented information modeling methodology is proposed as a new approach for information requirements analysis.

4.3 Selection of Process Modeling Method

4.3.1 Comparison of Existing Process Modeling Representations

How to choose the most suitable method? Godwin and his associates (1989) have done work on creating a methodology to assess systems development tools. Fulton et al. (1999) has also created a set of requirements to modeling tools and methodologies for integrated manufacturing information systems. In this research a key subset of the requirements is adopted as the basis on which the process modeling methods are compared. The comparison of process modeling methodologies is presented in Table 4.1.

Table 4.1 Comparison of Existing Process Modeling Methods

		Levels of Abstraction	Hierarchy	Ease of Use	Flexible	Versions Control	Constraints	Exceptional Events	Sequences & Interactions	Flows & Quantities	Resource Requirements	Relationships & Aggregates	Verifiable/ Testable
Process/Flow Model	ACT										×		
	Behavior Diagrams							×		×	×		
	FFBD		×					--	×				
	Gantt Charts	×	×					×			×	--	
	IDEF0		×	×			×		×	×	×	--	
	IDEF2								×	×	×	--	×
	IDEF3		×				×		×			--	
	OZONE		×						×		×		
	PAR2		×						×		×	×	
	Part 49										×		
	PFR		×						×		--		×
	VPML		--						--		--	--	
	DFD		×	×	×					×		--	
	SAMM		×						×	×	×	--	

(Note: '×' means the corresponding method can satisfy the requirement shown in the column completely. '--' means it can satisfy the requirement partially.)

An explanation of various requirements is given below.

<u>(a) Levels of Abstraction</u>

This is the ability of the model to describe levels of detail. The ER/EER, IDEF1 have the capability to do this via abstraction hierarchies; the other methods have no vehicle to do this.

(b) Hierarchy

This is the ability of the model to break down hierarchically into a more detailed description. IDEF0, DFD, SAMM and IDEF3 all have a hierarchical breakdown from a general level to a more detailed description.

(c) Ease of Use

This is the ease of learning, using, and interpreting/communicating the method. IDEF0, DFD, ER/EER, and NIAM are relatively easy to learn, use, and read, while the others increase in complexity.

(d) Versions Control

This is the ability to maintain a history of versions of the model, and regulate changes. None of the methods have this capability.

(e) Constraints

This is the ability to describe and incorporate any process and information constraints that exist. IDEF0 incorporates constraints, and IDEF3 has a way of detailing constraints with a language; but the others can not.

(f) Exceptional Events

This is the ability to incorporate events such as human error, mechanical failures, electrical failures, start-ups, and shut-downs. All of the methods are generally suited for steady-state, success-oriented situations, but do not account for unusual events.

(g) Sequences and Interactions

This is the ability to describe the sequence in which events occur, the timing of the events, and the interactions events have with other events. This really does not apply to the data models; all of the process models can do this, except for DFD, which only shows the flows but not the interactions and sequences.

(h) Flows and Quantities

This is the ability to describe the flows of material and information and the quantities of the flows. The process models, except IDEF3, can do this; the data models all lack this, being weak in the dynamic aspects of modeling.

(i) Resource Requirements

This is the ability to describe the resources required -- manpower, machines & tools, computer hardware, and materials. IDEF0 and IDEF2 require that the resources supporting the processes and events be included; SAMM generates amount of data, allowing computer resource requirements to be estimated; the other methods are lacking in this regard.

(j) Relationships and Aggregates

This is the ability to describe groupings of information and materials (bundles, kits, et al.) and relationships between information and materials. All the data models can do this, which is useful for implementing on a database; applicability to the process models is questioned.

(k) Verifiable/Testable

This is the ability to verify and test that the model is essentially a correct representation of reality. IDEF2 is implementable on computers, and dependency diagrams can be rigorously checked, but the others are weak in this--the correctness of the model depends on the creator's knowledge of/familiarity with the method and his implementation of it.

4.3.2 Selection of IDEF0

The requirement for an appropriate method is that it can satisfy the basic function requirements. Generally all the above methods have this function which has already been validated during past years. As can be seen in Table 4.1, none of the methods is comprehensive. Some areas are not addressed at all. At this time, the ease of use should be considered as one of key decision criteria in order to increase the usability of this method, even for person who has never been involved in any modeling activities and has little knowledge about this area. A user-friendly modeling method should be selected when it could achieve the primary functions.

On the other hand, during the long history of IFC development since 1995, IAI has formed a set of standards, conventions, rules and guidelines for the IFC models development. And a set of languages and modeling tools are preferred to support the IFC extensions development, which is explained in Section 4.7. Traditionally, the developer provides the definition of domain processes through the IDEF0 process models which are formal descriptions of the tasks undertaken to complete a defined industry process and set them into a sequence. As an easy-to-understand process modeling method, IDEF0 has already been proposed for the future IFC releases. The IDEF0 process model is taken for granted as the basis for identification of the object model scope.

The two points mentioned above make IDEF0 a preferred model to others. In addition, when compared with another modeling method in the same system, IDEF3, the use of IDEF0 is also preferable. This is because the objective of this research is not to consider the sequencing of the activities in a process, nor to highlight their eventual simultaneity, but to direct attention to the objects that participate in the process, such as control, input, output or mechanism.

The primary strength of IDEF0 is that the concise method has proven effective in detailing the system activities for process modeling. Also, the description of the activities of a system can be easily refined into greater details until the model is as descriptive as necessary for the decision-making task at hand.

The advantage of IDEF0 modeling is that the method fits well with the sequential process of construction decision making. The structure of the input, output, constraints and support mechanism of each process is also easily understood by people without prior modeling skills. Of all methodologies discussed above, the Integrated Definition (IDEF) methodology is perhaps the simplest to use and the easiest to extend. It has been broadly accepted by companies to model diverse processes (SofTech, 1981). Furthermore, it has already been taken for granted as a recognized process modeling language by IFC developing members. Domain experts, with some guidance from modeling specialists, can create and understand process models with little training.

4.3.3 Basic Concepts of IDEF0 Process Modeling

IDEF0 is a method to produce a process model which is a structural representation of the functions of a manufacturing system or environment, and of the information and objects which interrelate those functions. It is a top-down hierarchical method, which allows for system definition in any level of detail, down to the level required for analysis (Bravoco and Yadav, 1985a). As a communication tool, IDEF0 enhances domain expert involvement and consensus decision-making through simplified graphical devices (Lu, Ang and Gay, 1996). As an analysis tool, IDEF0 assists the modeller in identifying what functions are performed, what is needed to perform those functions, what the current system does right and what the current system does wrong. Thus, IDEF0 models are often created as one of the first tasks of a system development effort.

4.3.3.1 The Elements of a Process Model

The basic concepts of IDEF0 are shown in Figure 4.1. A process is shown in a process model as a rectangular box. It contains a unique text description or label that describes what the process is. The label may contain several words and these are usually justified about the centre point of the box (both horizontally and vertically). The size of the process box can be increased to enclose the description. A process is an action. Because of this, the label is expressed as a verb phrase. For instance, in a process model, the load calculation process in structural design would be labeled as "Calculate Load Value" and not as "Load Calculation".

Arrows are constraints (input, output, control and mechanism) that define the box. "Data" labeled on arrow may be information, objects or anything that can be described with a noun phrase. The input data (on the left) are transferred into output data (on the right). Controls (on the top) govern the way an activity is done. Mechanism (on the bottom) indicates the means by which a function is performed.

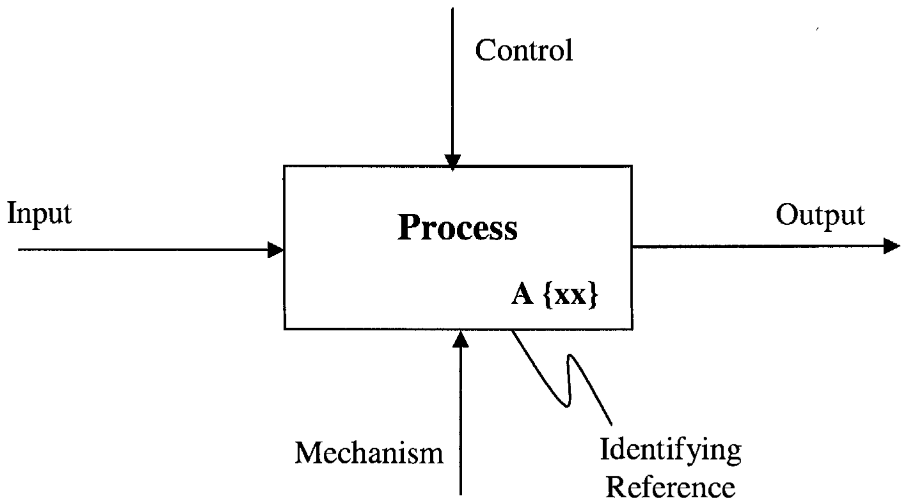

Figure 4.1 IDEF0 Functions
(Adapted from NIST, 1993)

Decomposition

IDEF0 allows the structure of a system to be represented in a hierarchically structured set of diagrams. The top-level diagram in the hierarchy represents the system as a set of interacting activities, as shown in Figure 4.2. The second-level diagrams represent each of these (top level) activities as a set of interacting (lower level) activities, and so on down through as many levels as are necessary. A process at the higher decomposition level is a 'parent' process and may be regarded as describing the boundary of the page on which the sub-processes at the lower decomposition level are drawn. The sub-processes are drawn on a 'child' model and are wholly contained within the boundary of the parent process.

Decomposition allows a process to be described initially in a broad manner, e.g. "Do Structural Design" and then decomposed into sub-processes like "Do the Preliminary

Design", "Produce the Structural Analysis" and "Do the Detailed Design" etc. As required, sub-processes may be further decomposed until further decomposition is not possible or necessary.

A process, when decomposed, has its own sub-processes. These do not take part in the decomposition of any other process. Thus, there is no overlap between the decomposition of one process and the decomposition of another process.

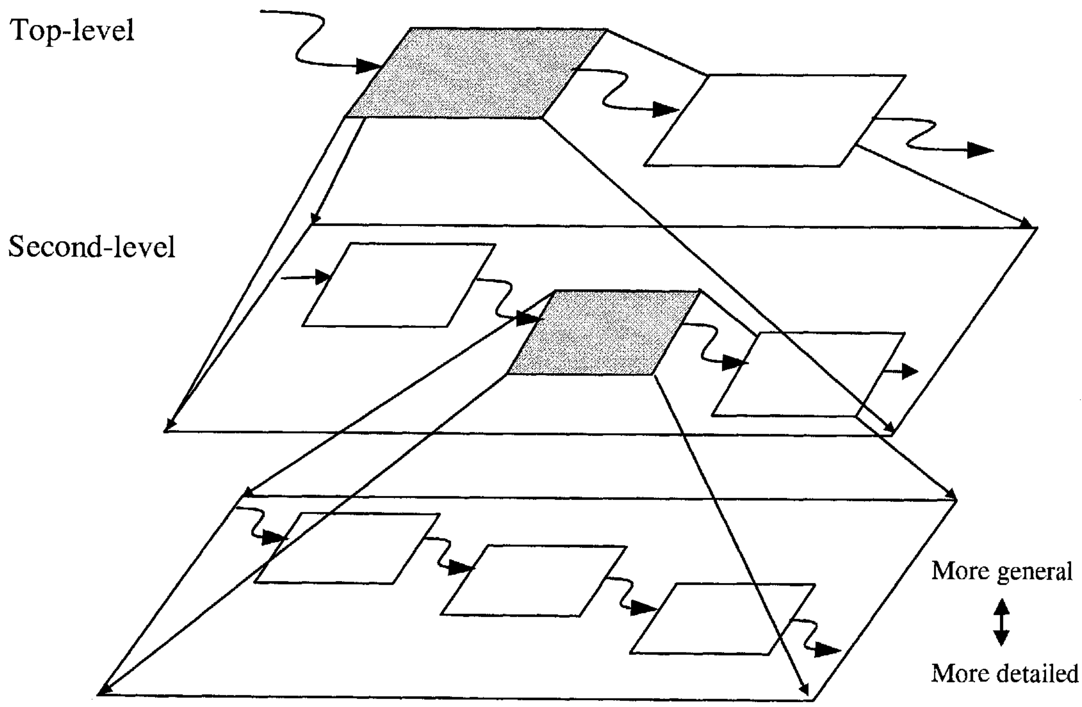

Figure 4.2 Decomposition of IDEF0 Diagrams (Adapted from NIST, 1993)

4.3.3.2 Data Collection for IDEF0

When analyzing or designing any system, it may be necessary to obtain or verify facts about the system or subject matter at hand. There are many sources of factual information. The following ways are suggested by NIST (1993):

- Read existing documents, using each table of contents and index to locate needed information.
- Observe the system in operation, if it already exists.
- Survey a large group of people, through questionnaires or other such means.
- Talk to one or more experts who possess the desired knowledge.
- Use whatever is already known by the author.
- Guess or invent a hypothetical description, and ask readers to help bring it closer to reality.

Requirements capturing is carried out through case studies and interview techniques. It involves the researchers identifying several previous and on-going projects and collecting project information. Interviews with the key professionals help to define the main project processes and the decision-making sequences.

Of all these methods, the most important is face-to-face interaction with an expert. Seldom will all existing information be written. Preconceived notions that are reflected in questionnaires are often faulty.

The purpose of an interview is to gather information from an individual who possesses an expertise and is considered important to the analytical effort. There are four types of interviews that might be conducted during the course of performing the analysis phase of an IDEF project (NIST, 1993):

(a) Fact finding for understanding current operations. This type of interview is used to establish the content of a current operations model or to help understand the existing environment.

(b) Problem identification to assist in the establishment of future requirements. This type of interview is used to validate the current operations model and to provide the foundation for a future operations model.

(c) Solution discussion regarding future system capabilities. This type of interview i used to establish the content of a future operations model.

(d) IDEF author-reader talk session. This type of interview is used to resolv problems which have surfaced during the construction of an IDEF model.

4.4 Selection of Information Modeling Method

4.4.1 Comparison of Existing Information Modeling Methods

Using the same comparison parameters in Section 4.3.1, Table 4.2 shows the difference among the existing information modeling methods reviewed in Chapter 2.

Table 4.2 Comparison of Existing Information Modeling Methods

Information Model		Levels of Abstraction	Hierarchy	Ease of Use	Flexible	Versions Control	Constraints	Exceptional Events	Sequences & Interactions	Flows & Quantities	Resource Requirements	Relationships & Aggregates	Verifiable/ Testable
	ER/EER	×		×	×				--			×	
	IDEF1	×	×	×	×				--			×	
	NIAM			×	×		×		--			×	
	Semantic Nets		×	×		×							×
	Express		×		×		×					×	
	UML	×	×		×				--				

(Note: '×' means the corresponding method can satisfy the requirement shown in the column completely. '--' means it can satisfy the requirement partially.)

4.4.2 Selection of IDEF1

Based on Table 4.2 and consider the possibility of integration with IDEF0, IDEF1 is selected as the preferred method because both of them belong to the same family. The IDEF family has about 14 methods, each of which is used to describe or model a system from its own perspective. Each type of model or description focuses on a relatively narrow set of relationships and system characteristics comprising a particular viewpoint of the overall system. They describe different information and knowledge of the same system. Therefore, each type of model cannot be converted or generated from another type of model directly and automatically.

However, as these models are the models of the same system they should have consistency, to a certain degree, with each other. Some rules can be found to ensure consistency among various types of models. Secondly, these models should share some common information or data sources although the models describe different characteristics or relationships of common data.

Therefore, the integration of IDEF methods, in which various types of IDEF models are created, is necessary and feasible on the basis of these two points mentioned above. Additional, considering that the IDEF methodology is more integrated within itself (IDEF0, IDEF1, and IDEF2) than the other methodologies, the IDEF1 method was finally chosen.

IDEF1 is a method to establish the requirements about what and where information is used or should be managed by the enterprise (Mayer, 1992). IDEF1 is generally used to 1) identify what information is currently managed in the organization, 2) determine which of the problems identified during the needs analysis are caused by lack of management of appropriate information, and 3) specify what information will be managed in the TO-BE implementation. It is designed to assist in discovering, organizing and documenting the information image of physical and conceptual objects (e.g. people, places. things, ideas, etc.) found in the real world.

IDEF1 has proven to be an effective method for documenting the informational requirements of an enterprise. The IDEF1 modeling exercise provides a foundation for database design, gives a definition of the information structure, and provides a requirements statement reflecting the basic information needs. IDEF1 uses a disciplined, structured technique to uncover the information and business rules used by an organization. This gives needed rigor to the method for untangling the complex challenge of modeling the information of the organization. Finally, information models are useful throughout the life-cycle of the enterprise.

4.4.3 Necessity to Enhance IDEF1

However, IDEF1 is too simple to be used for representing information. It only reflects that some kinds of relationship may exist, but cannot clarify the kind of relationship that exists, such as the relationship of hierarchy. To support the development of an integrated approach and model the information requirements completely and clearly, enhancements to the well-established IDEF1 information model are deemed necessary.

Moreover, most modern systems contain a significant amount of software, and efforts to develop them must successfully integrate systems and software engineering. A process that integrates systems and software engineering should use an information modeling technique that is compatible with both disciplines. Object-oriented techniques are good candidates because they have been used by the software community for years and are coming to be used by systems engineers (Oliver, Kelliher, and Keegan 1997). The overwhelming popularity of object-oriented analysis and design has been witnessed in recent years. This phenomenon is evidenced by the number of articles and papers published in various journals, conference proceedings, books, and other forms. The object-oriented modeling methodology is one in which the data are grouped into packages which occur "naturally"; this makes it compatible with the way people think about the real world (Kilov and Ross, 1994). It allows for data abstraction, inheritance, information hiding, and dynamic binding.

Correspondingly, reusability is consistently presented as one of the key benefits of object oriented software development. Meyer (1987) stated, "object-oriented design is the most promising technique now known for attaining the goals of extensibility and reusability." Meyer (1988) and Booch (1994) also said that the use of the object model encourages the reuse not only of software but of entire designs, leading to the creation of reusable application frameworks. Object-oriented techniques yield structures that are more readily reused than other design techniques (McGregor and Sykes, 1992). It (object-oriented development) was intended to promote future reuse and reduce downstream errors and maintenance (Rumbaugh et al., 1991). These positive comments have confirmed the importance of object-oriented concepts and trend for popular use in future.

In this research an enhanced IDEF1 methodology conforming to object-oriented concepts is developed in order to not only specify detailed information and let the model have good extensibility, but also for it to be easy to be used. The detailed concept of this enhanced methodology will be explained in the following section.

These enhancements to IDEF1 allow additional classes of knowledge. The additional enhancements include: introduction of domain class, and supplements of types of relationship between entity class.

4.5 Augmented IDEF1 methodolody

The basic concepts of enhanced IDEF1 are very similar to IDEF1. But in respect of relationship and entity types, some new thoughts are synthesized within the concept of IDEF1.

Since the augmented IDEF1 inherits all the functions and notations of IDEF1 and is enriched by more relationship characteristics, it should have all the advantages IDEF1 has and with other additioanl benefits. Enhanced IDEF1 enforces a modularity that eliminates the incompleteness, imprecision, inconsistencies and inaccuracies found in the modeling process. An enhanced IDEF1 information model is a reflection of the entire system and provides a baseline definition of its informational needs, gives a definition of the information structure and provides a requirement statement reflecting the basic information needs. It ensures that the information can be shared and that the information system is integrated.

The components of this model include: entites, domains, attributes and relationships, as shown in Figure 4.3. Entity class and attribute class are represented by a rectangular box, and domain class is represented by a grey shadowed box. The relationships between entities are represented by the arrows around the box. The following sections will give the detailed discriptions for these components respectively.

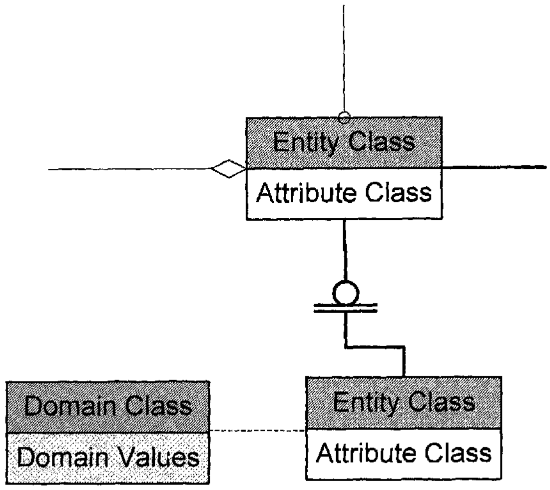

Figure 4.3 An Enhanced IDEF1 Diagram

4.5.1 Entity Class

An IDEF1 entity may be thought of as an object, either real or abstract, that has common properties or characteristics. An entity class refers to a collection of entities or the class of information kept about objects in the real world. Entities have characteristic attributes associated with them. The term attribute class refers to the set of attribute-value pairs formed by grouping the name of the attribute and the values of that attribute for individual entity class members (entities). An entity is represented as a box divided into two compartments shown in Figure 4.3 with the name in the upper compartment. The entity name is a noun phrase that describes the set of things the entity represents. The noun phrase is in singular form, not plural. And the entity name must be meaning full and consistent throughout the modeling.

4.5.2 Domain Class

A domain is a set of all possible values from which an attribute of an entity draws its values. It is not an association between entities. Domains are defined separately from entities in order to permit their reuse and standardization throughout the model. For example, "Load Type" would be considered as a domain, where the set of allowable values for the domain would satisfy the definition of a load type (e.g. Dead Load, Live Load, Earthquake Load, etc.). Similarly a domain is represented as a gery shadowed box shown in Figure 4.3 with the name in the upper layer and domain's value listed in the lower layer. The value list defines the set of all acceptable instance values for a domain. A dash line is used to connect a domain and the entity whose attribute will draw values from the domain.

Most systems support trivial domains equivalent to base types: integers, reals, strings, and sometimes Booleans, date, and time. User-defined domains provide not just better property checking, but also better understanding of the information model, in particular, by getting rid of redundant and inconsistent property definitions (Kilov, 1989).

Domains are considered immutable classes whose values do not change over time. In contrast, entities are time-varying classes; their instance data varies over time as the data is modified and maintained.

Domains are a primary notion with respect to properties: property values belong to a user-defined type, and this type is a domain. Therefore, it is recommended to define domains first and always include a domain name in a property definition. Domain names (unlike property names) should be unique within an application.

4.5.3 Attribute Class

An attribute represents a type of characteristic or property associated with a set of real or abstract things (people, objects, places, events, ideas, combinations of things, etc.). Attributes are associated with specific entities and defined in the lower compartment of entity class (see Figure 4.3). An "attribute instance" is a specific characteristic of an individual member of the set. An attribute instance is defined by both the type of characteristic and its value, referred to as an "attribute value." An instance of an entity, then, will usually have a single specific value for each associated attribute.

4.5.4 Relationships

A relation class can be thought of as the template for associations that exist between entity classes. Relationships are used to represent associations between entities. In enhanced IDEF1, the relationships existing between two entities are classified into four types: dependency relationships, composition relationships, generalization relationships and non-specific relationships. Composition relationships are used to represent an entity "consists of" (in other words, is an "aggregate of") other entities referred as component entities. Generalization relationships are used to represent structures in which an entity is a "type" (category) of another entity. Dependency relationships are used to represent existence dependence between entities. Non-specific relationships are used in high-level Entity-Relationship views to represent many-to-many associations between entities.

(i) Composition Relationships

A composite entity "consists of" (in other words, is an "aggregate of") component entities. A component may or may not exist independent of the composite entity. A composite entity may or may not exist without components. Attributes of a composite are not inherited by components. A component entity may belong to zero or more than one type of composite entity. For example, the relationship between "Structural Model" and "Structural Connection", "Structural Member" would be composition relationship. Structural model is composed of more than one structural members and connections. In IDEF1 diagram, as shown in Figure 4.4, this type of relation is represented by a line drawn between composite entity and the component entity with a diamond at the component end of the line.

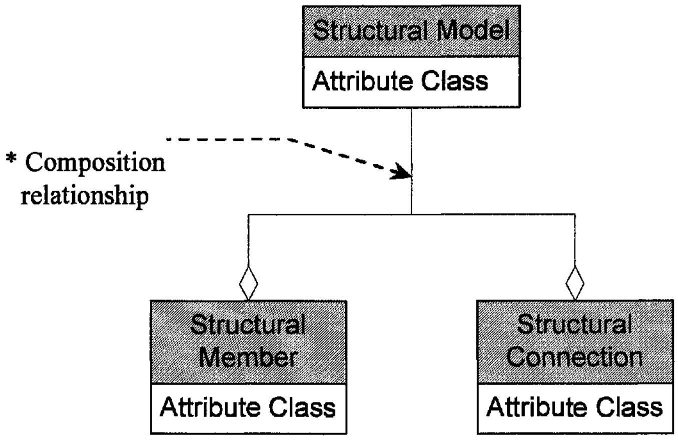

Figure 4.4 Representation of Composition Relationship

(ii) Generalization Relationship

Entities are used to represent the notion of "things about which we need information." Since some real world things are categories of other real world things, some entities must, in some sense, be categories of other entities. A "generalization relationship" is to specify the classification relationship between one entity, referred to as the "generic entity", and another entity, referred to as a "specific entity", which also may be termed as supertype and subtype in some cases. For example, as to structural members, although there is some information needed about all structural members, additional information may be needed about frame members which are different from the additional information needed about shell members. Therefore, the entities "Frame Element" and "Shell Element" are categories of the entity "Structural Member". Here, they are related to one another through generalization relationships.

In fact, the term "generalization" specifies a viewpoint focused on a classification hierarchy. A "category cluster" is a set of one or more generalization relationships. An instance of the generic entity can be associated with an instance of only one of the specific entities in the cluster, and each instance of a specific entity is associated with exactly one instance of the generic entity. Each instance of the specific entity represents the same real-world thing as its associated instance in the generic entity. From the previous example, "Structural Member" is the generic entity, and "Frame Element" and "Shell Element" are the specific entities. There are two generalization relationships in this cluster, one between "Structural Member" and "Frame Element" and the other one between "Structural Member" and "Shell Element".

The associations between a generic entity and its specific entities give rise to two orthogonal constraints: the "exclusiveness" and the "exhaustiveness" of the specific entities.

The exclusiveness refers to whether or not a given generic entity instance can belong to more than one subtype. If it can, the subtypes are overlapping; if not, the subtypes are disjoint. By default, generalization symbolizes an exclusive decomposition. That is, an instance of a generic entity can only be an instance of one of the specific entities. However, a generic entity may be specialized according to several simultaneous criteria. In this case, the specific entities defined under one criterion are not mutually exclusive with those under others. For example, "Structural Member" could be a generic entity in a second category cluster with "Line Member" and "Face Member" as the category entities. An instance of "Structural Member" could be associated with an instance of either "Frame Element" or "Shell Element" and with an instance of either "Line Member" or "Face Member".

The exhaustiveness refers to the participation of all generic entity instances in the subtyping hierarchy. Constraint "complete" indicates every instance of the generic entity is associated with an instance of a specific entity, i.e., the generalization is finished, and it is no longer able to add specific entities. Conversely, "incomplete" constraint specifies an extensible generalization. An instance of the generic entity can exist without being associated with an instance of any of the category entities, i.e., some categories are omitted.

Sometimes a class may be specialized according to several simultaneous criteria. Each generalization criterion could be indicated in the diagram by associating a discriminator with the generalization relationship. The value of the discriminator determines the category of an instance of the generic. In the previous example, the discriminator for the cluster including the line members and face members categories might be named "Member Shape". If a cluster has a discriminator, it must be distinct from all other discriminators.

A specific entity inherits the properties of its generic entity. This relationship is represented by a circle underlined, as shown in Figure 4.5.

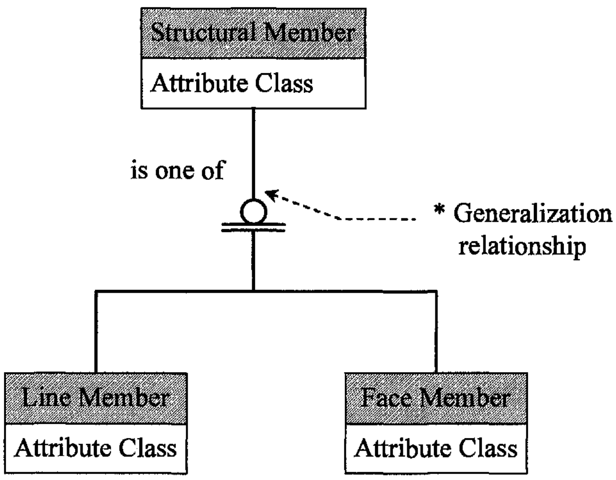

Figure 4.5 Representation of Generalization Relationship

(iii) Dependency Relationships

The existence of an entity instance may be declared to depend on the existence of another entity instance: if the latter is deleted, then the former must disappear as well. And there is no composition or generalization relationships existing between these two entities. This construct represents a dependency association between a parent entity and a dependent entity. Properties of a parent entity do not depend upon properties of its dependent entity.

A dependent entity instance is not necessarily automatically deleted when its parent instance has to be deleted: sometimes the deletion of a parent instance is not permitted if dependents exist. On the other hand, a dependent instance cannot be created unless a parent instance already exists.

For example, in Figure 4.6, a dependency relationship would exist between the entities "Structural Analysis Model" and "Structural Response Model", if no analysis model exists, then no response model will exist. Each response model is a response to a certain analysis model.

A dependency relationship is depicted as a line drawn between the parent entity and its dependent entity with a circle at the dependent side end of the line (Figure 4.4).

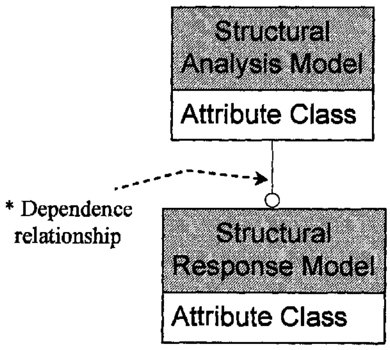

Figure 4.6 Representation of Dependence Relationship

(iv) Non-specific Relationships

All the three relationships previous described are considered to be specific relationships because they define precisely how instances of one entity relate to instances of another entity. However, in the initial development of a model, it is often helpful to identify "non-specific relationships" between entities.

A non-specific relationship in this thesis is an association between two entities in which each instance of the first entity is associated with zero, one, or many instances of the second entity and each instance of the second entity is associated with zero, one, or many instances of the first entity. For example, a kind of material can be assigned to many structural members and a structural member may be constructed by more than one material, then the relationship between the entities "Material" and "Structural Member" can be expressed as a non-specific relationship.

A non-specific relationship can not be represented only by a line. The third party is introduced to deal with this kind of relationship, which is explained in detail in the following Section "Location of Attributes According to Multiplicity Values".

(v) Relationship Naming

Each relation except for non-specific relationships may be named. A relationship is given a name, expressed as a verb or verb phrase placed beside the relationship line. The name of each relationship between the same two entities must be unique, but the relationship names need not be unique within the model. The relationship name for a dependency relationship is usually expressed in the parent-to-dependent direction, such that a sentence can be formed by combining the parent entity name, relationship name, multiplicity value, and dependent entity name. Because a relationship can be named from the parent perspective and dependent perspective as well, in this research all the relationship are stated from the parent perspective. As to non-specific relationships, a third entity will be introduced to as relation class, so it is not necessary to give a name to the line. For generalization relationship, the name of relationship is always "is-one-of" from generic perspective and "a-kind-of" from specific perspective. For composition relationship, the name is always "Has-a" from composite perspective and inversely "Part-of" from component perspective. So in this research these two relationships need not be stated in diagram in order to make diagram concise. The reader can explicitly get information from the type of line.

(vi) Multiplicity of Associations

Each role of an association has a multiplicity value that indicates how many instances of the given entity may be linked to an instance of the other entity. In some cases, it is represented by word "Cardinality". The relationship may be further defined by specifying the cardinality of the relationship.

The default component cardinality is zero, one or many. No any character is placed beside the diamond to indicate a cardinality of one or more. If the cardinality is an exact number, a positive integer number is placed beside the diamond. If the cardinality is a range, the range is placed beside the diamond. Cardinality is not specified for the generalization entity since it is always of zero or one. By convention, default cardinalities are omitted from the actual diagrams in order not to overload them with clutter.

(vii) Location of Attributes According to Multiplicity Values

The process of giving attributes to relationships is most beneficial in the case of many to many relationships. For one to one relations, relation attribute can always be moved into one of the classes that participate in the relationship. For one to N relations, the movement is generally possible into the class on the N side, although it is common to promote the association to the rank of a class, in order to increase its readability, or to accommodate the presence of associations with other classes.

For M to N relationship, the relationship can be replaced with specific relationships later in the model development by introducing a third entity, such as MaterialAssignment, which is a common child entity in specific relationships with the "Material" and "Structural Member" entities. The new relationships would specify that a "Material" has zero, one, or more "MaterialAssignment". Each material assignment is for exactly one material and exactly one structural member. Entities introduced to resolve non-specific relationships are sometimes called "intersection" or "associative" entities. Two thick black lines connect two main entities with the "intersection" entity.

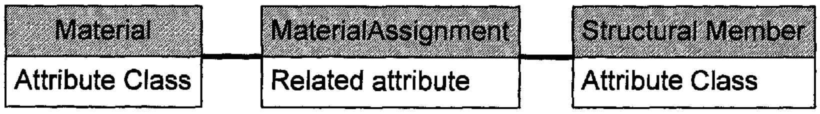

Figure 4.7 Representation of Non-specific Relationship

4.6 Process-oriented Information Modeling (PoIM) Methodology

Most of the recent research works that are related to IDEF methods deal with how to use IDEF methods in various application areas. Some researchers developed enhanced IDEF methods for specific applications. For example, Ang and Gay presented an enhanced IDEF0 modeling for project risk management in 1993. An assessment of

IDEF notations was done by Godwin, Gleeson and Gwillian (1989). Comparison with other tools has been studied in 1988 by Maji. The integration of IDEF methods has been studied and its CASE tools were developed by other researchers (Godwin 1989, Sanvido et al. 1989). System Modeling Corp. tried to integrate SIMAN simulation tools with the IDEF0 model. However, most of them only developed tools for the integration of IDEF0 model with the IDEF2 model or other simulation models. Very little research has dealt with the methodology for the integration of IDEF1 with IDEF0. Only a simple integration of them for CIM information systems design has been studied by Linzhi Lu, Ang Cheng Leong and Robert K. L. Gay in 1996.

In this research, the study would proceed further with the integration of IDEF0 model and augmented IDEF1 information model. Consequently process-oriented information modeling (PoIM) methodology is proposed as a new approach for information requirements analysis. The methodology is an integration of process models and information models. The information model is obtained from process models and all the information is process-related. Through this methodology, the information requirements can be easily identified and analyzed through the corresponding process models. The integration of information model and process model provides a comprehensive view of the information which makes communication more effective and efficient. Besides the principle of integration, some tools are also developed during the methodology in order to assist the modeller in quickly identifying the information.

4.6.1 Principle of the Integration of IDEF1 and IDEF0

In the proposed methodology, each IDEF0 diagram will be converted to a corresponding IDEF1 diagram according to the conversion rules listed in Table 4.3. These conversion rules are found out after examining the basic concepts of both IDEF0 models and augmented IDEF1 models. The integration begins from the relative bottom level IDEF0 diagrams. This is a bottom-up analysis method.

Table 4.3 Conversion between IDEF1 and IDEF0

		IDEF0 Process Model		IDEF1 Information Model
		Component	**Characteristic**	
Basic Elements		Input Output Control	Decomposable	Entity Class
			Indecomposable; Predefined values	Domain Class
			Indecomposable	Attribute Class
Relationships	**Within a Level**	Output— Input Output— Control	Depend-on	Dependency
			Has-a (Part-of)	Composition
			Is-one-of (A-kind –of)	Generalization
			Many-Many	Non-specific
	Between Levels	Outputs in parent diagram — Outputs in child diagram	Has-a (Part-of)	Composition
			Is-one-of (A-kind –of)	Generalization
		Inputs in parent diagram — Inputs in child diagram	Has-a (Part-of)	Composition
			Is-one-of (A-kind –of)	Generalization
		Controls in parent diagram — Controls in child diagram	Has-a (Part-of)	Composition
			Is-one-of (A-kind –of)	Generalization

(a) General Rules for Conversion

The input, control, and output arrows in IDEF0 diagrams should be entities, domains, or attributes. If the element has the characteristic of decomposability, then it is an entity. If not, it is an attribute. Among them, if the value of attribute can be pre-defined, it would be brought into the domain class. IDEF1 and IDEF0 can share the common data, the labels of entity classes. In other words, all the arrows at relative bottom level IDEF0 diagram should be mapped to an entity, a domain or an attribute class in the IDEF1 model. The names can be extracted from the IDEF0 models directly. For example, for the IDEF0 diagram in Figure 4.8, there should be an entity, or a domain, or an attribute named 'O111' because there is an arrow 'O111' existing in the IDEF0 model.

(b) Conversion within a Level of Abstraction

Relationships only exist between entity classes. Possible relationships could exist between output and input entity classes, and between output and control entity classes for the activity being currently analyzed. An IDEF0 three-activity model (Figure 4. 8) is assumed to illustrate these relationships.

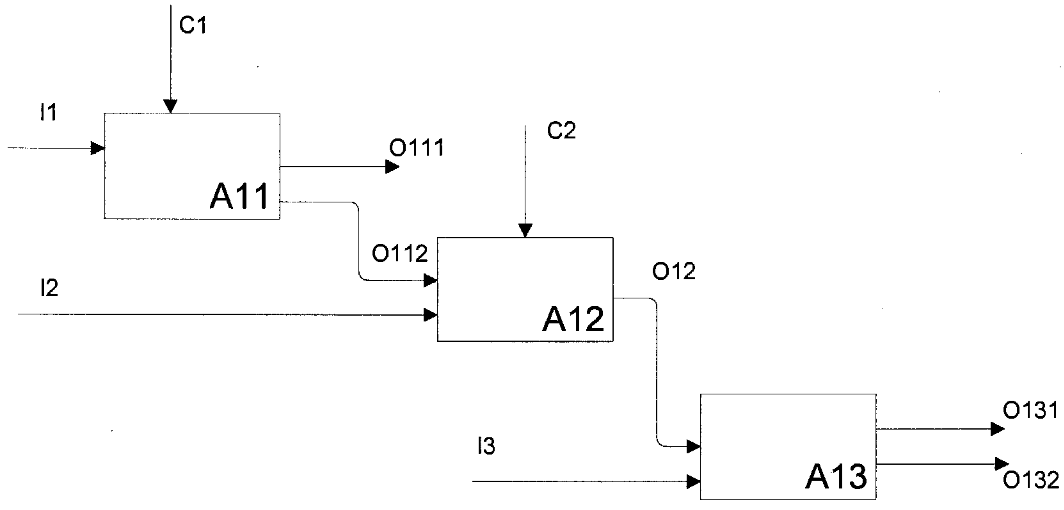

Figure 4.8 IDEF0 Process Model within a Level of Abstraction

From Table 4.4, it can be seen that there are at most 11 relationships existing in this three-activity process model.

Table 4.4 Possible Relationships for The IDEF0 Diagram in Figure 4.8

Activity	Output — Input	Output — Control
A11	O111 — I1, O112 — I1	O111 — C1, O112 — C1
A12	O12 — O112, O12 — I2	O12 — C2
A13	O131 — O12, O132 — O12, O131 — I3, O132 — I3	

The characteristics of these outputs, inputs and controls are used to identify the types of relationships. Generally, the type identification is governed by the following rules:

Rule 1: If these two elements are both entities, the dependency relationship is most likely to exist between them.

Rule 2: If one of elements belongs to a domain class or an attribute class, there is no relationship between them.

Rule 3: Sometimes, a cycle may exist between the output and input of two activities. For instance, B and A could be the input and output of activity 1 and, at the same time, A and B can be the input and output of activity 2. A cycle is formed in this case and, generally, a very weak relationship is thought to exist between A and B, which can be neglected when converted to an IDEF1 information model.

(c) Conversion between Levels of Abstraction

Besides conversion of information within a particular level of abstraction, relationships among information may also exist between different levels of abstraction, or a parent activity and its child diagram, as shown in Figure 4.9.

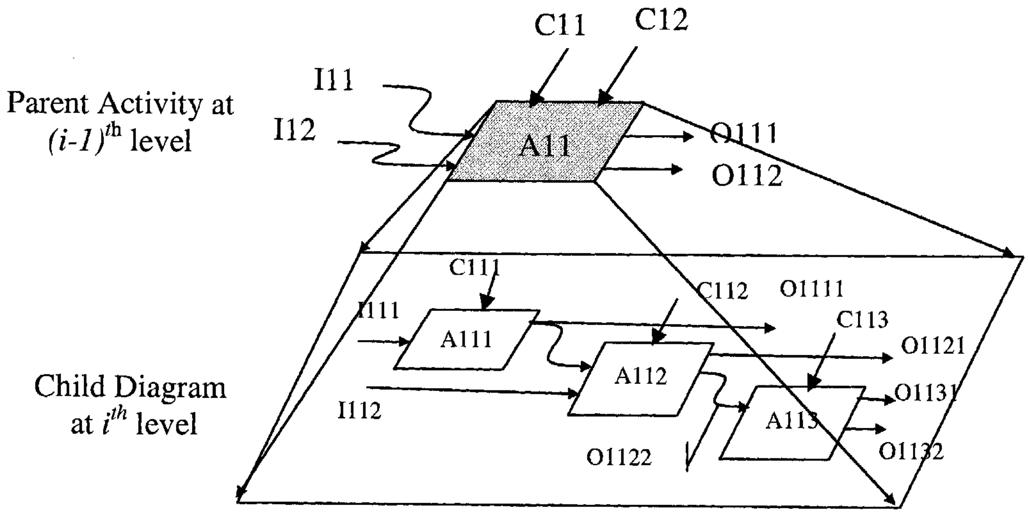

Figure 4.9 IDEF0 Model between Levels of Abstraction

There are five major types of conversion between levels of abstraction, which can be identified as follows:

Rule 1: The composition and generalization relationships most possibly exist between the outputs of a parent activity and the outputs of its child diagram if all outputs are entities.

For example, in Figure 4.9, 'A11' is a parent activity with two outputs, O111 and O112, and has four final outputs in its child diagram, O1111, O1121, O1131 and O1132. Then the relationship existing between them is that the union of all the contents of O1111, O1121, O1131 and O1132 constitutes the contents of O111 and O112. After further analysis, the detailed relationships between them may be divided in such a way that O111 is the union of O1111 and O1121, and O112 is the union of O1131 and O1132. The corresponding IDEF1 model then comprises two sets of relationships. One is between O111 and O1111, and O1121; and the other is between O112 and O1131, and O1132.

Rule 2: The way Rule 1 works is also applicable to identifying the relationships between the inputs of a parent activity and all the inputs in its child diagram, and between the controls of a parent activity and all the controls in its child diagram.

Rule 3: If all the elements in a child diagram are not entities, but attributes or domains, its corresponding parent element should be an entity which has the attributes with the same names as that of the elements in the child diagram. But normally, it is not suggested to break down the process model to such a detailed level.

Rule 4: If an element appears in several levels without any change, this element should be only considered in the top level. That is, this element can only appear once in the developed information model and only the relationships between this element and top-level elements should be considered.

For example, in Figure 4.9, if the input I111 of the child diagram is completely identical to the parent input I11, I111 and its relationships with other elements in the child diagram are not necessary to be considered because it has been included by I11 in the parent activity.

Rule 5: Intermediate outputs in a child diagram will be only considered in the conversion within a level of abstraction. For example, the output O1122 of activity 'A112' in the child diagram is an intermediate output and can be omitted during the conversion between levels.

4.6.2 Requirements for IDEF0 Model

Although from previous studies it can be clearly demonstrated that IDEF0 is well accepted by those who have themselves participated in a modeling exercise using IDEF0, there are still some problems with the IDEF0 method. One is that the diagrams can easily become fairly complex. However, if a model's structure is too simplistic, it tends to become trivial, without much explanatory content left. Also, the pure hierarchical tree structure of diagrams forces developers to compromise in choosing the model structure sometimes. Comprehensive IDEF0 models are often found to be difficult to understand by people who do not directly participate in the model development.

According to the original IDEF definitions, arrows are constraints that define the boxes. Arrows may be information, objects or anything that can be described with a noun phrase. Therefore arrows of the IDEF diagrams at the relative bottom level may not be entities.

In order to integrate the IDEF1 model with the IDEF0 model successfully, the following requirements should be met in the IDEF0 model:

- The IDEF0 model should be decomposed to a relative bottom level at which every input and output should not be bigger than an entity class.

- For the information modeling which aims to carry out the interoperability between different software applications, like this research, the decomposition of IDEF0 process model should be from the software applications' perspective. It can be found that the information entered by users can generally be regarded as an attribute to a certain entity. In this circumstance, the meaning of "relative bottom level" mentioned in first requirement can be considered as the layer which is one level higher than the layer for user-entered information. This defines that the IDEF0 model should be decomposed to the level which gives the general classifications of user- entered information. In addition, sometimes the choice values for a parameter is provided by the software, users only select the corresponding value directly in a pulldown menu. Then this parameter can be mapped to a domain class.

- To keep in line with the elements in a parent diagram, the difference between final outputs and middle outputs in the child diagrams should be identified as final outputs constitute the output of the whole diagram.

4.6.3 Procedures to Develop Information Model from IDEF0 Process Model through PoIM Methodology

The previous section describes the corresponding IDEF1 representation of a single IDEF0 activity. However, most IDEF0 diagrams, other than the top-most level, contain more than one IDEF0 activity. For an IDEF0 diagram with multiple activities, each activity can be converted, respectively, to an IDEF1 model, followed by linking all IDEF1 models to form a complete IDEF1 diagram.

The flow diagram for the integration of IDEF1 with IDEF0 through PoIM methodology is shown in Fig 4.10. The flow is theoretically based on the principle mentioned above. There are 8 steps that will be carried out to convert the IDEF0 models into an IDEF1 model, which will be explained in details in Section 4.6.4.

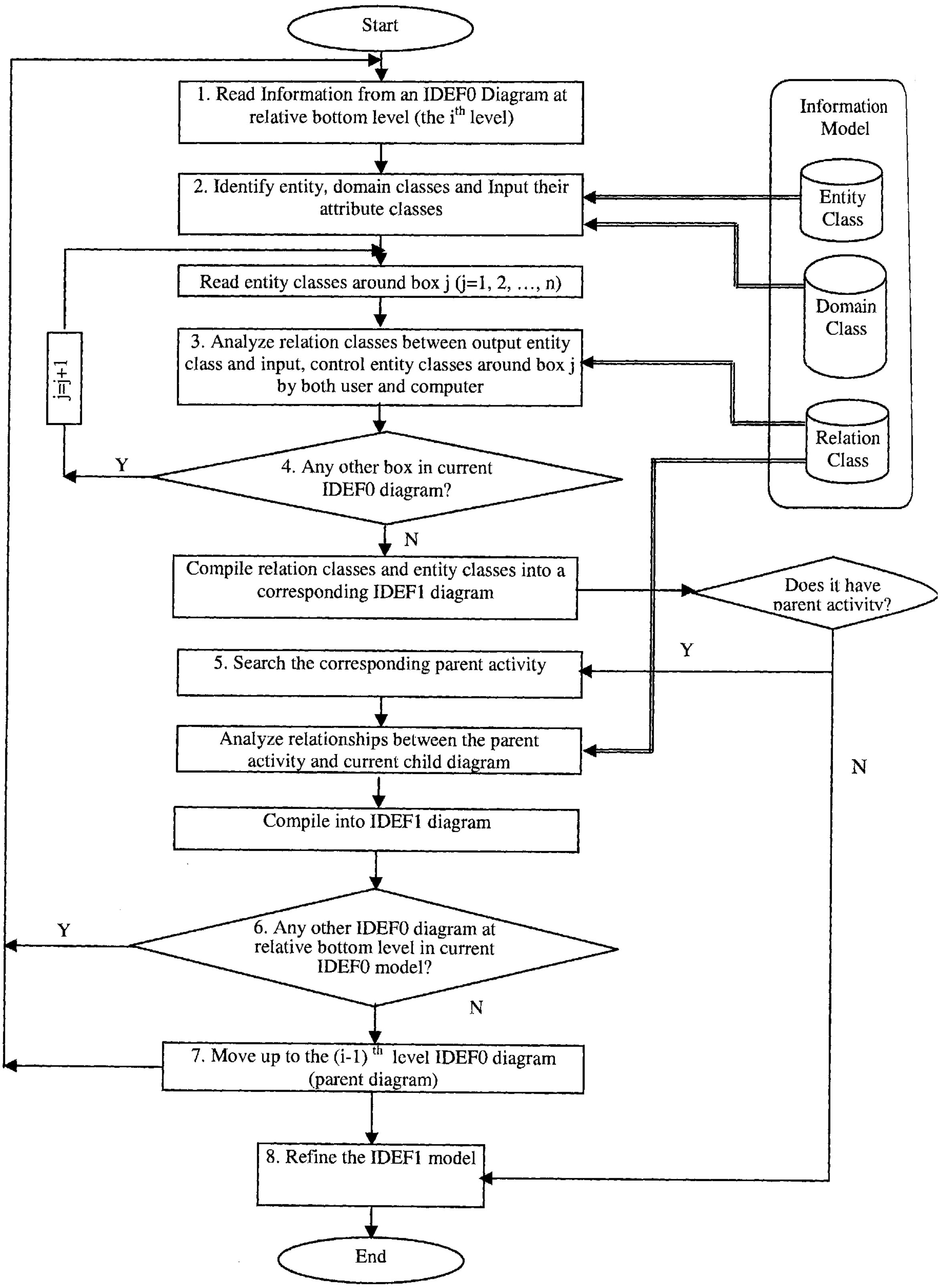

Figure 4.10 PoIM — From IDEF0 Model to IDEF1 Model: The Eight Conversion Steps

4.6.4 Mapping Tables and Information Model

During the conversion, a set of mapping tables is designed to complete the above eight steps. The purpose of the mapping tables is to guide the modeler to identify elements, corresponding information and relationships quickly. The development of this set of mapping tables will give a clear picture for the information involved which can assist modelers to minimize the errors made.

A set of mapping tables usually comprises two types of different tables, which are very similar in structure but different in content. The first type shows the mapping within the same level. The other type shows the mapping between a parent activity and its child diagram. The standard table formats are show in Table 4.5, where the information is extracted from the IDEF0 models in Figure 4.9.

In the following section, the entire eight steps in the mapping process shown in Figure 4.10 to obtain the PoIM information model is described. The process models in Figure 4.9 are used as the example and all the mapping results are listed in Table 4.5. The mapping begins with the activities in child diagram at i^{th} level of Figure 4.9 because they are at the bottom-level of the process model. Table 4.5A and 4.5B present the same-level mappings for the two respective process models in Figure 4.9. Table 4.5C is the mapping between the parent activities and their child diagrams. The focus here is on the procedures to develop information model from IDEF0 model. Therefore, all elements in the example are expressed by abstract symbols and all the relationships are also assumed just for the sake of illustration.

Step 1

Select an IDEF0 activity at the relative bottom level. It is recommended to start with the activity at top-left corner and proceed diagonally downwards. Here the modeling begins with the activity 'A111' in Figure 4.9, which is shown in the first column of Table 4.5A.

Step 2

For every Input, Control and Output interface to the selected IDEF0 activity, add corresponding elements according to their characteristics, which could be an entity, an attribute, or a domain. The name in IDEF1 can be the same name as in IDEF0. For activity 'A111', there are totally one output 'O1111', one input 'I111' and one control 'C111'. The information is listed in the second and forth columns of the first mapping table (Table 4.5A). The types of corresponding IDEF1 elements are also confirmed in the third and fifth columns, respectively.

Step 3

Identify the relationships between the input and output, as well as the relationship between the control and output, followed by adding them to the IDEF1 diagram. Here, it is supposed that there is a dependency relationship existing between 'O1111' and 'I111'. The relationship information is expressed in the sixth and seventh columns. The same relationship exists between 'O1111' and 'C111 '.

Step 4

Check if any other activity exists in this diagram. If yes, repeats Steps 1 to 3 until all IDEF0 activities have been analyzed. If no, go to Step 5 directly. In Figure 4.9, there are three activities. Similarly, all the inputs, outputs to the other two activities 'A112' and 'A113' should be analyzed. After that, the conversion within a level for the bottom level process model can be considered complete.

Step 5

Use the bottom-up method to find the parent activity in the parent diagram for each bottom level diagram, and add the corresponding IDEF1 elements to the information model. Then identify the relationships between the elements of the parent activity and the elements in its child diagram, as Step 3.

Activity 'A11' in Figure 4.9 is the parent activity. Suppose the inputs to activity 'A11', 'I11' and 'I12', are identical to the inputs of its child diagram, 'I111' and 'I112'. Then there is no relationship between the inputs. And when considering the within-level conversion in Steps 3 and 4, the elements 'I111' and 'I112'', and relationships involved should be omitted because they are included in parent level. The second row of Table 4.5A is made grey to show the essential omission of related relationships, which is actually deleted in the final mapping tables. However, composition relationship exists between its output 'O111' and child diagram's outputs, 'O1111' and 'O1121', and generalization relationship exists between its output 'O112' and child diagram's outputs, 'O1131' and 'O1132'. Similarly, it can be assumed that the control 'C12' is identical to the child diagram's control 'C113' and the other control 'C11' is the composite of child diagram's controls, 'C111' and 'C112'. All relationships have been shown in Table 4.5C. Up to this stage, all the elements and the corresponding relationships in the bottom level process model of Figure 4.9 have been identified.

Step 6

For a complex process model, it is normal to have more than one bottom level diagrams. The main task in this step is to check if any other diagram exists in the bottom level. If yes, repeat Steps 1 to 4 until all bottom-level diagrams are analyzed. If no, go to Step 7 directly. In this example, there is no other bottom level process model, so go to Step 7 directly.

Step 7

After finishing all the bottom-level diagrams, move up to a higher level, which means the parent diagram of the bottom–level diagrams. The first moving is from level *i* to level (*i*-1), where *i* denotes the total number of levels. Take this parent level as a bottom level and repeat Steps 1 to 7 until the top level is reached. A combined and complete IDEF1 information model is then achieved. It should be noted that there is no parent activity for top level diagram. Thus, just the conversion with a level for top diagram is needed.

Now take the process model with activity 'A11" as the bottom level diagram which is not shown in Figure 4.9 and repeat Steps 1 to 7. To keep it simple, it is assumed that this is the top-level diagram and 'A11" is the top activity. The results of mapping within a level are shown in Table 4.5B.

Step 8

Modeling is an iterative process, and refinements are often necessary. As iteration continues, the information model obtained at the end of each iteration can be presented to the users to obtain further feedback. Based on the feedback, either another iteration will start or the information model is finished. In this step, the main tasks include checking if all necessary entity classes are listed, if there are any relation classes missing or any wrong relation classes shown, and if the relation classes are applied correctly in both directions.

Table 4.5 Standard Mapping Tables

IDEF0 Activity	IDEF0 Output	Correspon-ding IDEF1 Element	Relative Input & Control	Correspon-ding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
(A)						
A111	O1111	Entity	C111	Entity	Dependency	Based on
			I111	Entity	Dependency	Based on
A112	O1121	Entity	C112	Entity	Dependency	Based on
			O1111	Entity	Non-specific	Entity: R1
	O1122	Entity	C112	Entity	Dependency	Based on
A113	O1131	Entity	C113	Entity	Dependency	Based on
	O1132	Entity	C113	Entity	Dependency	Based on
			O1122	Entity	Non-specific	Entity: R2
(B)						
A11	O111	Entity	I11	Entity	Non-specific	Entity: R3
			I12	Entity	Dependency	Based on
	O112	Entity	I11	Entity	Dependency	Based on
			I12	Entity	Dependency	Based on
			C12	Entity	Dependency	Based on

(C)

Parent Activity	Parent Element	Correspon-ding IDEF1 Element	Child Element	Correspon-ding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A11	O111	Entity	O1111	Entity	Composition	Has-a
			O1121	Entity	Composition	Has-a
	O112	Entity	O1131	Entity	Generalization	(Has-a) Is-one-of
			O1132	Entity	Generalization	(Has-a) Is-one-of
	C11	Entity	C111	Entity	Composition	Has-a
			C112	Entity	Composition	Has-a

After finishing all the eight steps, based on the mapping tables in Table 4.5, a set of IDEF1 diagrams can be obtained for all the IDEF0 models. The complete information model for Figure 4.9 is presented in Figure 4.11. The work of information requirement analysis and information modeling can be deemed to be completed at this stage.

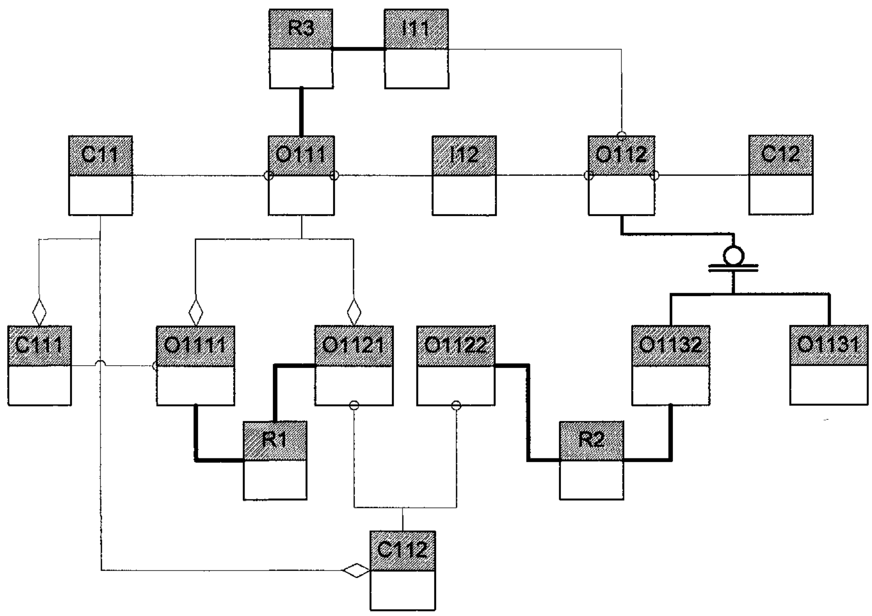

Figure 4.11 Combined Information Model for IDEF0 Model

4.7 Developing IFC Extensions based on the PoIM Methodology

4.7.1 Work Processes for IFC Extensions Development

The work processes to using the proposed methodology on IFC extensions development are schematically described as an IDEF0 model in Figure 4.12 below. The explanations for each activity are given in the following paragraphs.

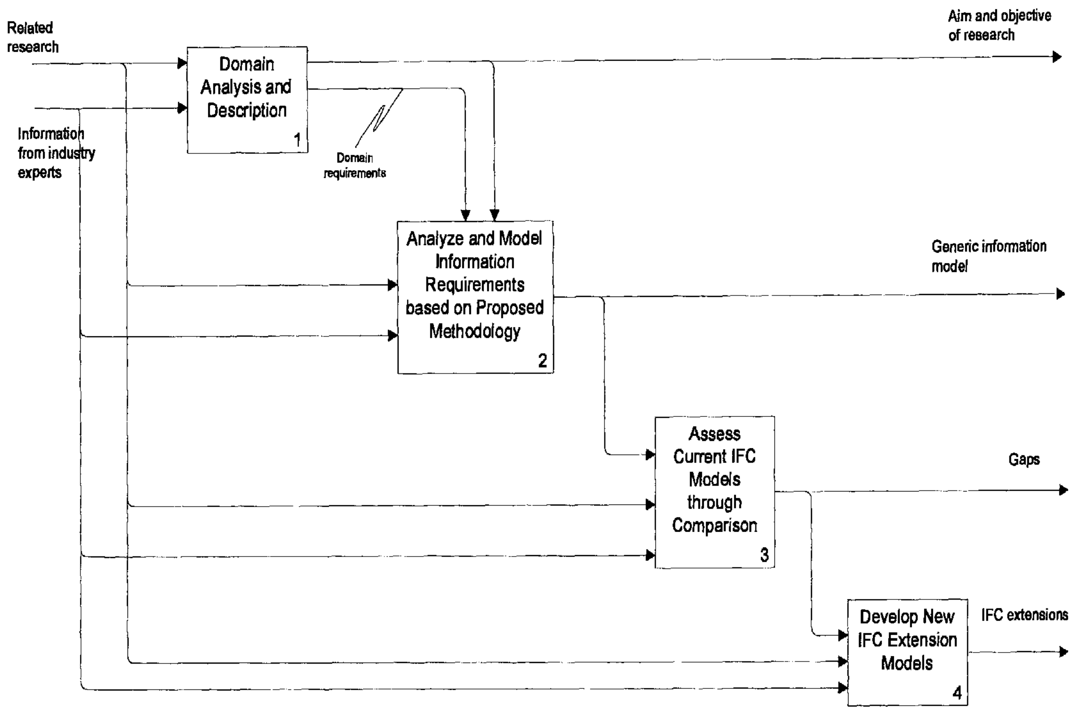

Figure 4.12 Work Processes for IFC Extension Development

The development starts with the definition of the scope of the model's application. The scope statements include the purpose as well as viewpoints of the model, the type of product, the type of data requirements, the supporting scenario, the supporting activities, and the supporting stage in the product life cycle. A well-defined scope should be accurate, unambiguous, viable, and be able to meet the industry's need. During the course of the modeling, the scope should be revisited and may be refined. The scope not only provides the boundaries of the application domain, but also serves as a guideline for evaluating the "completeness" of the information model (Lee, 1999). The scope and processes are described as IDEF0 models.

The next phase is conducting the requirement analysis and modeling. For which collecting adequate and appropriate information is important. There is no standard method for collecting information required and it may be accomplished by: literature survey, standards surveys, domain experts' interviews, and industrial data reviews. Depending on the scope, the analysis may include today's industry practices, traditional practices, and near-future needs. The PoIM methodology will be used to develop the information models, to extract all the information requirements, and to express them in an augmented IDEF1 model. The information model is intended to be independent of any physical implementation and be sufficiently explicit to fully describe the data needs of the application. It can be the basis to define a standard product model.

After comparing the information model with the existing IFC models, the capabilities of IFC product models to support domain of discourse at multiple levels of detail can be assessed and the information gaps can be identified. Then a fully standard product model for the domain will be proposed.

This methodology changes the traditional IFC extensions development processes which would be explained in Section 4.7.2. It is proposed as a new approach for information requirement analysis and to support the standard model development so as to improve the effectiveness and efficiency of IFC extension development.

4.7.2 Traditional IFC Extensions Development

During the long history of IFC development from the foundation year of IAI in 1995, IAI has formed a set of standards, conventions, rules and guidelines for IFC extension development. Referring to IFC 2x Extension Modeling Guide (IAI, 2001) and the major development steps highlighted by Liebich and Wix (1998b), the traditional cycle of one IFC release would comprise the following nine steps:

1. Definition of user requirements;
2. Definition of domain processes;
3. Test by usage scenarios;
4. Specification of domain models;
5. Integration into current release of IFC;
6. Review of new release of IFC;

7. Final documentation;

8. Conformance class definition;

9. Implementation support.

In addition, IAI prefers a set of languages and modeling tools to support the IFC extension development. Figure 4.13 shows the traditional processes of IFC extension development as well as the corresponding language and modeling tools used in the whole process.

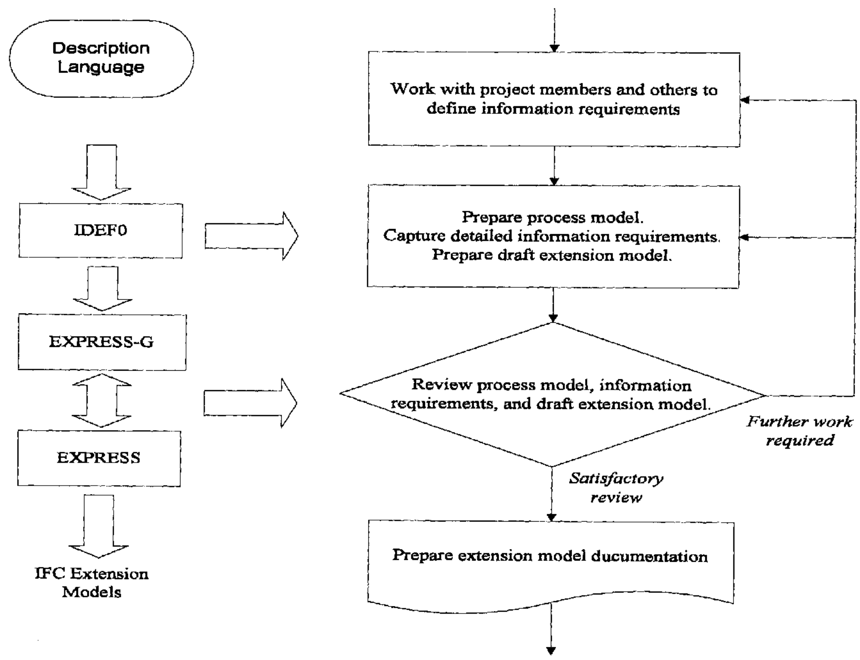

Figure 4.13 Traditional Processes of IFC Extension Development (Adapted from IAI, 2001)

Traditionally, the developer will give the definition of domain processes through process models which are the formal descriptions of the tasks. Based on these process models, the object model scope is identified and the information requirements are captured, analyzed and described by EXPRESS-G. The draft IFC extension model expressed by EXPRESS is then developed. EXPRESS is a textual language to formally specify the information requirements of a product data model and the EXPRESS-G is a subset of EXPRESS (ISO 1993, Schenk et al. 1994). The development of IFC extension models is an iterative process, as refinements are often necessary. All the previous tasks require the active participation of many contributors. The IFC 2x Extension Modeling Guide provides the modus operandi for the collaboration. But it does not require the scope definition and requirements capture which are necessary activities prior to model development.

In recent years the research and implementation activities related to IFC models are actively carried out in different research projects. Most of them emphasize on the development of representations of buildings and the implementation environment for such representations in the integrated system. Very few publications covered the detailed methodology for developing IFC extensions, especially for information requirement analysis. Little research has dealt with the modeling methodology and their integration. For example, a new modeling approach, Process Matrix is proposed by Wix and Liebich et al. in 2002. The approach is based on a modified application of the Generic Process Protocol (GPP), coupled with a dedicated usage of the UML technique. The essence of the approach is in recognising user requirements and use cases (scenarios) in the context of the real building construction process, identifying the actors and actor roles for each individual activity and at any level of detail, and associating these activities with information and communication requirements. The methodology builds upon a formalised specification based on the idea of a reference process matrix which enables its consistent use in downstream ICT (Information and Communication Technology) developments – starting with a general survey of end user requirements to continuously refine these to the level of UML diagramming where the actual software realisation can start. In that respect, this methodology can be seen to support the feasibility and outline design phases of ICT development for AECO (Architecture, Engineering, Construction and Operation). In simple terms, it can be seen as a multi-dimensional table that sets down a series of reference activies and, for each activity, identifies the project participants (actors) sending and receiving information. Its emphasis is placed on the process of sender to send and receiver to receive the information. It gives a detailed illustration to this process, including the actors, activities and the content of activities. But for the material content of information, it does not give an intuitionistic display.

With the maturity of IFC, the subsequent model development will not be the "writing on a blank paper" any more. If the traditional developing process is followed, it is unavoidable to do some repeated work with the finished project. In this situation the traditional developing process is not efficient and effective any more. Therefore in order to avoid any duplicate work and to improve the effectiveness and efficiency of model development, a new IFC extension development based on process-oriented information modeling methodology is proposed in this research.

4.7.3 Flow for IFC Extension Development

Figure 4.14 shows the integrated process and information modeling flow for the model development of IFC extensions. The development starts with the definition of the scope of the model's applicability. The scope specifies the domain of discourse and the processes that are to be supported by the information model which are expressed through IDEF0 models. A second step of the requirement analysis and modeling is conducted. On the basis of the information collected, the process-oriented information modeling (PoIM) methodology is used to abstract the information requirements and to express them in enhanced IDEF1 models. By comparing the modelled information with the latest IFC release, the usefulness of present IFC models is assessed and the gaps between these two concepts can be identified. When an information gap represents a general requirement for the domain, it is necessary for an IFC extension to be developed. Otherwise, different ways could be used to solve the issue of missing information. Therefore some objective rules are expected to guide the extension development process. In fact, this information modeling process can be the basis to define any standard product model, i.e. this methodology is not limited to the use in IFC extension development.

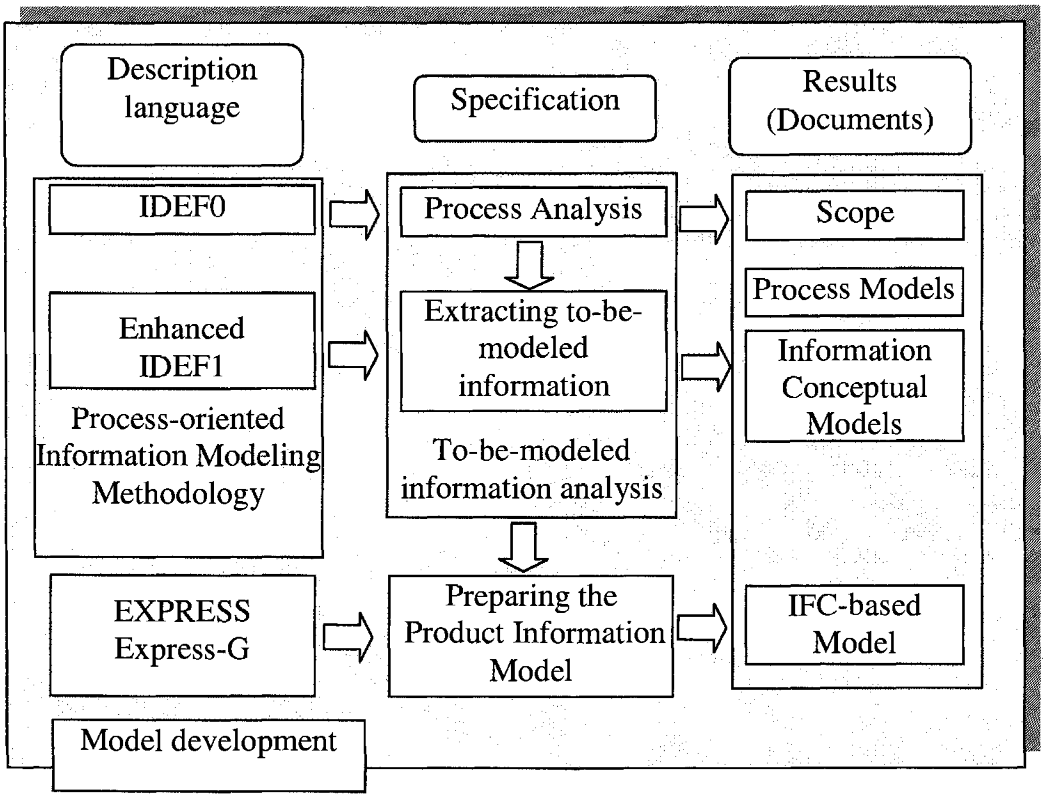

Figure 4.14 Integrated Process and Information Modeling Flow

4.7.4 Ways to Develop IFC Extensions

Based on the information models and guidelines produced by the proposed methodology, there are two approaches to develop the IFC extensions for the domain of discourse and integrate them into current release of IFC. One is to directly develop new standard models for the domain. The other one is to develop the IFC extensions after comparison is made with the current release. In this research, the second approach is preferred because of the existence of ST-4 project in order to improve the effectiveness of development and eliminate any reduplicated works for the same definitions. That is, the development of IFC extensions will be based on the information models and the analysis of existing gaps between the concepts that need to be incorporated for the extension model development and concepts that already form part of IFC Model.

According to IFC 2x Extension Modeling Guide (IAI, 2001), various approaches may be adopted for different scenarios to extend the IFC Model and three scenarios may be observed from gap analysis:

1. Concepts that exist in the IFC Model,
2. Concepts that extend the IFC Model, and
3. New Concepts.

Concepts existing in the IFC Model imply that the classes required by the extension model development already exist in the IFC Model and the attributes of these classes can fully capture the information requirements.

Additional information requirements determined by the extension can be captured by additional property sets, or implementation agreements (locally or globally specified).

Concepts extending the IFC Model mean that the classes required by the extension model development already exist within the IFC Model. But they need extension to fully capture additional information requirements.

Extended information requirements determined by the extension can be captured by: (1) new classes that are subtypes of existing classes or that are related to existing classes, (2) additional property sets, or (3) implementation agreements (locally or globally specified).

New concepts mean that the extension model development specifies information requirements that are not captured by classes at the interoperability layer or domain layer within the IFC Model. Therefore, new classes need to be specified that get support from the fundamental ideas within the resource layer and the core layer. The classes, relationships and attributes for new concepts need to be fully defined, including the connection to the other parts of the IFC Model.

New concepts determined by the extension can be captured by new classes that are subtypes of existing classes, or additional property sets.

4.7.5 Basic Rules for IFC Extension Development

For different scenarios, different approaches are adopted to extend the IFC models, such as additional new classes developed for new concepts. In some scenarios, more than one kind of approaches can be adopted. Additional information requirements can be captured by creating new classes, or adding additional attributes to existing classes or additional property sets. The extension developer has to evaluate which approach is most suitable. Adding new classes or additional attributes to existing classes means change to the corresponding schema. It is open-and-shut for end user to understand what information is required for this domain. But for current works on IFC implementation, whether they have been developed or are under development, this will address the problem to modify current program in order to comply with the new schema. It will impact exchange of files previously generated. Therefore, difficulties or additional iterative works are unavoidably induced for the on-going or finished IFC-implementation activities. However if all missing information is bridged by the way of defining additional property sets, there would not have any influence upon current implementation projects. IFC Property Set provides the capability for dynamic extension.

Therefore the basic rules for IFC extension model development are proposed. Extension model developer should generally try to use the same attribute names and definitions as already exist within the IFC Models to express the same or a similar idea. Adding new classes are minimized to the best of one's abilities. This minimizes conflict and confusion for organizations that will implement the extension model.

IFC Property Set provides the capability for dynamic extension. Referring to IFC 2x Extension Modeling Guide (IAI, 2001), an IFC Property Set is a container that holds collections (or sets) of properties. A property set is (normally) defined externally to the IFC Model. In Section 10.2 of the Guide, the following circumstances are presented as suggestions as to when it may be appropriate to consider using a data driven property set rather than defining a class with attributes within the IFC Model.

- Where a class has a lot of properties that resolve to simple data types,

- Where attributes can be grouped in particular ways that express functional data requirements (for instance, to express different data requirements at various stages of the project lifecycle) and where the same property may need to be repeated in several property sets,
- Where attributes or properties may be used in a particular view, discipline, lifecycle phase or other subset purpose of the object description,
- Where attributes or properties can be used in regional extensions in addition to the international IFC specifications.

4.8 Summary

In this chapter, process-oriented information modeling methodology is proposed as a new approach to analyze information requirements and develop IFC extension models. This methodology provides the principles to integrate process models with information models. With this methodology, the information requirements can be easily identified and analyzed through the corresponding process models. In addition, a set of standard transformation procedures and mapping tables is designed to help the modeller quickly identify elements, corresponding information, and relationships. The development of the set of mapping tables has provided a clear picture of information. Furthermore, the new process for IFC extensions development based on this methodology is also proposed.

This methodology will be used to catch the information requirements as the basis for model development and consequently for system development. In the following two chapters, the general information flow and model of structural analysis and design process from different perspectives are analyzed by this methodology. In this way, the comprehensiveness of the IDEF0 and IDEF1 enhancement, as well as the effectiveness and ease-to-use of the methodology is also demonstrated. From industry user's viewpoint, this research aims at developing methods, IT-based tools and reusable models for information analysis and planning. From an academic viewpoint the research aims at making an original contribution to design and IT research in the sub-domain of design information modeling.

Chapter 5 Information Modeling for Structural Analysis

5.1 Introduction

The IFC specifications are developed from the research projects undertaken by many experts and researchers. The necessary standard of requirements can be achieved by: (1) AEC/FM experts define the requirements; (2) technical experts formalize and integrate the requirements into the specification; and (3) software vendors implement the requirements (IAI, 1999). In this case, the assessment to IFC specifications is also necessary to be concerned with both AEC/FM experts and software vendors. Therefore, in the following two chapters, the information requirements are modeled from the perspective of AEC/FM experts and software' vendors. The IFC specifications are evaluated and subsequently new possible extensions are developed and integrated into the specifications.

In the previous chapter, the process-oriented information modeling (PoIM) methodology is proposed as a new modeling approach. This chapter shows the application of this methodology in the structural analysis domain. The purpose is to provide a generic framework for the structural design process in a higher level by (a) definition of the scope of the model's applicability; (b) analysis of process models for structural design; and (c) identifying the information requirements for structural analysis and design. The information in this chapter was obtained mainly from the literature survey and interviews. It represents a conceptual model for the flow of design information which is not tied to any specific analysis process model. The modeling is based on the classical books on structural engineering and design (Fraser 1981, Biggs 1986, Sriram1986, Maher et al 1988, Payne 1989, Addis 1990, Arbabi

1991, Christiano and Au 1993, Kassimali 1993, West et al. 1993, Rajan 2001, Leet and Uang 2004).

The chapter is organized as follows:

- Section 5.1 gives a brief description of the content and structure of the chapter.
- Section 5.2 gives an introduction to the building design process.
- Section 5.3 proposes the process models for structural analysis as the basis to information model developing.
- Based on the process models constructed in section 5.3 and using the conversion rules of the PoIM method presented in Chapter 4, the generic information requirements for structural analysis are modelled and developed in section 5.4. The relationships between the information of architectural design and structural design are also discussed in order to prove the necessity and feasibility of their integration.
- The capability of current IFC Release 2x Edition 2 and its addendum to support structural analysis is assessed by the comparisons in section 5.5.
- Section 5.6 concludes the chapter with a summary.

5.2 The Design Process

This section provides a broad description of the general building design process, with emphasis on structural design. The design process is based on fundamental concepts, and composed of a few fundamental strategies and operations.

5.2.1 Building Design Process

Building design is a complex multidisciplinary process. It involves not only structural engineering, but also mechanical and electrical systems, architecture, aesthetics, economics, and politics etc.

The success of building design depends on its coordination with other construction activities and building services. For example, structural frames have to be designed and built in collaboration with the other disciplines and services. Plumbing lines and heating, ventilating, and air-conditioning ducts pass through or below floor framing. Electrical conduit is buried in concrete. Walls, doors, and windows are attached to the concrete frame. Owners will insist that the structural frame accommodate other parts of the building with ease.

The main processes involved are shown in Figure 5.1. The introduction to each process is provided below. The shaded boxes in Figure 5.1 show the two processes that are included in this research.

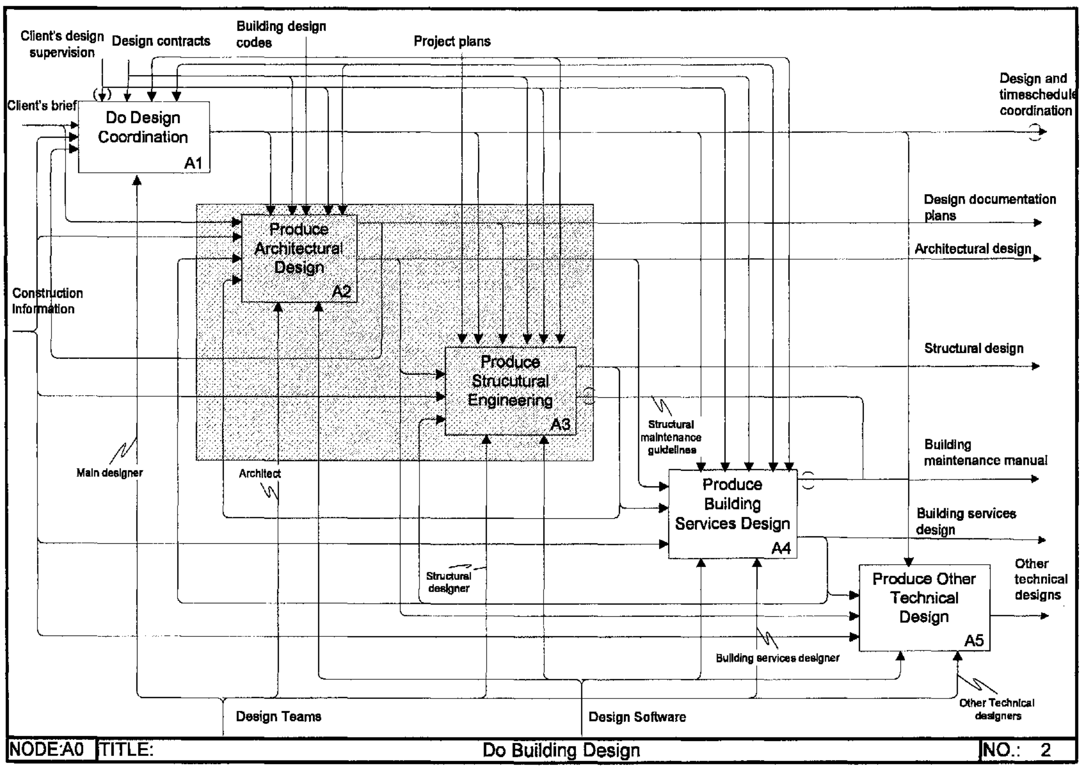

Figure 5.1 Building Design Processes

a. Design Coordination

This is the stage during which client's brief and requirements are established. To enable Clients to specify project functions and permissible costs, Architects, Engineers, Quantity Surveyor, and other members of the design team assist and interpret Client's wishes and provide cost estimates (Serén 2002, Merritt 2001).

b. Architectural Design

Architectural design is a process to plan a building in advance with help of models. The functions of architectural design include carrying out feasibility studies on site, user information and local conditions, in order to (1) establish facts about boundaries, rights of way, rights of light, easements, etc., (2) make preliminary enquiries with Local Authority, Local Planning Authority, etc., (3) obtain outline planning consent.

The architect does the overall planning of the building and incorporates the output of consultants into the contract documents. Services include evaluation, design, drawing, and specifications. The architect determines what internal and external spaces the client needs, the sizes of these spaces, their relative locations, and their interconnections. The results of this planning are shown in floor plans, which also diagram the internal flow, or circulation, of people and supplies. Major responsibilities of the architect are enhancement of the appearance inside and outside of the building and keeping adverse environmental impact of the structure to a minimum. The exterior of the building is shown in drawings, called elevations. The location and orientation of the building is shown in a site plan. The architect also prepares the specifications for the building. These describe in detail the materials and equipment to be installed in the structure. In addition, the architect, usually with the aid of an attorney engaged by the client, prepares the construction contract (Merritt, 2001).

c. Structural Engineering

The term structural engineering is very wide in scope and refers to the design of any system the purpose of which is to resist and transmit forces. It cuts across the traditional fields of engineering, such as civil, mechanical, and aeronautical engineering (Biggs, 1986). Structural engineering is essentially a trial and error procedure. Various experts divided the process of structural engineering to different sub-processes, as shown in Table 5.1 (Fraser 1981, Sriram1986, Addis 1990, Arbabi 1991, Christiano and Au 1993, Kassimali 1993, West et al. 1993, Rajan 2001, Leet and Uang 2004). From the table it can be concluded that typically the structural engineering process consists of four interacting primary stages: conceptual design, preliminary design, analysis, and detailed design (Fraser 1981, Maher et al. 1988, Payne 1989).

Table 5.1 Sub-processes of Structural Engineering

Experts	Year / Functions	Sub-processes			
		Establishing functional requirements, selection structure types	Simple calculation & tentative configurations	Modeling the structure and determine its responses to external effects	Selection and proportioning of the structural components
Fraser	1981	Conceptual design		Structural analysis	Proportioning & detailed design
Sriram	1986		Preliminary design	Analysis	Detailed design
Biggs	1986	Conceptual & panning design	Preliminary design	Rigorous analysis and design	Design
Addis	1990	Client's brief	Scheme design	Detailed design	Final design
Arbabi	1991	Planning &	Conceptualization	Analysis	Design
Christiano and Au	1993	Planning		Analysis	Design
West et al.	1993	Conceptual design	Preliminary design	Selection of preliminary design Structural analysis	Final design
Kassimali	1993	Planning	Preliminary structural design	Estimation of loads Structural analysis	Safety etc. check Revised structural design
Rajan	2001	Need	Preliminary structural design	Intermediat e design	Final design (analysis & design changes)
Leet and Uang	2004	Conceptual design	Preliminary structural design	Analysis of preliminary structural design Redesign of the structures	Final design & analysis

A project begins with a specific need of client. The conceptual design usually involves the recognition of functional requirements of the proposed structure and clients' need, and consideration of the possible types of structures that may be feasible and the types of materials to be used (Fraser 1981, Biggs 1986, Kassimali 1993, West et al. 1993).

In the preliminary structural design stage, the engineer conceives the various structural systems that might be appropriate, and selects or synthesizes a feasible structural configuration that provides the intended structural function, sizes their main components (Leet and Uang 2004, Sriram 1986, West et al. 1993).

The third stage of structural engineering, analysis, involves the transformation of the feasible structural scheme into a mathematical model to estimate the forces and external effects acting on the components of the structure (Maher et al, 1988). It is this area, the structural analysis of the system, which is examined in detail in latter research.

The fourth and last stage, detailed design, involves the proportioning of components or members of the structural system, such that all applicable constraints are satisfied (Christiano and Au, 1993).

d. Building Services Design

Building services design includes mechanical and electrical design, as well as the design on heating, ventilation, and air conditioning (HVAC).

e. Other Technical Design

This refers to any other designs needed, such as the design of external façade.

Figure 5.2 shows the top level processes of building design which set the direction to do further decomposition and analysis. The model in Figure 5.2 provides a basic structure on which a particular system, together with its applications, could be built as a layered architecture. This model should facilitate the endeavor towards integration of the structural design process and systemization of the structural design information. The main focus of this research lies on the process of structural analysis and design. As shown in Figure 5.2, only the activities in shaded boxes have been analyzed in the research.

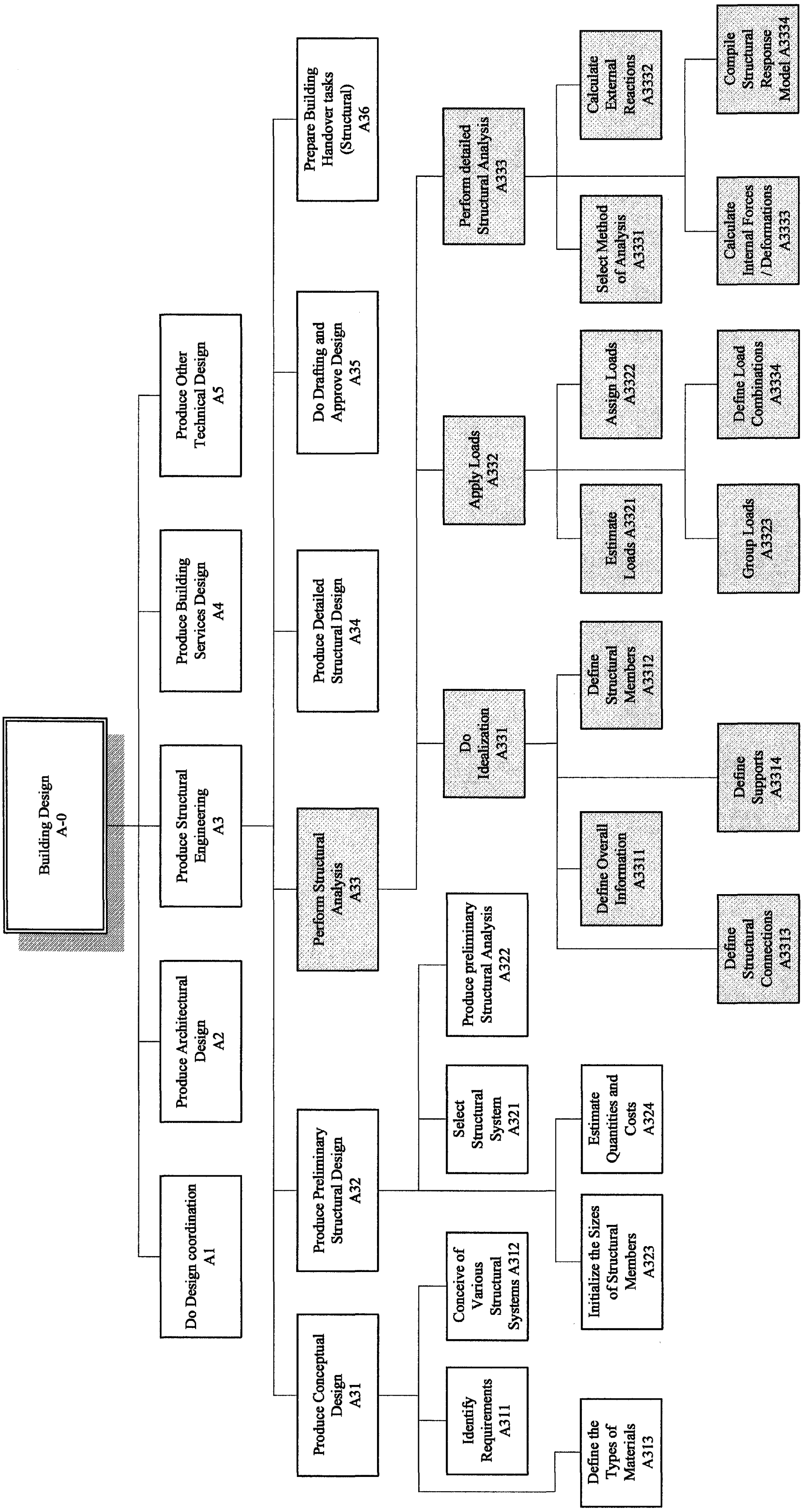

Figure 5.2 IDEF0 Node Tree of Building Design Process

5.2.2 Structural Engineering Process

Structural engineering is the science and art of planning, designing, and constructing safe and economical structures that will serve their intended purposes (Kassimali, 1993). Figure 5.3 represents the process model of structural engineering. Six activities are involved in the whole process of structural engineering. Among them, the most important sub processes are the first four steps: conceptual design, preliminary design (scheme design), structural analysis and detailed design.

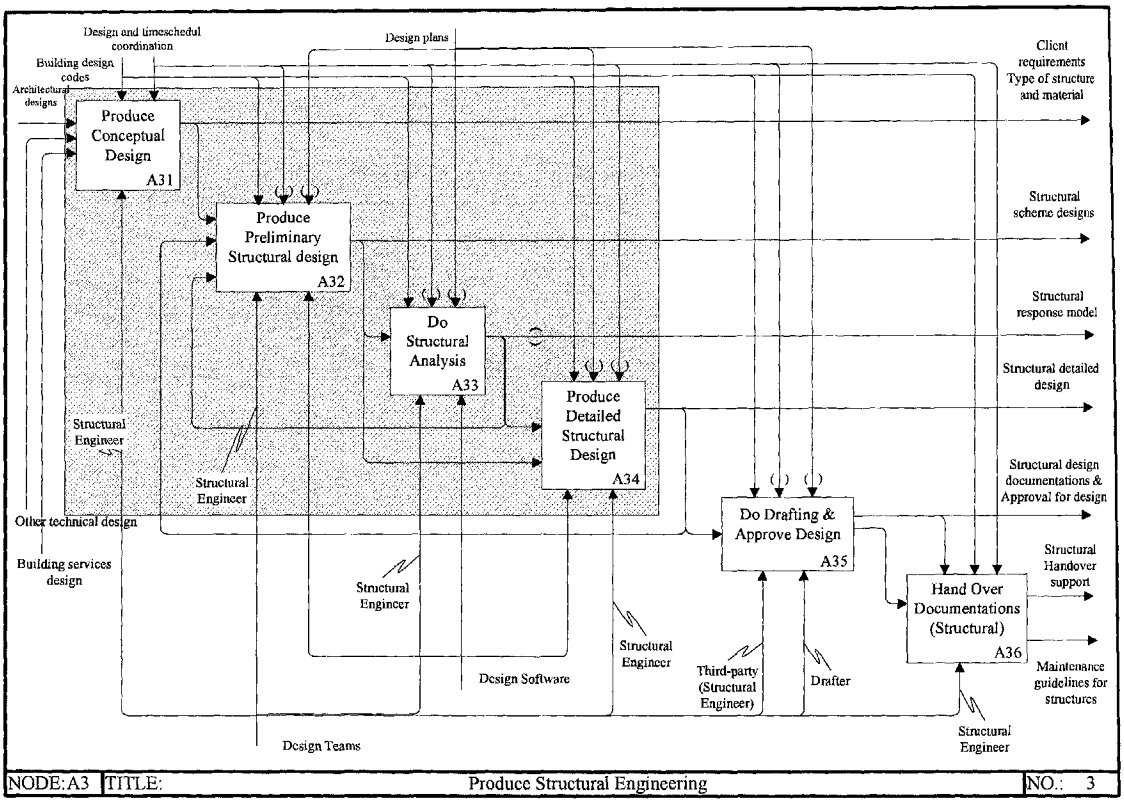

Figure 5.3 Process Model for Structural Engineering

a. Conceptual Design

During the conceptual planning stage, the specific needs are identified and the objectives are carefully articulated to meet these needs. These objectives must be consistent with the desires of the client and the interests of other involved parties (West et al., 1993). This stage requires input from the client, architects, the engineer, planners, the public (in the case of government project and represented by elected officials, governmental regulatory agencies or civic organizations). The conceptual design requires the recognition of the constraints and parameters relevant to the project, and the devising of a type of structure to comply with the demands of the constraints (Fraser, 1981). The conceptual stage should bring forth a plan that maximizes the satisfaction of the stated objectives while minimizing any objectionable features of the project.

b. Preliminary Structural Design (Scheme Design)

The plan that emerges from the conceptual stage frequently includes several alternatives that are to be investigated through the preparation of individual preliminary design. In this step, the framing scheme, the general layout and dimensions of the key elements of the structure such as column are established. The selection of a suitable structural form for a given situation is one of the most important steps in structural analysis. The form that a structure is to take is dependent on many considerations, such as the functional requirements, aesthetic requirements, etc. The development of structural forms is also influenced by the properties of new materials (Christiano and Au, 1993). For a reinforced concrete frame preliminary design is the selection and delineation of a framing scheme and member outlines. The purpose of a preliminary design is to allow the final design to proceed in an orderly manner, especially when it is performed by several individuals and when the structural frame affects the work of other team members (Fling, 1987).

This stage is regarded as the most creative stage in structural design (Harty and Danaher, 1994). Here, rules of thumb and experience are the basis of decision. And comparing with subsequent stages, this stage has greater effect on the quality of a structure. This is because generally the activities of latter stages are based on the constraints imposed by the preliminary design and aim to satisfy them.

c. Structural Analysis

"Structural analysis is the process by which the structural engineer determines the response of a structure to specified loads or actions. This response is usually measured by establishing the forces and deformations throughout the structure. A given method of structural analysis is commonly expressed as a mathematical algorithm." (West et al., 1993)

Structural analysis is an integral part of any structural engineering project, its function being the prediction of the performance of the proposed structure (Kassimali, 1993). The primary objective of structural analysis is to determine the response of a structure in order to satisfy essential requirements of function, safety, economy and sometimes aesthetics. The responses include the reactions, internal forces of members and displacements of the structures. This stage involves the transformation of the feasible structural scheme into a mathematical model to estimate the forces and external effects acting on the components of the structure (Maher et al., 1988). Section 5.3 describes the procedures and information requirements in structural analysis phase. The analysis process can be a part of preliminary design, final design, or construction, as was described in the preceding section.

d. Detailed Design

The detailed design stage involves determining the sizes of the individual members belonging to a structure in order to ensure a safe, serviceable, and economical design. It also involves the proportioning of components such that all applicable constraints are satisfied.

It should be observed that design is almost inseparable from analysis. The exact sizes of structural members can be determined only after a complete analysis of the structure. On the other hand, there are certain items in analysis that depend on the results of design. Hence, the procedure of analysis and design may involve cycles of successive corrections.

e. Draft, Checking and Documentation

After structural analysis and design are completed, it is necessary to transfer the concept and details of the engineer to the contractor who will actually build the structure. Without the proper execution of contract documents, a structural design is useless or dangerous if the builder misinterprets the intention of the engineer. Preparation of clear documents is an essential part of the design.

The results of detailed design are capsulated in a set of complete design drawings, which gives a graphic portrayal of the details of the entire system. These are generally accompanied by written specifications that stipulate the materials to be used, the quality of workmanship, the pertinent codes to be employed, and many other items.

5.3 Proposed Generic Process Model for Structural Analysis

5.3.1 Basis of Structural Analysis

Taking the objective of structural design as a starting point, a generic structural analysis process model is developed. The model is described below, at different levels of detail, with IDEF0 notation.

Structural analysis is the process of modeling the selected structural configuration and determining its response to external effects. Analysis may be viewed as the satisfaction of the functional constraints of equilibrium, compatibility and material stress-strain relationships. It includes the analysis of the loading conditions and the structural response to those conditions. This response is usually measured by establishing the forces and deformations throughout the structure.

For different types of structures, such as planar structures and non-planar structure, as well as planar truss and truss-type space framework, various criteria for statical classification of the structure are applied. Based on the statical classification, including both external classification and internal classification, different analysis method is used and different response is obtained. Different simplification methods and equations of equilibrium are used. Generally, structural response includes the reactions at the support points, the member forces (internal forces) in trusses, and the member forces (shear forces and bending moments) in beams and frames (West et al., 1993). For serviceability requirements, elastic deflections of structures are needed by the computation of deformation quantities. To carry out the analysis, different methods are used, such as complementary virtual work method for the truss deflections, integration method, moment-area method, elastic load method, the conjugate beam method, energy method for the beam and frame deflections. For a static determinate and stable structure, equations of static equilibrium are used to calculate reactions.

For structures as a whole, there is an important distinction between statically determinate and indeterminate systems. For statically determinate cases, the forces can be determined by considering static equilibrium alone, and the deformations are then determined as a function of these forces. Each member deforms according to its own force-deformation relationships, and the overall deformation of the structure will result from the accumulation of the individual member effects. However, for statically indeterminate situations, the determination of forces and deformations must be coupled since they are mutually dependent through the combined requirements of static equilibrium and compatibility. It requires systematic synthesis of the member force-deformation relationships. In either statically determinate or indeterminate structures, the member force-deformation relationships must be known.

The classical methods mentioned above provide exact answers, but only for simple structural models. Presently, a more general approach to structural analysis, matrix methods, is developed. It can handle structures of any size and complexity, but are approximations. Matrix methods model a structure as an assembly of small elements with varying forms of connection between elements. The first matrix methods were frame analyses with individual beams and columns used as elements. More advanced matric methods, usually referred to as "finite element analysis" break an entire structure into small elements and can be used on structures (such as a pressure vessel) with no inherent divisions. Commercial computer software for frame analysis typically uses matrix methods.

However, irrespective of what type of structures and what analysis method is used, the procedure of structural analysis should consist of the following three steps: modeling structural systems (idealization), loading assessment, and performing structural analysis, which is illustrated in Figure 5.4.

The aim of this chapter is to develop a generic model for the process of structural analysis. Considering the differences and complexity in different analytical methods, the process models will be decomposed only to a high level in order to show the basic analytical procedure which is applicable for any type or geometry of structural system designed with its own type of member. The modeling is primarily concerned with the inputs and final results of structural analysis, but not any intermediate output generated during the process using different method. In addition currently most modern methods of analysis require the use of computer for their practical application and most engineers usually use structural analysis and design software to reduce their hand calculations and improve the accuracy of calculations. The detailed requirements for the process of running structural analysis are much more from software's points of view, vis-a-vis hand calculation. Therefore, the emphasis of this chapter is not to discuss the information needed for structural analysis in great detail but rather to model the process of structural analysis in a generic level, and to assess the capability of IFC definitions to support structural analysis from professionals' knowledge in the notional level. The assessment at the detailed level is carried out in Chapter 6 from software's viewpoint.

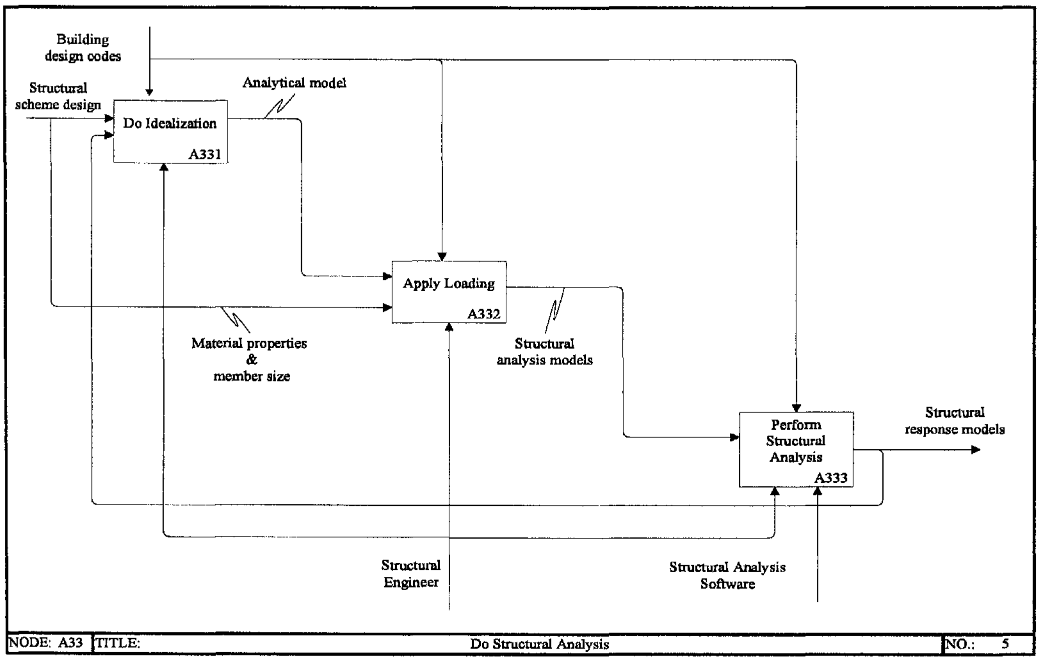

Figure 5.4 Process Model for Structural Analysis

As mentioned before and shown in Figure 5.4, the process of structural analysis consists of three sub processes: idealization, loading application, and performing structural analysis. First is the process of structural idealization, which means to transform the structural configuration from a real structure to an analytical model. Then it requires the representation of the real structure and the loading as well as other conditions to which it is subjected by one or more simplified analytical models, which is then analyzed. These three parts are further described below.

5.3.2 Structural Idealization

For purposes of analysis it is usually appropriate and necessary to simplify or idealize the actual structure. An analytical model is illustrated by a line diagram which is a simplified representation, or an ideal, of a real structure that allow us to calculate forces, stresses, displacements, and strains due to given arrangements of loads or imposed deformations. The objective of the model is to simplify the analysis of a complicated structure. The analytical model represents, as accurately as practically possible, the behavioral characteristics of the structure of interest to the analyst, while discarding much of the detail about the members, connections, and so on, that is expected to have little effect on the desired characteristics (Biggs 1986, Kassimali 1993).

The idealization process is necessary because the human mind, the analytical capabilities of the computer, and the time which can be devoted to the solution of any one problem are all finite, in contrast to the infinite complexity of the object to be analyzed.

Establishment of the analytical model is one of the most important steps of the analysis process; it requires experience and knowledge of design practices in addition to a thorough understanding of the behavior of structures. In structural engineering, the choice of model has important consequences for many aspects of the analytical process. In particular, the choice of model often has a controlling effect on the choice of the method of analysis to be used (Gauvreau, 2003). And the structural response predicted from the analysis of the model is valid only to the extent that the model represents the actual structure. Thus the importance of proper modeling is evident. It is the responsibility of the analyst to make sure that the model adequately reflects the true structural behaviour.

Process Model for Idealization

Structural analytical models generally can be considered as an assembly of components with the purpose of transmitting external loads to the surrounding environment or foundation (Gauvreau, 2003). The makeup of a structural system is rife with details at least concerning three fundamental distinct components—members, connections, and supports. The nature or characteristics of the members, connections, and supports dictate how effectively the system will support the applied loads. Therefore the structural idealization involves four processes as shown in Figure 5.5. First the overall information of the structure should be identified. A set of consistent units must be selected and general information about structure such as the material properties should be given. Then the nature and characteristics of members (also often referred as elements in the technical literature), connections (also often referred to as nodes) and supports should be defined.

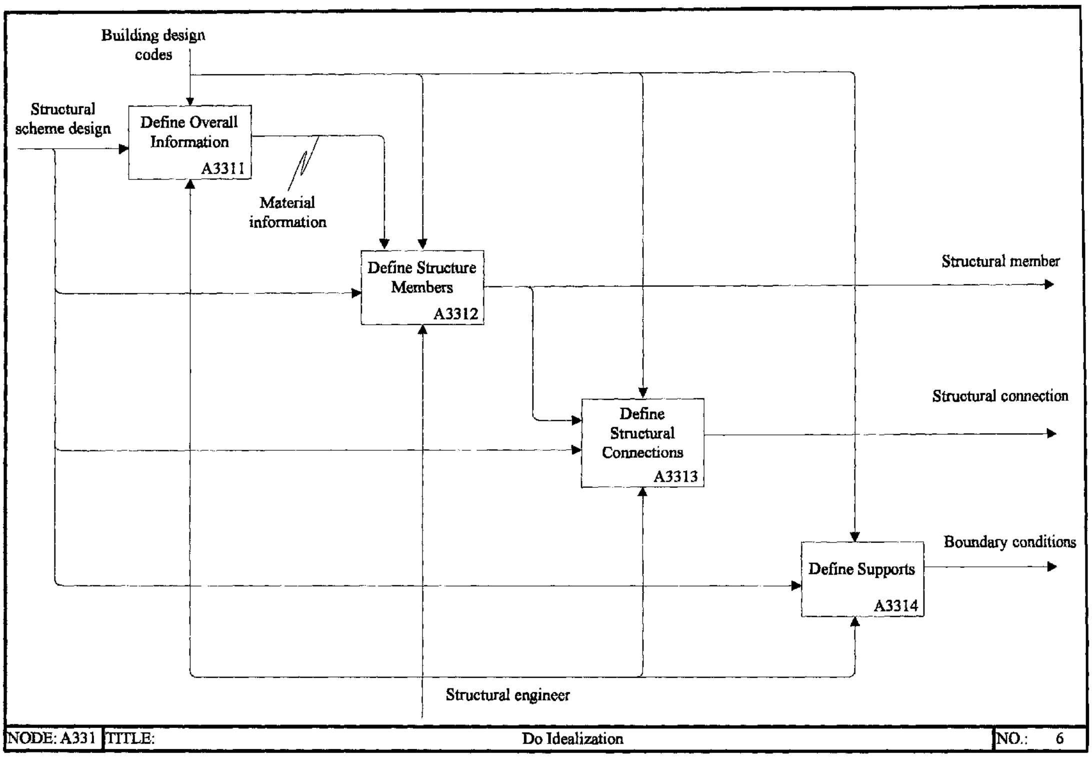

Figure 5.5 Process Model for Idealization

(i) Structural Members

The primary load-bearing components of a structural system are the members. The typical structural members to be considered include beam members which are subjected to bending moments or flexure, truss members which are subjected to axial force only and columns which are subjected to both bending moments and axial forces (McCormae et al. 1988, Kassimali 1993).

(ii) Connections

Connections or joints are used to tie different structural members together. There are several types of connections, such as the more common ones: rigid connection, flexible, or internal hinged connection. The types of connectors that are commonly used in making joints can be characterized as either point connectors, line connectors, or surface connectors.

(iii) Supports (Boundary conditions)

The applied loads on a structure are finally transmitted to the supports through the members and connections. The types of supports include rocker, roller, pin, fixed. In structural analysis applications, the defining process is very similar with the definition of connection. The natures of simplified supports are also very similar with natures of simplified connections. The details concerning how a structure connects to its supports are enumerated by boundary conditions. Some boundary conditions are related to constraints that the supports provide on movement and are referred to as *displacement boundary conditions*. Other boundary conditions express conditions relative to the forces that can be developed at a support point. These are referred to as *force boundary conditions* (West et al., 1993).

5.3.3 Applying Loads

Establishment of the loads that act on a structure is one of the most difficult and yet important steps in the overall process of design. The computer has made it possible to analyse structure that could not be analysed a mere decade ago, but the accuracy of the results of the analysis is directly dependent on the accuracy of the loads used.

The main objective of applying loads is to identify how many and what type of loads are acting on the structure and to define the manner in which the imposed loads filter through the structure. The loads on structures may be classified in different ways. For example, the loads can be of the following three different types (West et al., 1993). *Concentrated loads* are those that are applied over a relatively small area. *Line loads* are distributed along a narrow strip of the structure. *Surface loads* are loads that are distributed over an area. The loads on a warehouse floor and the snow load on a roof are examples of surface loads. If divided by the source of action, the loads can be grouped according to three categories: *dead loads, live loads, and environmental loads* (Arbabi 1991, Christiano and Au 1993). *Dead loads* are those that act on the structure as a result of the weight of the structure itself and of the component of the system that are permanent fixtures. *Live loads* include only loads that produced through the construction, use of occupancy of the structure and not to include environmental or dead loads. These loads are dynamic in character in that they are fixed in neither magnitude nor position. *Environmental loads* are numerous loading conditions that a structure experiences as a result of the environment in which it exists. These categories can be further divided according to the specific nature of the loading, such as *snow and ice load, rain loads, wind load, earthquake loads, earth or water pressures* and *temperature loads* are all included in environmental loads. In addition, loads can be classified as (a) *those caused by gravity* and (b) *lateral loads.* Dead, live and snow loads are examples of gravity-induced loads whereas wind and earthquake loads are lateral loads.

Process Model for Applying Loads

How to model the loading conditions in the structural analytical model is one of the most important parts of structural analysis. It also constructs the main task of this stage. The procedure of applying loads includes the following steps: estimation of loads, assigning loads, grouping loads and determination of load combinations (see Figure 5.6).

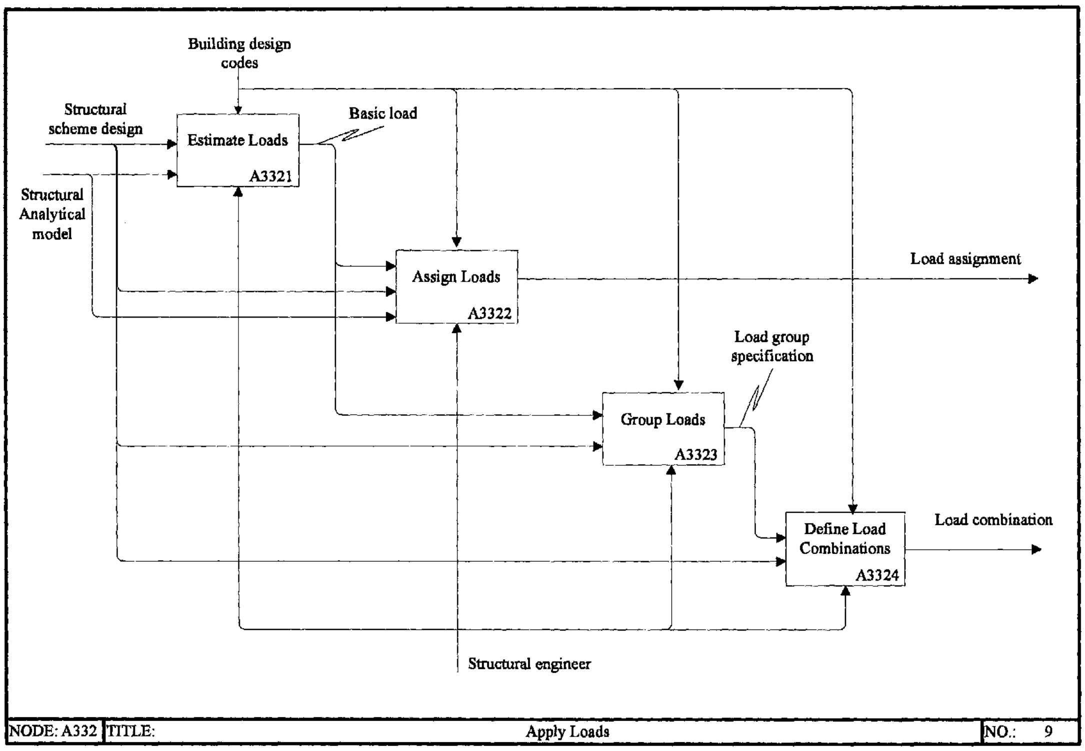

Figure 5.6 Process Model for Applying Loads

Perhaps the most important and most difficult task faced by the structural designer is the accurate estimation of the loads that may be applied to a structure during its life. After loads are estimated the next problem is to assign these loads to appropriate structural members and connections. Next, group different loads based on the source of action in order to determine the worst possible combination of the loading condition that might occur at any one time. The last question which is of critical importance in determining design loads is whether or not all of these loadings act on the structure simultaneously. Dead loads by definition always act on a structure. The variability is in the live load or combination of live loads. The final design of a structure must be consistent with the most critical combination of loads that the structure is to support. However, some judgment is necessary in selecting loading conditions that can reasonably be combined. Obviously, the maximum effects of all loading conditions should not be combined because it is unlikely that they will all occur simultaneously. In fact, certain combinations are highly unlikely: full snow load is not likely to occur with full wind load; likewise, an earthquake is unlikely to occur at the instant that the structure is subjected to full wind load. In recognition of this, the load combinations that must be considered are normally specified by the governing codes (BS, ACI, etc.); in some cases, designers must exercise their judgment, many codes or regulations allow specific reductions in design loadings when certain load combinations are present.

5.3.4 Performing Structural Analysis

In structural analysis, the values of the loads are used to carry out an analysis of the structure in order to determine the stresses or stress resultants in the members and the deflections at various points of the structure.

The objective is to compute the maximum moment, shear, torsion, and axial load at each critical section. Normally, only moment and shear are computed for flexural members because small axial load does not affect the design. Likewise, only axial load and moment are normally computed for columns (and frequently only axial load) because small moment and shear do not affect the design.

Structural response contains: (1) the displacements at the nodes; (2) the element nodal forces, the min-max internal forces in every member etc., including shear, moment, rotation; and (3) support reactions. Deformed shape, shear force, and bending moment diagrams can be displayed (Holzer, 1985).

Process Model for Performing Structural Analysis

Figure 5.7 describes the processes involved in performing structural analysis. Actually, when structural analysis software is used to compute these responses, it seems they are produced simultaneously to user and there is no strict sequence about their generation. So the current process model shown is in accordance with traditional computing order. Of course the most important information concerned is the results of the analysis, rather than the sequence of generation.

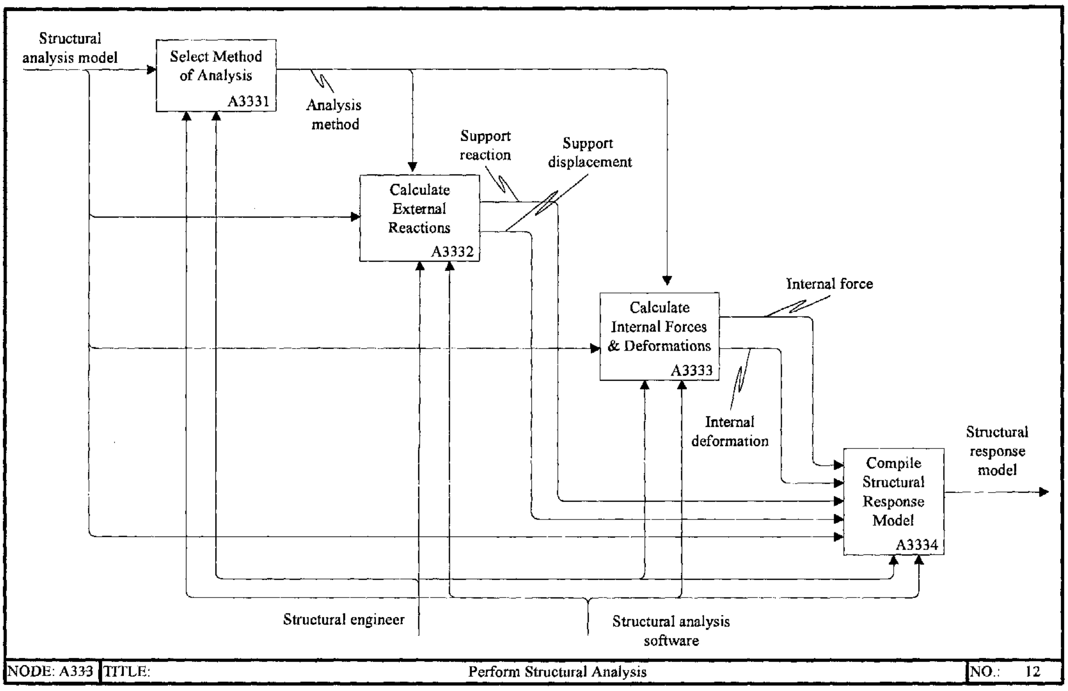

Figure 5.7 Process Model for Performing Structural Analysis

5.4 Proposed Information Model for Structural Analysis

5.4.1 Information Models for Each Level of Process Models

After establishing the process models, PoIM methodology is used to capture the specific IDEF1 diagrams. A set of IDEF1 diagrams and mapping tables can be obtained for each level of IDEF0 models (from Figure 5.4 to Figure 5.7). Table 5.2 lists all mapping tables generated during the whole conversion. It follows the sequence of conversion which begins from the relative bottom level of IDEF0 models. The first four tables represent the mapping within a level for four child diagrams, that is, the process models for activities 'A331', 'A332', 'A333' and 'A33', respectively. And the fifth table is the mapping between the parent activities and their child diagrams. As described in Chapter 4, the rows in grey mean the relative inputs or controls are repeated in different levels, which will be incorporated into the highest level of information model. Here in order to make the mapping clear, they are kept in the mapping tables for the bottom level process model.

Table 5.2 Mapping Table of IDEF0 and IDEF1

(a) A331 Do Idealization

IDEF0 Activity	IDEF0 Output	Corresponding IDEF1 Element	Relative Input & Control	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A3311 Define overall information	Material information	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design codes	Entity	Dependency	Based on
A3312 Define structure members	Structural member	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design codes	Entity	Dependency	Based on
			Material information	Entity	None-specific	(M:N) Entity: RelMaterial
A3313 Define structural connections	Structural connection	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design codes	Entity	Dependency	Based on
			Structural member	Entity	None-specific	(M:N) Entity: RelConnection
A3314 Define supports	Boundary conditions	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design codes	Entity	Dependency	Based on

Table 5.2 (b) A332 Apply loads

IDEF0 Activity	IDEF0 Output	Corresponding IDEF1 Element	Relative Input & Control	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A3321 Estimate loads	Basic load	Entity	Structural Analytical model	Entity	Dependency	Based on
			Structural scheme design	Entity	Dependency	Based on
			Building design codes	Entity	Dependency	Based on
A3322 Assign loads	Load assignment	Entity	Structural Analytical model	Entity	Dependency	Based on
			Structural scheme design	Entity	Dependency	Based on
			Building design codes	Entity	Dependency	Based on
			Basic loads	Entity	Non-specific	M:1
A3323 Group loads	Load group specification	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design codes	Entity	Dependency	Based on
			Basic loads	Entity	Composition	Has-a (1:M)
A3324 Define load combinations	Load combination	Entity	Load group specification	Entity	Composition	Has-a (1:M)
			Structural scheme design	Entity	Dependency	Based on
			Building design codes	Entity	Dependency	Based on

Table 5.2 (c) A333 Perform Structural Analysis

IDEF0 Activity	IDEF0 Output	Corresponding IDEF1 Element	Relative Input & Control	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A3331 Select method of analysis	Analysis method	Entity	Building design codes	Entity	Dependency	Based on
			Structural analysis model	Entity	Dependency	Based on
A3332 Calculate external reactions	Support reaction	Entity	Structural analysis model	Entity	Dependency	Based on
			Analysis method	Entity	Dependency	Based on
	Support displacement	Entity	Structural analysis model	Entity	Dependency	Based on
			Analysis method	Entity	Dependency	Based on
A3333 Calculate internal forces & deformations	Internal forces	Entity	Structural analysis model	Entity	Dependency	Based on
			Analysis method	Entity	Dependency	Based on
	Internal deformations	Entity	Structural analysis model	Entity	Generalization	Is-one-of
			Analysis method		Dependency	Based on
A3334 Compile structural response model	Structural response model	Entity	Structural analysis model	Entity	Dependency	Based on
			Support reactions	Entity	Composition	Has-a
			Support displacements	Entity	Composition	Has-a
			Internal forces	Entity	Composition	Has-a
			Internal deformations	Entity	Composition	Has-a

Table 5.2 (d) A33 Do Structural Analysis

IDEF0 Activity	IDEF0 Output	Corresponding IDEF1 Element	Relative Input & Control	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A331 Do Idealization	Analytical model	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design codes	Entity	Dependency	Based on
			Structural response model	Entity	Dependency	Based on
A332 Apply loads	Structural analysis model	Entity	Structural analytical model	Entity	Composition	Has-a
			Material information	Entity	Composition	Has-a
			Member section	Entity	Composition	Has-a
			Building design codes	Entity	Dependency	Based on
A333 Perform structural analysis	Structural response model	Entity	Structural analysis model	Entity	Dependency	Based on
			Building design codes	Entity	Dependency	Based on

Table 5.2 (e) Mapping Tables for the Conversion between Levels

Parent Activity	Parent Element	Corresponding IDEF1 Element	Child Element	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A331 Do idealization	Structural Analytical model	Entity	Structural member	Entity	Composition	Part-of
			Structural connection	Entity	Composition	Part-of
			Boundary conditions	Entity	Composition	Part-of
	Structural response models	Entity	Structural response models	Entity	Same (NA)	NA
A332 Apply loads	Structural analysis model	Entity	Load assignment	Entity	Composition	Has-a
			Load combination	Entity	Composition	Has-a
A333 Perform structural analysis	Structural response model	Entity	Structural response model	Entity	Same (NA)	NA
	Structural analysis model	Entity	Structural analysis model	Entity	Same (NA)	NA

Based on the mapping tables, the corresponding information model for these diagrams can be achieved which has been illustrated by Figure 5.8 to Figure 5.11. In these information diagrams, the attributes represent conceptual properties of the entities, rather than the forms in reality. Figure 5.8 shows the information model for the bottom level diagram, the process model for the activity 'A331' of 'Do Idealization'. The IDEF1 helped define a set of attributes of information of interest. This created a data dictionary for the system.

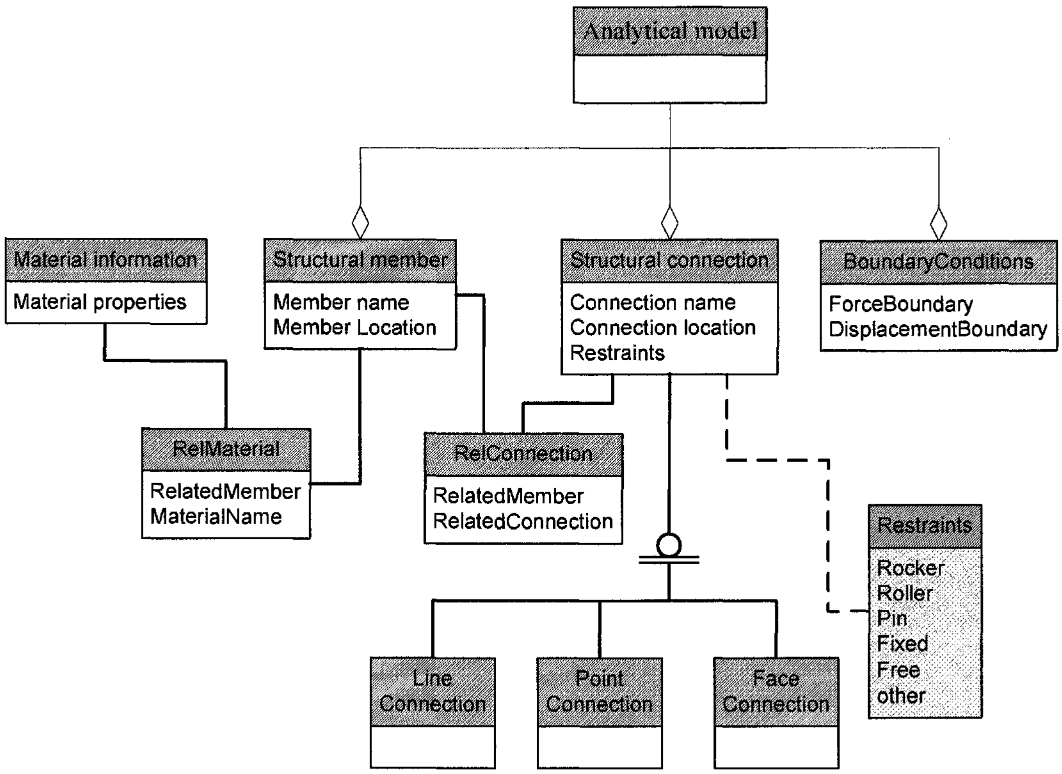

Figure 5.8 Information Model for Idealization

By using the same procedure, the information models for applying loads (Figure 5.9) and performing structural analysis (Figure 5.10) can be attained.

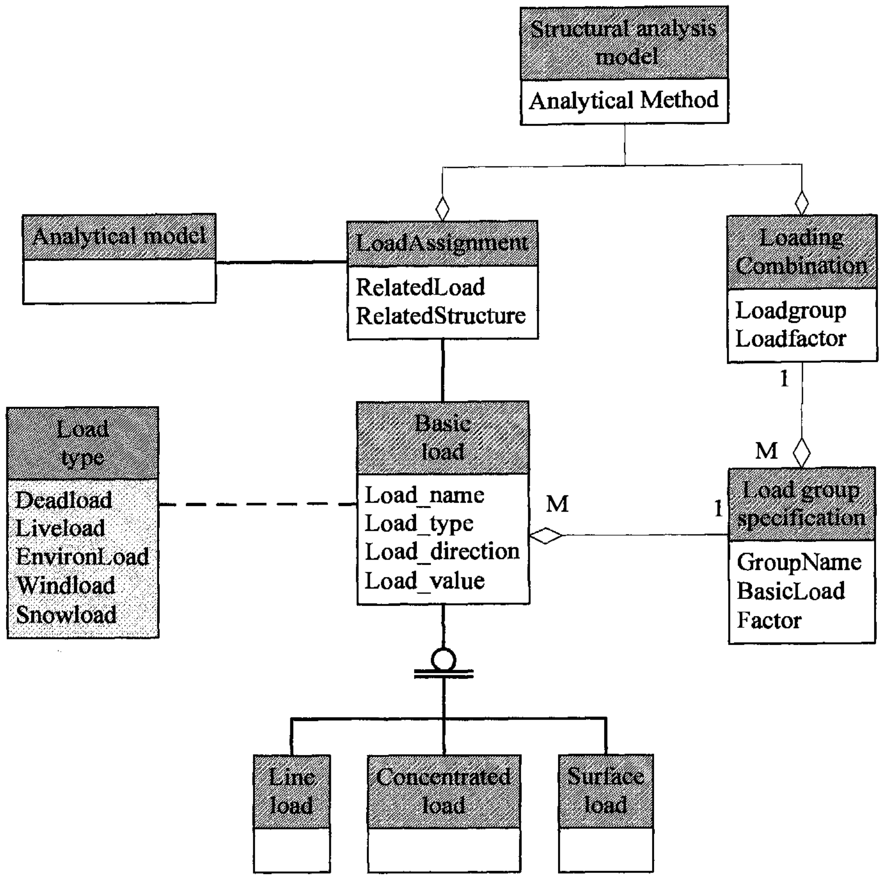

Figure 5.9 Information Model for Applying Loads

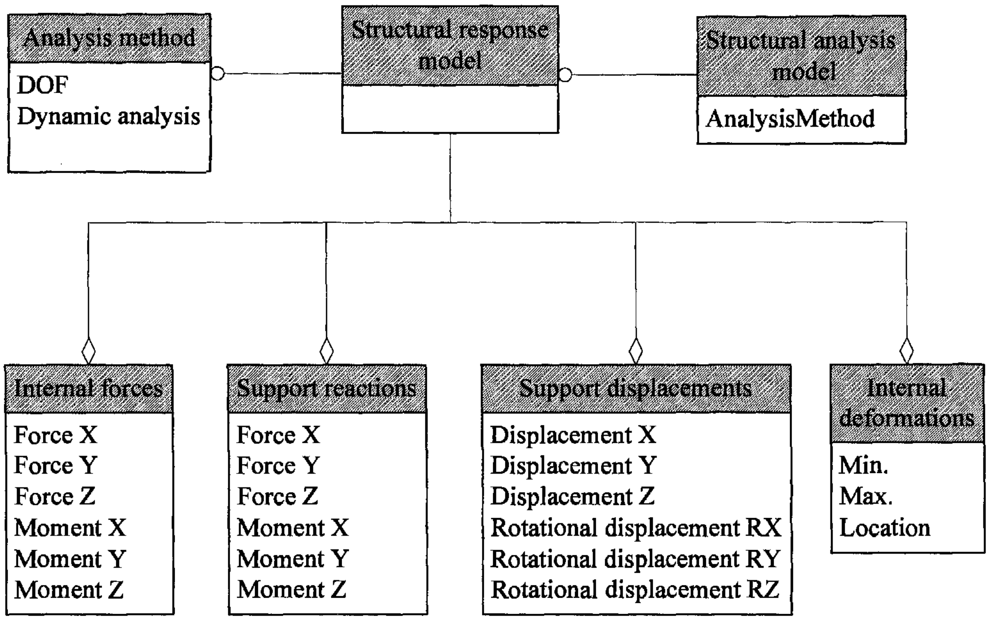

Figure 5.10 Information Model for Performing Structural Analysis

It should be noticed that the above application of the PoIM methodology in establishing information model for structural analysis demonstrates the proposed methodology's effectiveness. It also shows the comprehensiveness of the IDEF0 and IDEF1 enhancements as well as the transformation procedures. And the simplicity and consistency of proposed methodology is also proved by this example. That this methodology can be used in modeling of complex projects as well as the analysis of simplified model.

5.4.2 Combined Information Model for Structural Analysis

Finally, by combining all the above information diagrams for each level of process models, the information model for the whole structural analysis process can be achieved (see Figure 5.11).

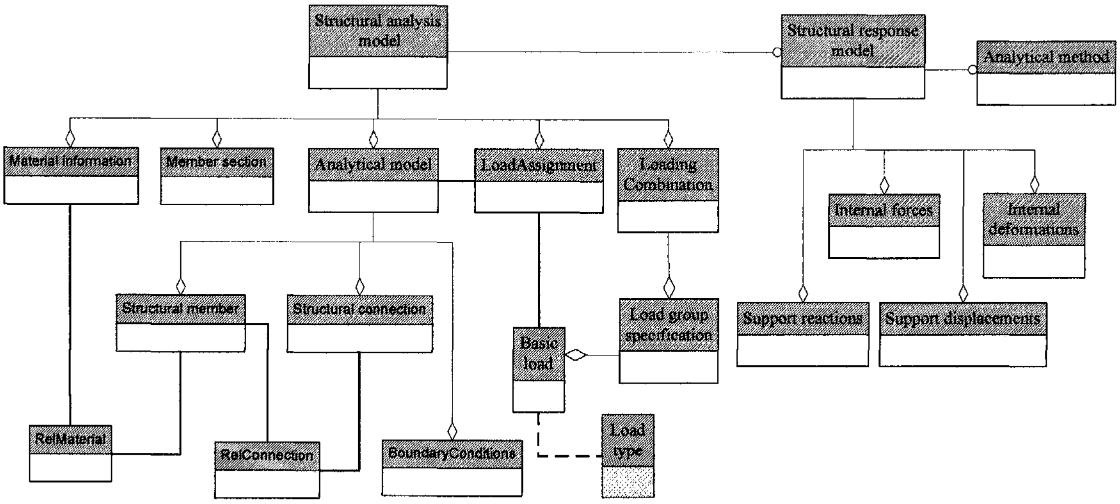

Figure 5.11 Combined Information Model for Structural Analysis

This combined information model is a complete model for structural analysis, which represents all the information requirements during structural analysis process. Two kinds of information are needed: the information that constitute structural analysis model and the corresponding structural responses. From this analysis, five categories information should be defined in order to perform structural analysis.

1. Topology information for each structural component, including member, connection and support.

2. Material information.

3. Geometry information, including sectional information.

4. Load information, including not only the information about basic load cases, but also load combinations.

5. Relating the above information to structural components, including the relationships between material information, sectional information and structural members or connections.

5.4.3 Relationships between Architectural Design and Structural Design

Actually, at this phase, there is no direct relationship between the structural and architectural design information model. That is because before doing structural analysis, a preliminary design of structural scheme should be done in order to choose the basic plans. In the preliminary design stage engineers have already completed the task of identifying the related information in architectural design and transforming the information in architectural design to usable information which will be used by structural design.

Although no direct relationship between information models for architectural design and structural design, some information, which is required by structural analysis, comes from architectural design, or it is determined in architectural design. From Figure 5.11, as to the 'Material Information' entity, the selection of a material may be done in architectural phase by the architect, so at least part of material's information comes from architectural design.

Therefore through identifying the source of information, the relationship between information models for architectural design and structural design can be achieved. Generally there are three kinds of structural information is related to architectural design.

1. Geometry and topology information. When doing structural idealization, part of geometry information is based on architectural design. Engineers often use idealizations of the geometry and behavior of a structure to simplify and reduce the size of a mechanical analysis problem (Haber, 2000). For example, in architectural design, column is more usually considered as a 3D solid object. Correspondingly, in structural design, it should be simplified from a solid object to a line between two nodes. It is obvious that there are still connections between these two different representations to a same object. The length of line is related to the length of column and the space height of building. How to transform this information to the useful information for structural design is also the part of work of integration.

2. Part of load information. Architect may define the live load in architectural design in accordance with the requirements of clients. Some loads may be given in architectural design drawings directly and some can be derived from geometric information.

3. Material information. The structural properties of material are comparatively constant. So the focus is on the material selection. Generally the material selection is carried out in architectural design phase. At least it should be decided that the building is in steel structure or reinforced concrete structure etc. because this has direct effect on the architectural design of building.

The above describes that part of structural information need come from architectural design. The design of structural scheme should influence architecture by making it more rational and efficient, but it should not dictate architecture. Architects need the knowledge of structures to ensure that the practical expressions of their architecture are both rational and efficient. The structural system that enables buildings to withstand the loads imposed on them and the materials of construction, if properly chosen, help further the expression of architects' ideas rationally and economically (Gauld 1984, Benjamin 1984). Since embedded relationships exist between the two design phases, the integration is necessary and possible.

5.5 Assessment of Current Release IFC 2x2 Addendum 1

From previous descriptions, the generic framework and information requirements for structural engineers to do structural analysis are identified. Although the identified information is not in a great detail, the usefulness of current IFC Release 2x Edition 2 and its addendum can still be assessed. The comparison is shown in Table 5.3 based on the information model produced before. As shown in Table 5.3, it can be concluded that basically the current IFC models are enough to support the requirements of engineer to do structural analysis at a higher level.

Table 5.3 Comparison with Current Release IFC 2x 2 Addendum 1

General Requirements			IFC Extensions	
	Elements	**Properties**	**Related Entities**	**Related Attributes**
Structural analysis model			IfcStructuralAnalysisModel	
Analytical model	Analytical model		IfcStructuralItem	
	Structural member	Member name	IfcStructuralMember	GlobalId /Name
		Member location	IfcStructuralMember	ObjectPlacement
			IfcRelAssociatesPrfileProperties	
	Structural connection	Connection name	IfcStructuralConnection	GlobalId /Name
		Connection location	IfcStructuralConnection	ObjectPlacement
		Restraints	IfcStructuralConnection	AppliedCondition
	(Subtypes)	LineConnection	IfcStructuralCurveConnection	
		PointConnection	IfcStructuralPointConnection	
		FaceConnection	IfcStructuralSurfaceConnection	
	RelConnection	RelatedMember	IfcRelConnectsStructural Member	RelatingStructuralMember
		RelatedConnection	IfcRelConnectsStructural Member	RelatedStructuralConnection
	Boundary condition	FaceBoundary	IfcBoundaryCondition	LinearStiffnessX /Y/Z
		Displacement-Boundary	IfcBoundaryCondition	RotationalStiffnessX/ Y/Z
Material	Material Informaiton	Material properties	IfcMaterialProperties	IfcMechanicalMaterialProperties
			IfcMaterialProperties	Material (IfcMaterial)
	RelMaterial	RelatedMember	IfcRelAssociatesMaterial	RelatedObjects
		MaterialName	IfcRelAssociatesMaterial	RelatingMaterial

Table 5.3 <Continued>

Member section	Member section	Section Properties	IfcProfileProperties	IfcStructuralProfileProperties
			IfcProfileProperties	ProfileDefinition (IfcProfileDef)
Load combination	Load Combinations	LoadGroup	IfcStructuralLoadGroup	IsGroupedBy
		LoadFactor	IfcStructuralLoadGroup	Coefficient
	Load group specification	GroupName	IfcStructuralLoadGroup	GlobalId /Name
		Basicload	IfcStructuralLoadGroup	IsGrouptedBy
		Factor	IfcStructuralLoadGroup	Coefficient
Load Assignment	Load Assignment	RelatedLoad	IfcRelConnectsStructural-Activity	RelatedStructuralActivity
		Related-Structure	IfcRelConnectsStructural-Activity	RelatingElement
	Basic loads	Load_name	IfcStructuralAction	GlobalId /Name
		Load_type	IfcStructuralAction	
		Load_ direction	IfcStructuralAction	GlobalOrLocal & ProjectedOrTrue
		Load_value	IfcStructuralAction	AppliedLoad
	(Subtypes)	Concentrated load	IfcStructuralPointAction	AppliedLoad (IfcStructuralLoadSingle Force)
		Line load	IfcStructuralLinearAction	AppliedLoad (IfcStructuralLoadLinear Force)
		Surface load	IfcStructuralPlanarAction	AppliedLoad (IfcStructuralLoadPlanar Force)
Structural response model			IfcStructuralResultGroup	ResultForLoadGroup
Structural response model	Analysis method		IfcStructuralResultGroup IfcAnalysisTheoryTypeEnum	TheoryType
	Internal forces	Force X/Y/Z Moment X/Y/Z	IfcStructuralReaction IfcStructuralLoadSingle-Force	AppliedLoad Force X/Y/Z; Moment X/Y/Z
	Support displacements	Displacement X/Y/Z RX/Ry/RZ	IfcStructuralPointReaction IfcStructuralLoadSingle-Displacement	AppliedLoad Displacement X/Y/ Z; RotationalDisplacementRX/ RY/ RZ
	Support reactions	Force X/Y/Z Moment X/Y/Z	IfcStructuralPointReaction IfcStructuralLoadSingle-Force	AppliedLoad Force X/Y/Z; Moment X/Y/Z
	Internal deformations		IfcStructuralReaction IfcStructuralLoadDisplacement	AppliedLoad

In order to ensure a successful implementation of integration between architectural design and structural design, it is not enough to consider it only from the general perspective; the more detailed assessment is done in Chapter 6.

5.6 Summary

Based on the methodology proposed in Chapter 4, a set of generic process model for structural engineering design and information model for structural analysis are achieved. This application demonstrates the comprehensiveness of the IDEF0 and IDEF1 enhancements as well as the transformation procedures. The simplicity and consistency of proposed methodology is also shown by this example.

This information model is a generic model which intends to characterize the flow of design information and not tied to any specific analysis process model. The information model distinguishes itself from any specific analysis method and structure type, with that it concentrates on the information that flows among individual design activities regardless of the activities' particular sequence and requirements. So this model appears to lend itself to implementation that can support a variety of development strategies.

On the other hand, the necessity and feasibility of the integration of architectural design and structural design is shown through the discussion of the relationships between their information. The capability of latest IFC models to support structural analysis is evaluated through the comparison between the generic requirements and current IFC extensions. At this stage, the model is capable of establishing a foundation for developing base-level representations to capture, store and retrieve design information. Further research is still going on until the complete information model for structural analysis process is obtained. The detailed assessment of the application at implementation level would be done in next chapter.

Chapter 6 IFC Extension Development for Structural Analysis Process*

6.1 Introduction

In Chapter 5 the PoIM methodology is applied to obtain a generic information model for structural analysis process which proves the effectiveness of the methodology on information modeling. The generic information model proposed and the assessment to IFC extensions in Chapter 5 primarily comes from professionals' knowledge in a higher level. However, during the implementation of the integration between structural design and architectural design, to a great extent it is much more from structural analysis and design software's point of view. Therefore, the information requirements are also needed to be modelled involving the implementation in software. In this chapter, the information modeling based on the detailed computer software's mechanism for structural analysis is further developed. The gaps between the detailed requirements and IFC models are analyzed so as to assess the usefulness of IFC to meet the practical needs of structural analysis in this chapter.

The chapter is organized as follows:

- Section 6.1 gives a brief description of the content and structure of the chapter.

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* Part of this chapter has been published in the paper " Assessment of IFCs for Structural Analysis Domain", on the Electronic Journal of Information Technology in Construction in ITcon Vol. 9 2004, pp. 75-95, which is available at http://www.itcon.org/2004/5.

- Section 6.2 introduces the procedures of structural analysis using SAP2000 and shows the corresponding process models.
- Based on the process models in Section 6.2, the information requirements of SAP2000 to perform structural analysis are identified and modelled in Section 6.3.
- The capabilities of current IFC models to support structural analysis are assessed in Section 6.4. It is found that most of the information for structural analysis can be explicitly supported by current IFCs. However there is still some information missing. And some need to be inferred from the data existing in IFC.
- In order to decide the approach to developing IFC extensions, the commonalities of information gaps are confirmed by the generality study in Section 6.5 which investigates into another ten structural analysis and design softwares.
- The necessary extensions for the missing information are developed in section 6.6 in accordance with IFC 2x Extension Modeling Guide and rules specified.
- Finally section 6.7 summarizes the works finished in current stage. The problems currently existed and future works are also proposed.

6.2 General Procedures of Structural Analysis and Design Software

After investigating software like SAP2000, ETABS etc., the procedures to structural analysis and design generally includes the following steps:

a. Choosing the units and defining the basic information for the project.
b. Setting up geometry.
c. Defining material and member section properties.

d. Assigning member section properties and element releases.
e. Defining load cases.
f. Assigning load magnitudes.
g. Assigning restraints.
h. Run Analysis
i. Displaying the deformed shape.
j. Displaying the member forces.
k. Printing the results.
l. Designing the structural members and checking the safety of a design.
m. Modifying the structure and trying again.

Since basically all structural engineering computer programs follow the same procedure, SAP2000 is selected as the representative software for modeling the practical processes of structural analysis. SAP2000 is an integrated software for structural analysis and design developed by Computers and Structures, Inc. (CSI, USA). For nearly 30 years, CSI has been the leader in the development of innovative numerical methods and software for structural & earthquake engineering. CSI software has been used for the analysis and design of major project by thousands of users in over 100 countries. The products offered by CSI (SAP2000, ETABS and SAFE) are often highlighted in many engineering software guides or magazines, like *Modern Steel Construction* (1998, 2003) and *Structure* (2004). Therefore, all of the following models are from SAP2000's requirements and referring to the Analysis Reference of SAP2000 (CSI, 2002), and all information is named with SAP2000's notations.

The above procedure involves a total of 13 steps. However, some steps can be carried out simultaneously and some follow the same working styles, such as steps 'c' and 'e' both belong to 'Define' activity. Therefore, the whole procedure can also be defined in seven processes: Define default parameters, Set up structural model, Define properties, Assign properties, Define analysis options, Compile whole model and Run analysis, which is shown in Figure 6.1. Figure 6.1(a) is the top model of activity "Do

Structural Analysis by SAP2000" and Figure 6.1 (b) is the child diagram for the top model.

Figure 6.1 (a): Top Model of Doing Structural Analysis by SAP2000

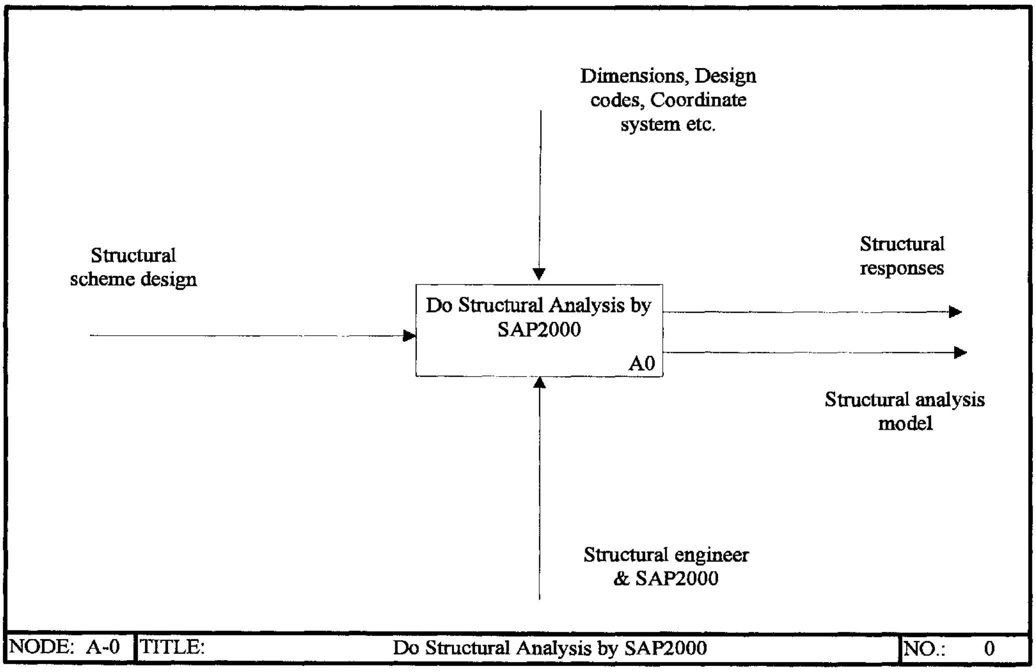


Figure 6.1 (b): Child Diagram of Figure (a)

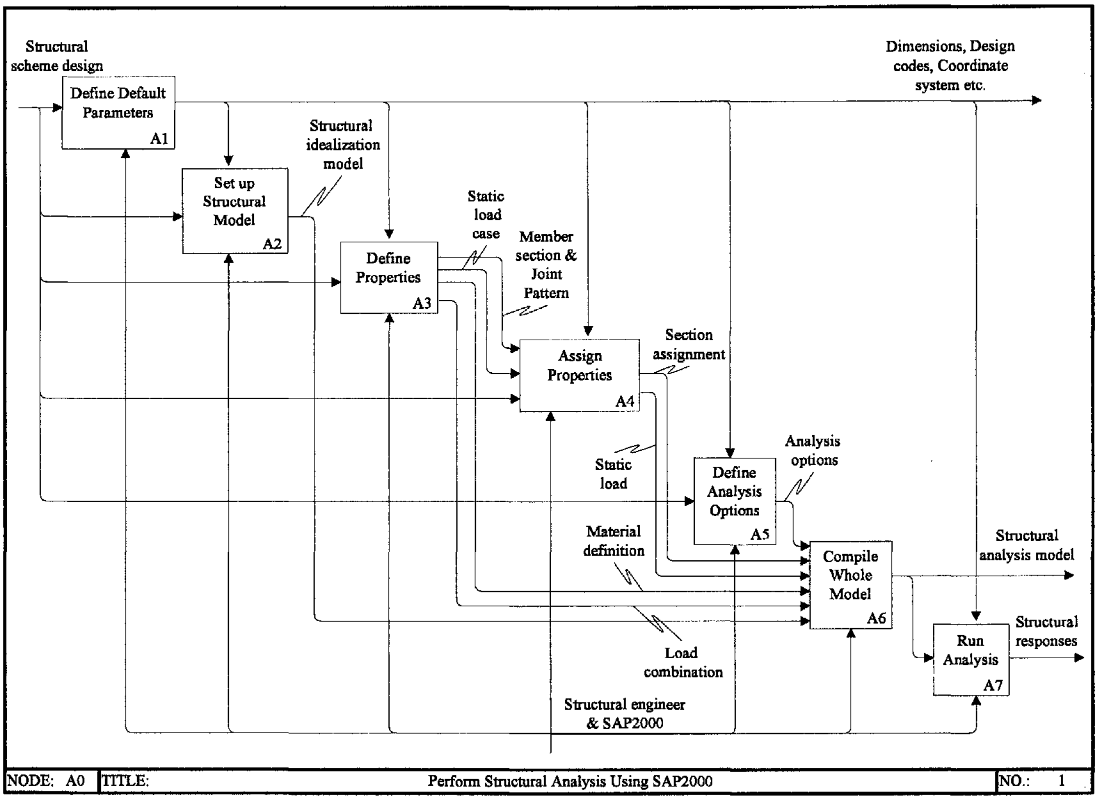


Figure 6.1 Process Model for Doing Structural Analysis by SAP2000

Similarly as in Chapter 5, the top level processes of structural analysis are also shown in Figure 6.2 as a brief introduction and a direction to do further decomposition. The following sections will present the necessary process models according to this layered architecture and provide the detailed descriptions for each process.

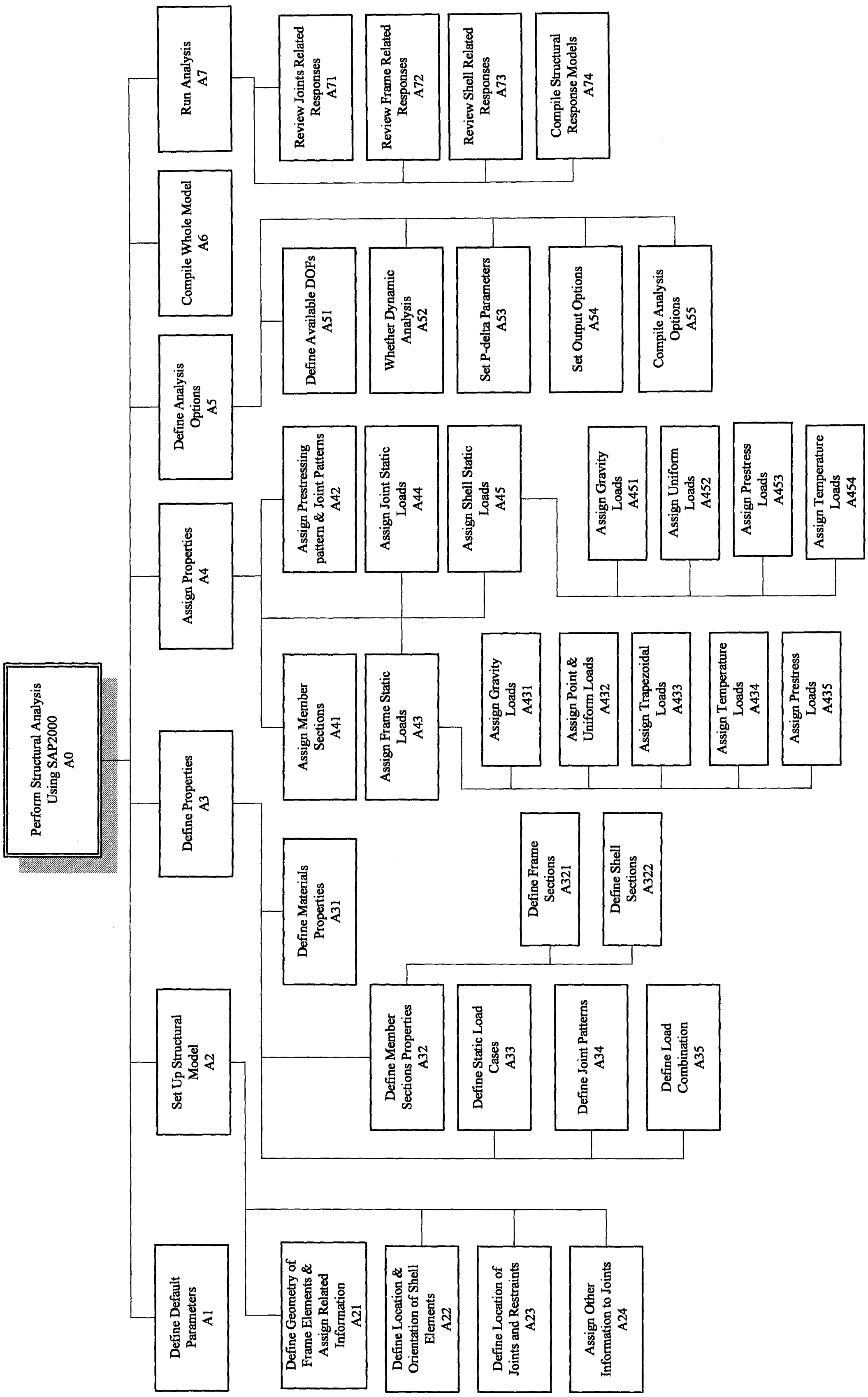


Figure 6.2 IDEF0 Node Tree of Structural Analysis Process by SAP2000

6.2.1 Define Default Parameters

Before carrying out structural analysis, SAP2000 has built-in tolerances and default values for some parameters and Design Codes. It is possible to change most of the default values by editing them in the three tabs under the menu "Preference", namely 'Dimensions', 'Steel and Concrete Design Codes' and 'Parameters'.

In addition, coordinate systems are also defined which are used to locate different parts of the structural model and to define the directions of loads, displacement, internal forces, and stresses.

All coordinate systems in the model are defined with respect to a single, global X-Y-Z coordinate system. Each part of the model (joint, element, or constraint) has its own local 1-2-3 coordinate system. All locations in the model are ultimately defined with respect to a single global coordinate system.

Each component of the model (joint, frame element, shell element, etc.) has its own local coordinate system used to define properties, loads, and response for that component. The axes of each local coordinate system are denoted 1, 2, and 3 in SAP2000.

6.2.2 Set up Structural Model

The first important step to structural analysis is to develop the idealization model of the structure. SAP2000 analyzes and designs the structure using a model that is defined with the graphical user interface.

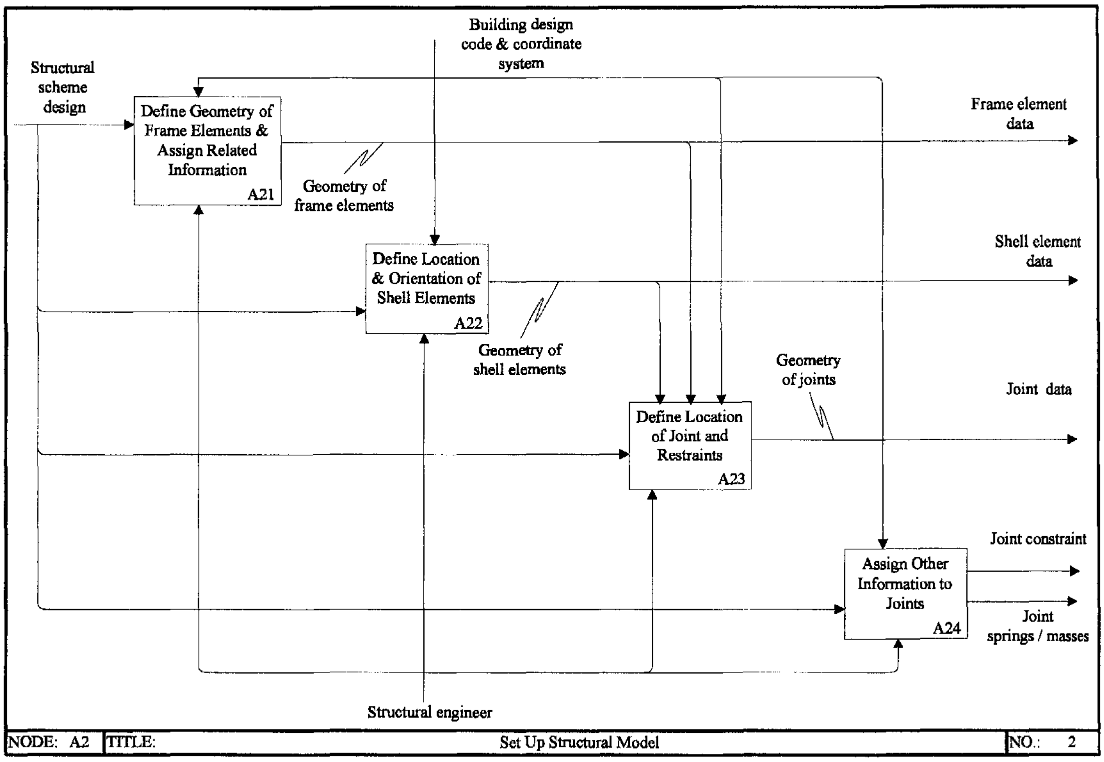


Figure 6.3 Process Model for Setting up Structural Model

As shown in Figure 6.3, the main task of this process is to define the geometry of the frame, shell elements and joints. The graphical user interface provides user with many powerful features to create the model. The user can start with a preliminary model, and then uses the SAP2000 design optimization feature to refine the model with little effort. The model may include the following features that represent the structure:

• Frame elements that are used to model beam-column and truss behaviour in planar and three-dimensional structures. The frame element can also be used to model cable behaviour when nonlinear properties are added. A frame element is modelled as a straight line connecting two points.

• Shell elements that represent walls, floors, and other thin-walled members. The shell element is used to model shell, membrane, and plate behaviour in planar and three-dimensional structures. The shell element/object is one type of area object.

• Joints that represent the points of connections between the elements. They are the primary locations in the structure at which the displacements are known or are to be determined.

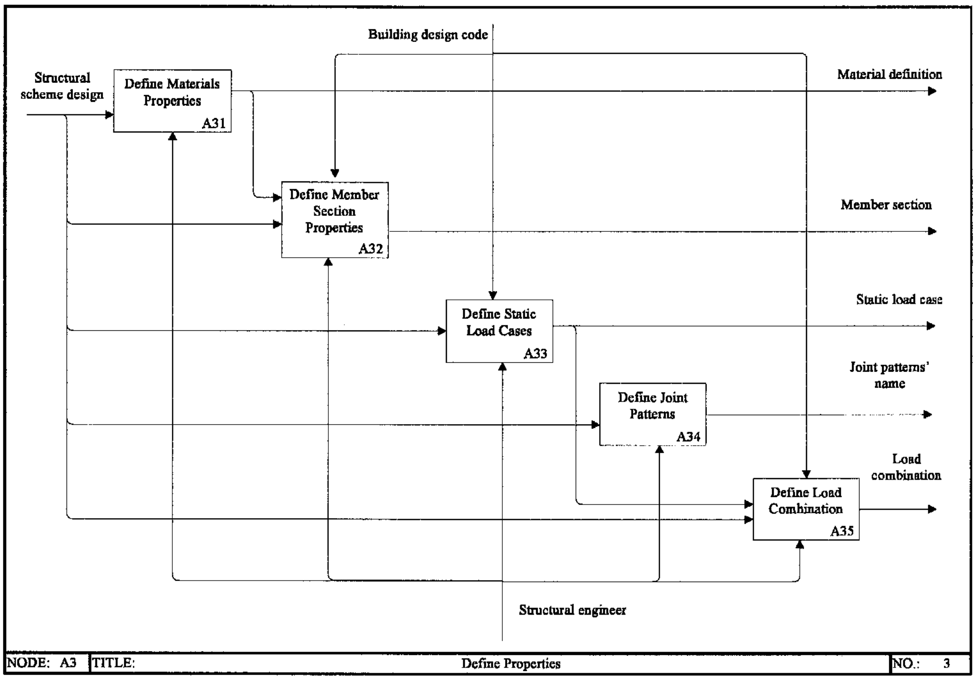
• Restraints and springs that support the joints and other properties with respect to frame elements. The displacement components (translations and rotations) at the joints are called the degrees of freedom. If the displacement of a joint along any of its degrees of freedom has a known value, either zero (e.g., at support points) or non-zero (e.g., due to support settlement), a restraint must be applied to that degree of freedom.

6.2.3 Define Properties

Defining properties is used to create named entities that are not part of the geometry of the model. These entities include material properties, frame and Shell section properties, static load cases, joint pattern for temperature and pressure loading, and load combinations. SAP2000 also provides the definition of properties for response spectrum analysis, time history analysis and static pushover analysis (such as response-spectrum functions, time-history cases, and hinge properties et al.) which are out of this research's scope and are not included when modeling this process.

Defining these entities does not require a prior selection of objects. The first three types of entities will be assigned to selected objects in the next step, which are the primary properties should be defined, as shown in Figure 6.4. Figure 6.4b represents that sections defined include the sections for frame members and the sections of shell members. The remaining entities apply to the model as a whole and are not assigned to objects.

(a)



(b)

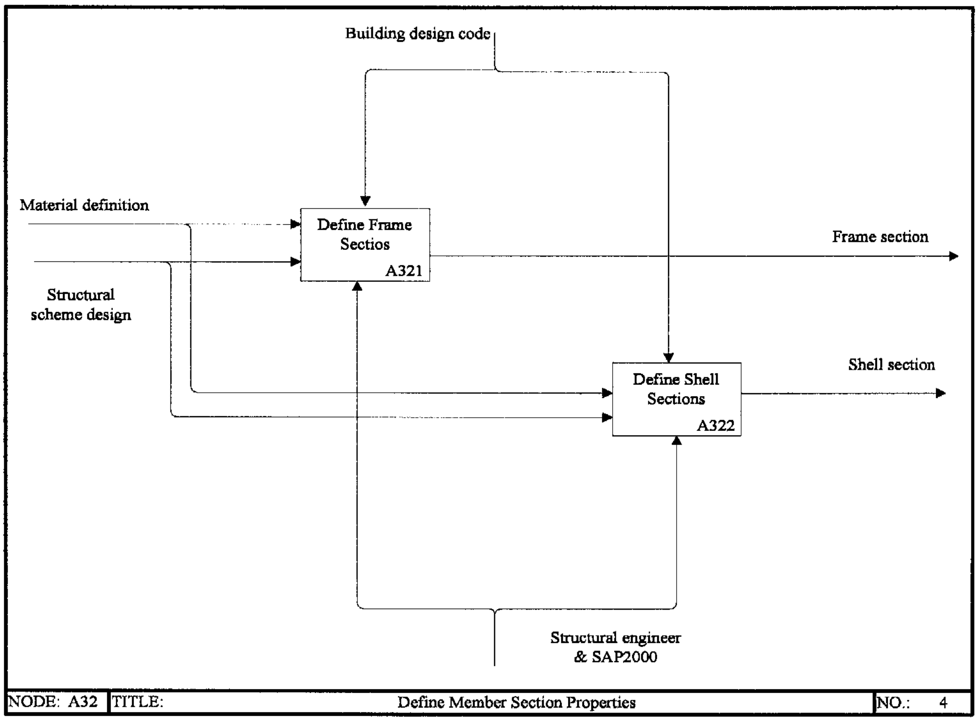


Figure 6.4 Process Model for Defining Properties

(1) Material Property

The material properties are always linear elastic. They may be defined as being isotropic, orthotropic or anisotropic. Isotropic behavior is usually assumed for steel and concrete, although this is not always the case. The behavior of an isotropic material is independent of the direction of loading or the orientation of the material. In addition, shearing behavior is uncoupled from extensional behavior and is not affected by temperature change. How the properties are actually utilized depends on the type of element. Each material that user defines may be used by more than one element or element type. For the Frame element, the Materials are referenced indirectly through the Section properties. The material properties include:

- The modulus of elasticity, **e1**, for axial stiffness and bending stiffness;
- The shear modulus, **g12**, for torsional stiffness and transverse shear stiffness; this is computed from **e1** and the Poisson's ratio, **u12;**
- The mass density (per unit of volume), **m**, for computing element mass;
- The weight density (per unit of volume), **w**, for computing Self-Weight Load;
- The Coefficient of Thermal Expansion;
- The design-type indicator, **ides**, that indicates whether elements using this Section should be designed as steel, concrete, or neither (no design).

(2) Section Property

Sections are defined independently of the elements, and then are assigned to the elements. Six basic general properties of frame section are used, together with the material properties, to generate the stiffnesses of the Section. These are:

- The cross-sectional area, **a**. The axial stiffness of the Section is given by a•e1;
- The moment of inertia, **i33**, about the 3 axis for bending in the 1-2 plane, and the moment of inertia, **i22**, about the 2 axis for bending in the 1-3 plane. The corresponding bending stiffnesses of the Section are given by i33 • e1 and i22•e1;

• The torsional constant, **j**. The torsional stiffness of the Section is given by j • g12;

• The shear areas, **as2** and **as3**, for transverse shear in the 1-2 and 1-3 planes, respectively. The corresponding transverse shear stiffnesses of the Section are given by as2• g12 and as3• g12.

As for the other six properties, section modulus, S33 and S22, the plastic modulus, Z33 and Z22, the radius of gyration, R33 and R22, can be computed from the six basic properties.

In SAP2000, the section properties may be specified directly, computed, or read from a specified property database file. The user can add a frame section by defining the physical dimensions of the section and accepting the section properties automatically computed from specified dimensions by software. This way is generally applicable to such sections in specific types as I/Wide Flange, Channel, Tee, or Angle etc. The other one is to give the section properties directly for general section types. Thus for each Section, the shape type, **sh**, is also specified by the user to determine the way of generating properties:

• If **sh** =G (general section), the six geometric properties must be explicitly specified

• If **sh** =R, P, B, I, C, T, L, or 2L, the six geometric properties are automatically calculated from specified Section dimensions.

• If **sh** is any other value (e.g., W27X94 or 2L4X3X1/4), the six geometric properties are obtained from a specified property database file.

(3) Static Load Case

A Load Case is a specified spatial distribution of forces, displacements, temperatures, and other effects that act upon the structure. The Load Cases form the basis for most of the loading used by the different types of analyses that can be performed by the program. For static analysis, the program automatically computes the linear response to each Load Case unless steady-state analysis has been requested.

User can define as many named Load Cases as user like. Typically user would have separate Load Cases for dead load, live load, wind load, snow load, thermal load, and so on. Loads that need to vary independently, either for design purposes or because of how they are applied to the structure, should be defined as separate Load Cases.

(4) Joint Pattern

Joint Pattern is used to describe complicated spatial distributions of loads and properties over the structure, such as joint spring and mass properties, Joint force and displacement loads, Pressure-type loads for shell elements, and Temperature-type loads for frame and shell elements.

The use of Patterns is optional and is not required or simple problems. Joint Pattern does not affect the location of the joints, or have any other effect upon the structure except as utilized in the specification of loads and properties. In this process, only the names of Patterns are defined and their detailed properties are assigned to selected joints in next process.

(5) Load Combination

In SAP2000, a Combo can be a combination of the results from Loads, Modes, Specs, Histories, Moving Loads, and/or previously-defined Combos. Combo results include all displacements and forces at the joints and internal forces or stresses in the elements.

User may specify any number of Combos. Each Combo produces a pair of values for each response quantity: a maximum and a minimum. In this research only the Load Combination under static analysis case is considered. With respect to Load Combination, the following properties should be defined: (1) combination name, (2) load combination type (ADD, ENVE, ABS, SRSS), (3) description of load combo which is optional, (4) selection of Load Case name from the Case Name drop down list box, and (5) typing in the multiplier in the Scale Factor edit box.

6.2.4 Assign Properties

Assignment is used to assign properties and loads to one or more selected objects. The properties assigned to frame members mainly include section properties, releases, local axes, end offsets, output segments, prestressing patterns, P-delta forces, pushover hinges and loads. Only section properties and local axes are assigned to shell members. The properties assigned to joints mainly include restraints, constraints, springs, masses, local axes, joint patterns and loads.

In fact, most of properties should be considered during setting up the structural idealization model, like frame releases, local axes, end offsets, output segments and joint restraints, constraints, springs, local axes. Therefore this part of assignments is included in the process of "Set up Structural Model" and is not included in this process. In addition, P-delta forces and pushover hinges is only concerned with P-delta analysis and static pushover analysis, and joint masses is used during dynamic analysis which both are out of the research scope in this phase. Thereby, the left properties need to be assigned in this step only include assigning section properties defined before, prestressing pattern, and static loads to frame elements or shell element, as well as assigning loads and joint patterns to joints. More information about prestreesing pattern is introduced in the description for "Prestress Load". Figure 6.5 shows all the related activities in this process.

The most important task in this step is to assign static loads to selected elements and joints. Loads represent actions upon the structure, such as force, pressure, support displacement, thermal effects, ground acceleration, and others. Force load and displacement load normally applies the concentrated forces or moments, and ground displacement to joints. For frame elements, six types of static loads can be assigned, gravity load, point load, uniform load, prestress load, temperature load and trapezoidal span load, as shown in Figure 6.6. Similarly, only gravity load, pressure load, uniform load and temperature load could be assigned to shell elements which are modelled as Figure 6.7. Different static loads have different properties needed to specify. The following section describes the primary static loads in detail.

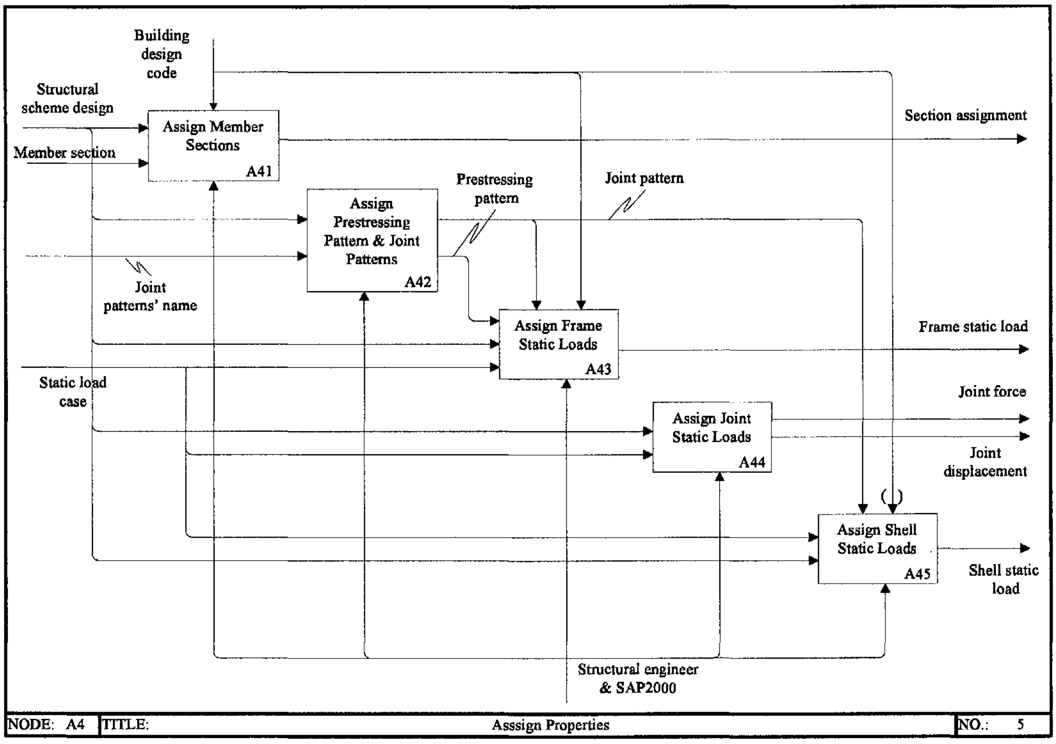


Figure 6.5 Process Model for Assigning Properties

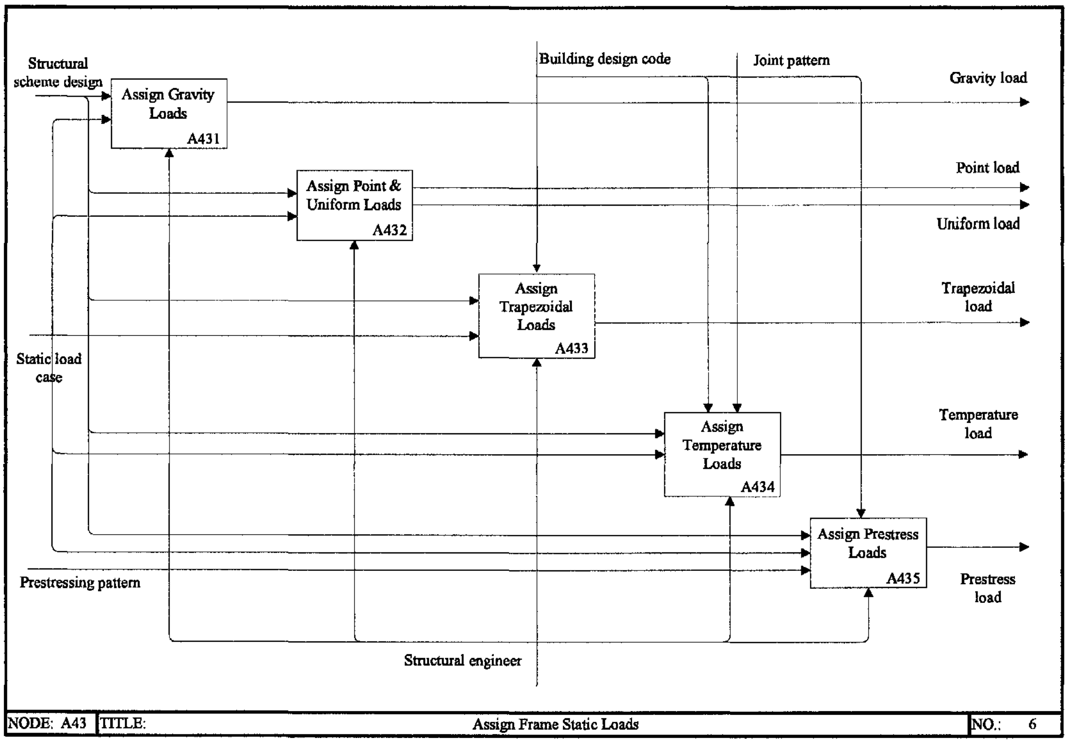


Figure 6.6 Process Model for Assigning Frame Static Loads

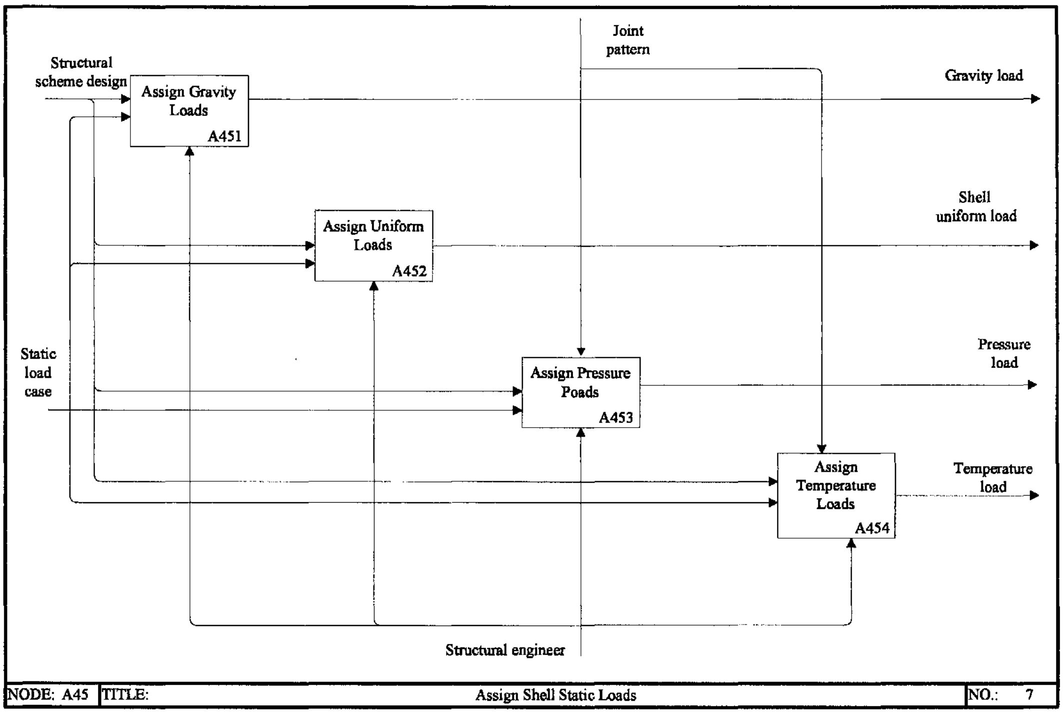


Figure 6.7 Process Model for Assigning Shell Static Loads

Gravity Load

Gravity Load activates the self-weight of the Frame, Shell, Plane, Asolid, Solid, and Nllink elements. For each element to be loaded, user may specify the gravitational multipliers in any fixed coordinate system.

Concentrated Span Load

Concentrated Span Load applies concentrated forces and moments at arbitrary locations on frame elements. The direction of loading may be specified in a fixed coordinate system (global or alternate coordinates) or in the element local coordinate system. The location of the load may be specified in a relative distance or an absolute distance. Any number of concentrated loads may be applied to each element.

Distributed Span Load

Distributed Span Load applies distributed forces and moments at arbitrary locations on frame elements. The load intensity may be uniform or trapezoidal. The direction of loading may be specified in a fixed coordinate system or in the element of local coordinate system. The load intensity is a force or moment per unit of length. The intensity is measured per unit of element length. For each force or moment component to be applied, a single load value may be given if the load is uniformly distributed. Two load values are needed if the load intensity varies linearly over its range of application (a trapezoidal load).

Prestress Load

Any of the frame elements in the model can be subjected to the forces and moments produced by one or more prestressing cables. This load always acts in the local 1-2 plane of the element. For each element user may specify a scale factor, which multiplies the effect of all cables that act on that element. The scale factors are additive.

In SAP2000, the precondition for defining “Prestress Load” is to define the “Frame Prestressing Pattern”. The prestressing pattern comprises the information about cable tension, the cable eccentricities at start, middle and end points respectively. ST-4 has no definition for this information.

Uniform Load

Uniform Load is used to apply uniformly distributed forces to the midsurface of shell elements. The direction of the loading may be specified in a fixed coordinate system or in the element local coordinate system. Load intensities are given as forces per unit area. The total force acting on the element in each local direction is given by the total load intensity in that direction multiplied by the area of the midsurface.

Surface Pressure Load

Surface Pressure Load applies an external pressure to any of the outer faces of the shell elements. The load on each face of an element is specified independently. Surface pressure always acts normal to the face. Positive pressures are directed toward the interior of the element.

Temperature Load

Temperature Load creates thermal strains in the frame and shell elements. These strains are given by the product of the Material coefficients of thermal expansion and the temperature change of the element. The temperature change is measured from the element Reference Temperature to the element Load Temperature.

6.2.5 Define Analysis Options

After a complete structural model is created using the operations above, user can analyze the model to determine the resulting displacements, stresses, and reactions. Before analyzing, analysis options need be set. Figure 6.8 shows that the options consist of:

1. Available degrees of freedom for the analysis;
2. Modal analysis parameters if a Dynamic Analysis is required;
3. P-Delta analysis parameters if P-Delta analysis is performed;
4. Which analysis results to be written to the output file if user want to have any analysis results saved to an output file;
5. The amount of memory (RAM) to be used in Kilobytes (KB).

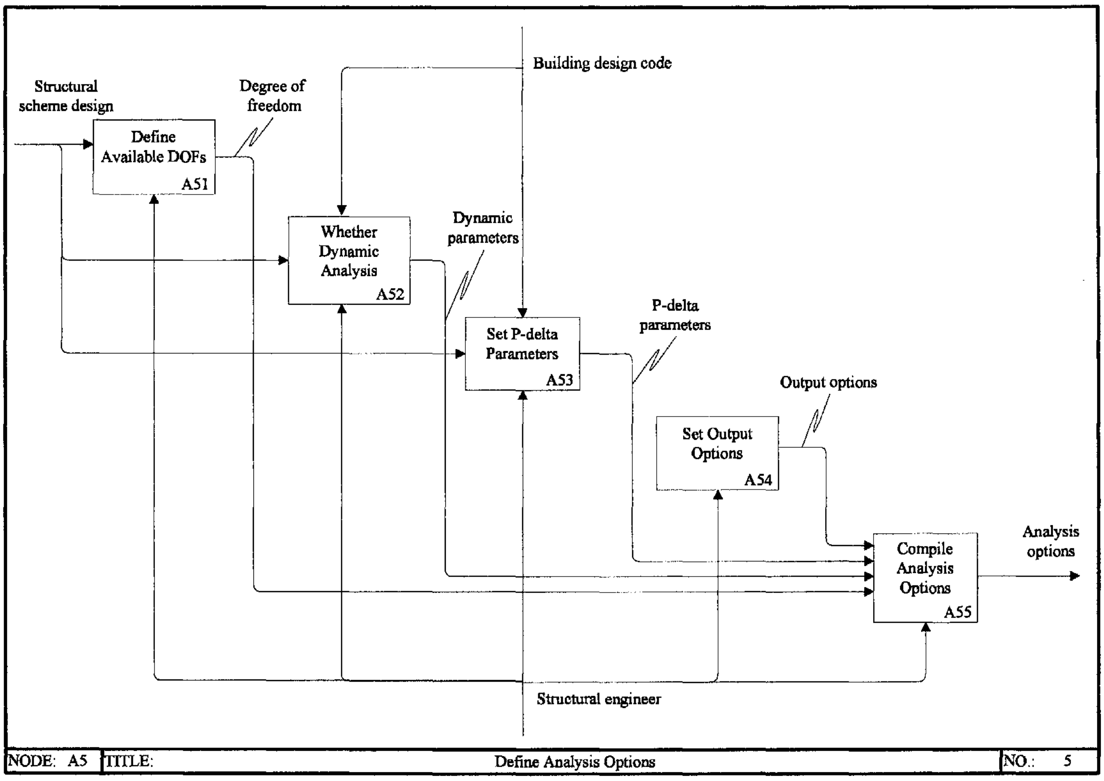


Figure 6.8 Process Model for Defining Analysis Options

6.2.6 Run Analysis and Display / Output the Results

Finishing all above works, the analysis is started simply by click the "Run Analysis" button on the SAP2000's main toolbar. Three kinds of displaying are provided to view the model and the results of the analysis, graphical displays, tabular displays, and function plots.

Analysis results that can be graphically displayed include deformed shapes; vibration mode shapes; frame-element force, moment, and influence-line diagrams; and shell-element force, moment and stress contour plots. Tabular display is used to reveal the detailed analysis results in a special text window for a single joint or element at a time. Function plots are graphs of one variable against another. These include response spectrum curves, pushover curves and time-history traces, all of which are generated from the results of a time-history analysis. In current research scope, only the first two types of display are used and the function plots are not applicable.

Anyway, no matter what types of display is chosen by user, the contents of displaying and what structural engineers concern are the same. Through software application, the concentration of engineer lies on the results of analysis rather than the process of how to calculate them by software. Thus, the modeling for this process just lists all the related responses (Figure 6.9).

The force or moment along the degree of freedom that is required to enforce the restraint is called the reaction. The reaction may differ form one Load Case to the next. The joints reaction includes the forces (or moments) from all elements connected to the restrained degree of freedom, as well as all loads applied to the degree of freedom.

For frame element, internal forces represent the forces and moments which result from integrating the stresses over an element cross section. These internal forces are the axial force, the shear forces in different planes, the axial torque, and the bending moments about different axis. The shell element internal forces include membrane direct forces, membrane shear force, and the plate bending moments, plate twisting moment, plate transverse shear forces for plate structures, such as floor slabs. The shell element stresses are the forces-per-unit-area that acts within the volume of the element to resist the loading. These stresses are in-plane direct stresses, in-plane shear stress, transverse shear stresses, and transverse direct stress (always assumed to be zero).

Among the analysis options defined in last process, the “Generate Output” item is used to save the results to an output file. The “Select Output Options” allows user to make selection for any result the user is interested in. The output file is an Access database file. After performing the analysis, an output (.mdb) file is generated, which includes the basic input data and selected analysis results. Appendix A illustrates a sample for the exported database file of SAP2000. Basically this database consists of all important information entered by users or generated by software which can give user a recapitulative view on the information requirements during structural analysis. To some extent it also represents the information requirements of structural analysis for SAP2000. Based on the above process models and referring to the database, the complete information requirements for SAP2000 to perform structural analysis can be extracted in the next section.

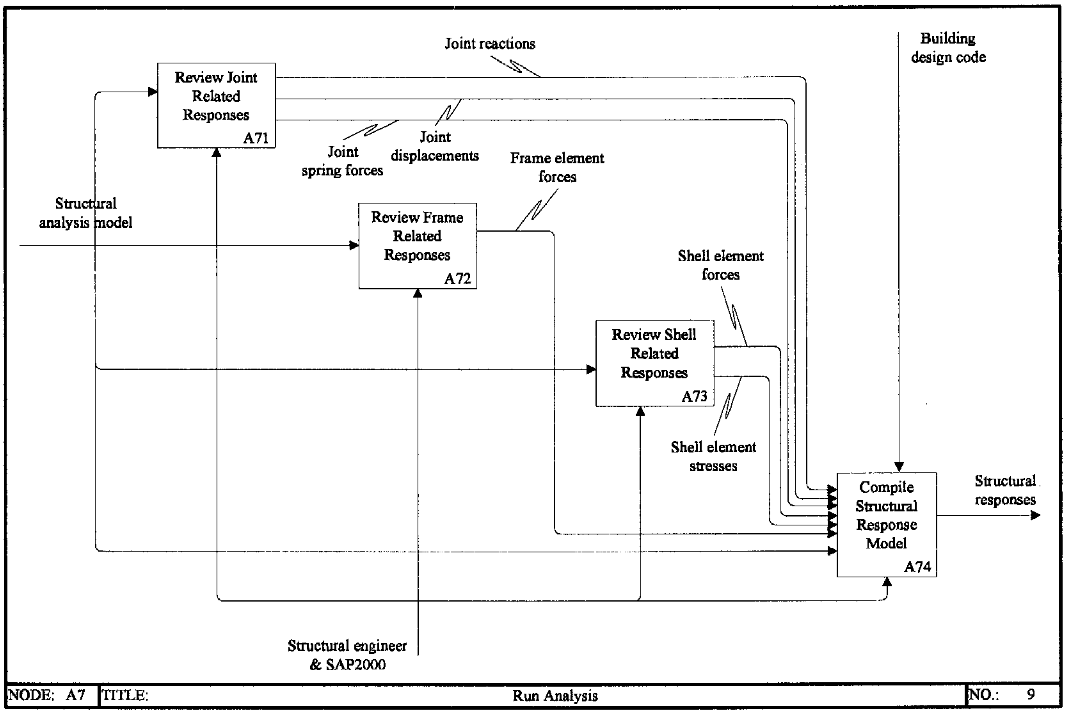


Figure 6.9 Process Model for Running Analysis

6.3 Identification of Information Requirements for SAP2000

After the investigation of SAP2000, the information or properties that are needed to do structural analysis can be classified in Figures 6.10. Following the rules of the PoIM methodology and the procedure presented in Chapter 4, the conversions and mappings are carried out. Appendix B lists all mapping tables generated during the course. Correspondingly, there is an information model diagram for each mapping table. Here only the final combined information model for SAP2000 to perform structural analysis is shown in Figure 6.10. This figure represents an overview of all information requirements. More detailed requirements including the properties for each entity are shown in the respective information diagram for each level of process model in Appendix B.

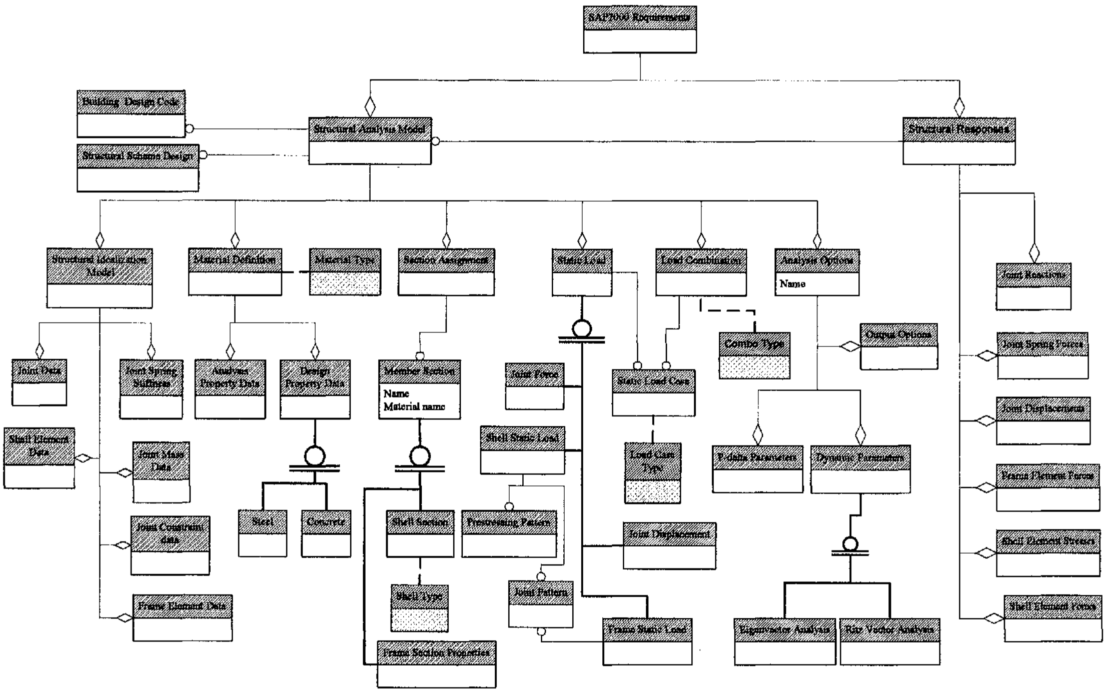


Figure 6.10 Information Requirements of SAP2000 for Structural Analysis

Two important parts of information constitute the whole requirements of SAP2000 to analyze structure. One is the part of information to set up structural analysis model. The other part is the structural responses, the results of analysis. And the information about structural analysis model can be classified into 5 different categories by their functions: (1) geometry information; (2) material information; (3) load information, involving static loads and load combinations; (4) member section information; (5) analysis options. A total of six categories can be identified with respect to the whole information requirements for SAP2000, the five types of information mentioned above and structural responses. The advantage of these classifications can make information more clear because they have similar functions and they should have some common characteristics. The assessment of IFC models performed in next section also complies with these classifications.

6.4 Assessment of IFC Models

In order to review the capabilities of IFC product models to support structural analysis at multiple levels of detail, comparison between the information requirements and current IFC models has to be done. After a series of comparison, shown in Appendix C, our initial findings with respect to the suitability of the IFC Release 2x Edition 2 Addendum 1 (IAI, 2004) to support structural analysis processes are as follows:

- For a simple frame structure, most of the mechanical features and properties necessary for static structural analysis can be found in current IFC release.
- Some information need to be deduced from the data in IFC.
- However, the only items IFC does not support include prestress load, description for stresses and types of load combinations, etc.

In the following section, the gaps are summed up and explained in detail under different categories. Table 6.1 lists the overall gaps between the information requirements of SAP2000 and current IFC extensions in Release 2x Edition 2 Addendum 1. Not only is the missing information given, it is also classified into different scenarios according to IFC 2x Extension Modeling Guide (IAI, 2001). As described in Chapter 4, there are three scenarios that may be observed from gaps analysis: (1) concepts exist in the IFC model, (2) concepts extend the IFC model, and (3) new concepts. For different scenarios, various approaches are considered to be adopted for the development of IFC extensions. The possible approaches are also listed in Table 6.1. Extension is based on analysis of the gaps that exist between concepts needed to be incorporated for the extension model development and concepts that already form part of the IFC Models.

Table 6.1 Overall Information Gaps between SAP2000 Requirements and IFC 2x2 Addendum1

	Gaps	Scenarios for IFC Development	Possible Different Ways of Development	
			Alternative Methods	Possible Extensions
Geometry	Location of Joints	Concepts exist in the IFC Model	1.Additional property sets 2. Implementation agreement	Derived the absolute displacements from relative displacements
	End offsets	Concepts exist in the IFC Model	1. New classes 2. Additional property sets	Pset_StructuralMemberCommon
	Rigid-end factor	Concepts exist in the IFC Model	1. New classes 2. Additional property sets	Pset_StructuralMemberCommon
	Length	Concepts exist in the IFC Model	1.Additional property sets 2. Implementation agreement	Pset_BeamCommon_Span Derived from IfcReldefinesByProperties or Depth of IfcExtruderAreaSolid
	Restraints of Joint	Concepts exist in the IFC Model	1. Add derived attributes 2. Additional property sets	Pset_StructuralConnectionCommon _Restraints
	Releases of Frame Element	Concepts exist in the IFC Model	1. Add derived attributes 2. Additional property sets	Derived from IfcBoundaryCondition Pset_StructuralMemberCommon (notice the conditions- release combinations which are not permitted)
	Local Axes	Concepts exist in the IFC Model	1. Add derived attributes 2. Additional property sets	Derived from IfcObjectPlacement
Load	Distance	Concepts exist in the IFC Model	1.Additional property sets 2. Implementation agreement	Derived the direct displacements from relative displacements
	Load Direction	Concepts exist in the IFC Model	1.Additional property sets 2. Implementation agreement	Pset_ StructuralActivity
	Load Type	Concepts exist in the IFC Model	1.Additional property sets 2. Implementation agreement	No need to modify the IFC Model, just process and decompose the load data to two parts: force and moment when programming
	Prestress Load	Concepts exist in the IFC Model	New class	New class as subtype of IfcStructuralLoadStatic
	Prestressing Pattern	New concept	New class	New class for prestressing cable: IfcPrestressingCablePattern
	Temperature Load	Concepts exist in the IFC Model	1.Additional property sets 2. Implementation agreement	No need
	Joint Pattern	New Concepts	1. New classes 2. Additional property sets	IfcPattern IfcRelConnectsJointPattern
	Combo type	Concepts extend the IFC Model	1. Add new attributes 2. Additional property sets	1. new attribute to IfcStructuralLoadGroup; 2. Pset_LoadCombination
Material	Type of Material	Concepts extend the IFC Model	1. New classes 2. Additional property sets	Current stage, no need do more extend for other anisotropic material
	Weight Per unit Volume	Concepts exist in the IFC Model	1.Additional property sets 2. Implementation agreement	1. new attribute to IfcGeneralMaterialProperties 2. new property sets
	Concrete Shear Stress	Concepts exist in the IFC Model	1. New attribute 2. Additional property sets	1. new attribute to IfcMechanicalConcreteMaterialProperties —Shear stress 2. Pset_ConcreteMaterialProperties

Table 6.1 <Continued>

	Gaps	Scenarios for IFC Development	Possible Different Ways of Development	
			Alternative Methods	Possible Extensions
Member Section	Radius of Gyration	Concepts exist in IFC Model	1.Additional property sets 2. Implementation agreement	Pset_StructuralProfileProperties
	Plastic Modulus	Concepts exist in IFC Model	1.Additional property sets 2. Implementation agreement	Pset_StructuralProfileProperties
	Shape Type	Concepts exist in IFC Model	1.Additional property sets 2. Implementation agreement	No need
	Material	Concepts exist in IFC Model	1.Additional property sets 2. Implementation agreement	No need
	Double angle/Double channel –	Concepts extend the IFC Model	1. New attributes/classes 2. Additional property sets	1. New classes: subtypes of IfcCompositeProfileDef 2. Additional property sets Pset_CompositeProfileDefProperties
Structural Responses	Shell Element Stresses	New concepts	New classes	Subtype of *IfcStructuralLoad*

6.4.1 Geometry

1. Joints, also known as nodal points or nodes, are a fundamental part of every structural model. Generally joints are automatically created at the ends of each Frame element and at the corners of each Shell element through the SAP2000 graphical interface. In SAP2000's database, the joint locations must be explicitly defined in order to describe the geometry of the structure. Usually the locations are expressed as absolute global placements. This information can be found from attribute *ObjectPlacement* of entity *IfcStructuralItem* by the instance of entity *IfcObjectPalcement.*

2. Considering the overlap between structural member, end offsets are automatically calculated by the SAP2000 graphical interface for each element based on the maximum Section dimensions of all other elements that connect to that element at a common joint. The clear length is defined to be the length between the end offsets.

Due to the stiffening effect caused by overlapping cross sections at a connection, the deflections in some structures may be overestimated. It is more likely to be significant in concrete than in steel structures. Thus, a **rigid-end factor** may be specified, which gives the fraction of each end offset that is assumed to be rigid for bending and shear deformation. The flexible length L_f of the element is given by: $L_f = L$ – **rigid (ioff+ joff)**. The default **rigid-end factor** is zero. The engineering judgment is used to select the appropriate value for this parameter. Typically its value would not exceed about 0.5.

3. Length can be inferred from the geometry information of two joints.

4. The "Restraints" of Joint in SAP2000 are represented by True/False in U1/2/3 & R1/2/3, which can be inferred from *IfcBoundaryNodeCondition* for *IfcStructuralConnection.AppliedCondition.* When the value of attribute *LinearStiffness* or *RotationalStiffness* of *IfcBoundaryNodeCondition* equals to infinite, then the corresponding displacement is restrained (its value equals to "Y").

5. Many combinations of end releases may be specified for a Frame element provided that the element remains stable; this assures that all load applied to the element is transferred to the rest of the structure. Similarly, the "Release" of frame elements can be inferred from *IfcBoundaryNodeCondition* for *IfcRelConnectsStructuralMember. AppliedCondition.* When the value of Property *LinearStiffness* or *RotationalStiffness* of *IfcBoundaryNodeCondition* equals to zero, then the corresponding end of frame is released (its value is equal to "I" which means it is released in joint I).

6. Each part (joint, element, or constraint) of the structural model has its own local coordinate system used to define the properties, loads, and response for that part. In SAP2000, the axes of the local coordinate systems are denoted 1, 2, and 3.

Normally the joint local 1-2-3 coordinate system is the same as the global X-Y-Z coordinate system. However, user may define any arbitrary orientation for a joint local coordinate system by specifying two reference vectors and/or three angles of rotation. For Frame and Shell elements, two methods are provided by SAP2000 to define the element local coordinate system. One is through the default orientation, where one of the local axes is first defined by the geometry of the individual element and the remaining two axes is determined by the relationship between the first axis and the global Z axis. The other way is to specify a single angle of rotation to define element orientations that are different from the default orientation.

In current IFC models, the entity *IfcLocalPlacement* defines the relative placement of a product in relation to the placement of another product or the absolute placement of a product within the geometric representation context of the project. The *IfcLocalPlacement* allows that an *IfcProduct* can be placed by this *IfcLocalPlacement* (through the attribute *ObjectPlacement*) within the local coordinate system of the object placement of another *IfcProduct*, which is referenced by the *PlacementRelTo*. If the *PlacementRelTo* is not given, then the *IfcProduct* is placed absolutely within the world coordinate system. The geometric placement that defines the transformation from the related coordinate system into the relating is defined by *IfcAxis2Placement*, which is referenced by the *RelativePlacement*. This transformation normally is defined in terms of a point and orientations of an axis in 2D or two axes in 3D. The angle can be derived from the orientation of axes. The orientation is defined in a general direction vector in two or three dimensional space. The angle can be calculated from the direction ratios of vector.

6.4.2 Load

1. When the user defines the location of given point loads and trapezoidal span loads to frame elements, the parameter of "Load Distance" is needed and often refers to the relative distance. Even though the "Absolute distance form end-I" is entered by engineer rather than "Relative distance form end-I", SAP2000 will change it to relative distance when saving the information in database. In IFC models, the location of action is denoted by the topology representation of *IfcStructuralPointAction* by the attribute *Representation* or the attribute *VaryingAppliedLoadLocation* of entity *IfcStructuralLinearActionVarying*. Finally the items *IfcVertex* or *IfcVertexPoint* and *IfcCartesianPoint*, or *IfcPointOnCurve* are used to give the location at which the actions act upon the structural items.

2. About "Load Direction", there are totally 11 kinds of direction in SAP2000, Local 1/2/3, Global X/Y/Z, Global X/Y/Z projected, Gravity and Gravity Projected. The

loads can be applied in different coordinate systems, global system or local system, projected or true, which are specified by the attributes *GlobalOrLocal / ProjectedOrTrue* of *IfcStructuralAction* in IFC models. The detailed directions are implied in the value of *IfcStructuralLoad*. For instance, if there is an *IfcStructuralLoadSingleForce (10, 0, 0, 0, 0, 0)*, then it only applied 10 units of force in x-direction. Consequently, the "Load Type" will be "Force" and direction is Global X or Local 1.

3. The value of "Load Type" can be "Force" and "Moment" which is defined when engineers input the static loads to various structural elements. In SAP2000, the force and moment should be assigned separately. However, in IFC models the entity *IfcStructuralLoad* contains the definitions both on forces and on moments. Since SAP2000 can only save either Force or Moment for every input, it is possible that some load definitions for the same element at the same position in SAP2000 may correspond to one *IfcStructuralLoad* Entity. By contraries, the value of each *IfcStructuralLoadStatic* should be decomposed in order to make it usable for SAP2000. Accordingly the value for "Load Type" is known. That is to say its value can be inferred from the status of value of *IfcStructuralLoad*.

4. As "Prestress Load" is out of the scope of project ST-4, there is no definition in current IFC models. As the precondition for defining prestress loads, the "Prestressing Pattern" is also missing.

5. In SAP2000 the definitions that are most different with IFC models are the definitions for temperature loads assigned to frame or shell elements, and for pressure loads assigned to shell elements. Besides in giving the change of temperature or pressures directly which are uniform over an element's surface, engineers can specify the variation of temperature or pressures which are interpolated from pressure values given by "Joint Pattern", which involves predefining "Joint Pattern".

In current IFC models, the entity *IfcStructuralLoadTemperature* is used to define actions which are caused by a temperature change, and *DeltaT-Y & DeltaT-Z* represent the values for the outer fibre of the positive Y and Z directions. Their way of expression is different.

6. In SAP2000, four types of load combinations are available. In current IFC models, the type of load combination is always set as additive by default (where the value is "ADD" in SAP2000). The other three types are ENVE, ABS and SRSS. For different types of Combo, the responses are calculated in different ways.

• Additive type: The Combo value is an algebraic linear combination of the maximum / minimum values for each of the contributing cases.

• Absolute type: The Combo value is the sum of the larger absolute values for each of the contributing cases.

• SRSS type: The Combo value is the square root of the sum of the squares of the larger absolute values for each of the contributing cases.

• Envelope type: The Combo maximum is the maximum of all of the maximum values for each of the contributing cases. Similarly, Combo minimum is the minimum of all of the minimum values for each of the contributing cases.

ENVE is used for moving loads and any analysis case where the load producing the maximum or minimum force/stress is required. ABS and SRSS are used for lateral loads.

6.4.3 Material Property

Generally speaking, nearly all properties of material can be found in current IFC extensions. The primary entity is *IfcMechanicalMaterialProperties*. By and large, it contains all properties which are independent of the actual material type. Properties for different material types, such as concrete or steel, are extracted as its subtypes *IfcMechanicalSteelMaterialProperties* and *IfcMechanicalConcreteMaterialProperties*. However, some micro aspects still need to be considered.

1. The value for two properties, Weight per unit volume and Type of material, are required by SAP2000, but not included in current IFC Release. In current IFC Release only isotropic materials are allowed for.

2. Shear strength, one of the design properties used for concrete, does not have the corresponding IFC definitions. In fact, different algorithms are used to calculate the shear strength of concrete under different design codes. For example, according to "British Standards Institute's Structural Use of Concrete (BSI BS8110, 1997)", the concrete shear strength is equal to 5N/mm2 or $0.8\sqrt{f_{cu}}$, which is less and where 'f_{cu}' is the characteristic strength of concrete.

6.4.4 Section Property of Member

Basically, most of the information can be found in current IFC extensions, directly or indirectly. However, the following three aspects still need to be considered.

1. Some information about member's section as defined in SAP2000 need to be derived from the existing information in IFC models.

At first, there are twelve general section properties that are required to be defined in SAP2000. But only the first eight general properties that must be explicitly specified; the other four can be calculated from given properties according to the following formulae:

a) Radius of Gyration: $r = \sqrt{\frac{I}{A}}$;

b) Plastic modulus: $Z = \frac{A(\bar{y}_1 + \bar{y}_2)}{2}$ or $Z = f \times S$, where, 'f' is shape Factor.

In the above formulae, 'I' stands for the moment of inertia, and 'A' stands for the area of cross section. Under fully plastic conditions, the neutral axis divides the cross section into two equal areas. And '$\overline{y_1}$' and '$\overline{y_2}$' are the distances from the neutral axis to the centroids of these two areas respectively.

In current IFC models, Moment of inertia '*I*' and area of section '*A*' are defined as attributes of entity *IfcStructuralProfileProperties.* Shape factor '*f*' is included as attributes '*PlasticShapeFactorY/Z*' in entity *IfcStructuralSteelProfilePropertie*". Two distances, '$\overline{y_1}$' and '$\overline{y_2}$', can be derived from the properties of entity *IfcProfileDef* and its subtypes. It has already been noted in IFC that "*The radii of gyration are not given explicitly but can be derived from moment of inertia and section area*". However, the value of one operand to compute plastic modulus should come from another class, it cannot be extended by the way of adding derived attributes.

Secondly, in SAP2000 there is a very important parameter named "Shape Type" that is used to determine the means about how to obtain the section properties (see Section 6.2.3). There is no explicit definition for this information in IFC models. But it is implied in the names of related entities. In IFC models, *IfcProfileDef* is used to define a cross section by the profile definition within the swept surfaces or swept area solids, which is the supertype of all definitions of standard and arbitrary profiles within IFC, such as *IfcIShapeProfileDef*, *IfcLShapeProfileDef*, *IfcCircleProfileDef*, etc. It is obviously that their Shape Types are I, L, and C respectively from the name of profiles.

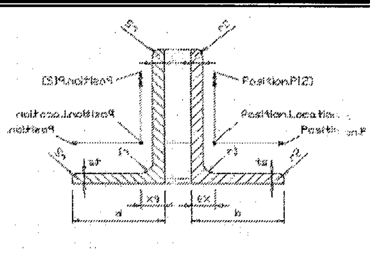
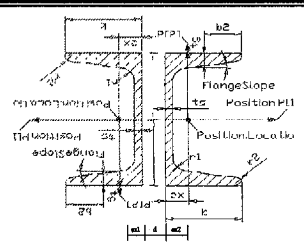
2. In SAP2000, users donot need to define material type for each structural element. The assignment of material type to structure is through the assignment of section. In IFC models, they are two independent parts which are connected by the common assigned structural member. Two association relationships, *IfcRelAssociatesProfileProperties* and *IfcRelAssociatesMaterial*, are used to specify the objectified relationships between non geometric profile properties and elements to which these properties apply, as well as between a material definition and elements or element types to which this material definition applies (IAI, 2004).

3. For special types of sections (e.g. "Double Angle" and "Double Channel" sections) , most defining parameters can be found their corresponding IFC definitions except the properties "Outside width" and "Back to back distance". In IFC models, the *IfcCompositeProfileDef* defines the profile by composition of at least two other

profile definitions (IAI, 2004). The dimensions of composite profile are determined by the dimensions of its component profiles. No any new definition for the dimension of composite profile is introduced in current IFC.

Double angle and Double channel can be treated as the composition of two angles and two channels respectively. The "Outside width" and "Back to back distance" can be calculated based on the defining parameters of component profiles, *IfcUShaperProfileDef* or *IfcLShapeProfileDef*. Their relationships are illustrated in Table 6.2.

Table 6.2 Expressions for "Outside Width" and "Back to Back Distance"

	Double Angle	**Double Channel**
Example Pattern		
Back to back distance	Distance between the position of two composite L-shaped sections – the sum of two locations of centre of gravity in X or Y axis which depends on the side to be composed	Distance between the position of two composite U-shaped sections – the sum of two locations of centre of gravity in X axis
Outside width	the sum of width or depth (which depends on the side to be composed) of two composite L-shaped sections + Back to back distance	the sum of flange width of two composite U-shaped sections + Back to back distance

6.4.5 Analysis Options

The dynamic analysis is outside of the scope of current IFC models. The setting of output options to saved file is entirely for the convenience of the operations of software which cannot be regarded as an information requirement for structural analysis. Referring to the scope of this research, the analysis options on dynamic analysis, P-delta analysis and output options would not be considered in this thesis.

Another analysis option is the definition of the appropriate degrees of freedom (U1, U2, U3, R1, R2, R3) to be available for structural model. Alternatively, in SAP2000 the available degrees of freedom may be automatically checked by clicking on the four fast DOF's options i.e. Space Frame, Plane Frame, Plane Grid and Space Truss. In fact, this part of information is implied during setting up of the structural idealization model.

Thus, Appendix C will not include the comparison of this part of information requirements with IFC models. Accordingly the information about SAP2000's analysis options will not be discussed in the subsequent study.

6.4.6 Structural Responses

In current IFC Release, only the output results for forces and displacements are considered. The outputs, like stresses and strains, are out of the scope of ST-4 project. There are no definitions for shell element stresses so far.

6.5 Generality Study of Information Gaps

As described in Chapter 4.7, different approaches will be adopted in different scenarios for IFC extension development. Thus the new problem faced is how to identify the character of information and make the decision on whether this information should be included in the IFC models by amending the current schema. This question cannot be answered without abstracting the common information requirements of popular structural analysis soft packages and comparing it with current IFC schema. Thereby in order to confirm whether it is necessary to add new classes or make any change to current schema, a generality study is carried out to investigate into other ten different structural analysis software in this research.

In 1998, Modern Steel Construction magazine published the results of a survey of practicing structural engineers. In the survey (as shown in Table 6.3), these engineers were asked to rate the quality of the programs they used. Whereas this survey was conducted nearly seven years ago, it is obviously and unavoidable that current status has changed. Nowadays this survey can only be an assistant reference to select appropriate software.

Furthermore, in January 2003, the Modern Steel Construction magazine highlighted 32 structural engineering software products and some product case studies were also provided. In August 2004, the STRUCTURE magazine also gave a software guide for structural engineers whereby around 60 kinds of general or specific engineering software were listed and their characteristics are also given, such as the functions, types of structures in point, materials involved etc. Based on this highlights and the guide, Table 6.4 extracts 35 kinds of structural engineering software and makes a comprehensive view on the applicability of these software for different design cases, such as the design of different structures, different materials, different analysis methods etc.

Table 6.3 Structural Engineering Software Survey

STRUCTURAL ENGINEERING SOFTWARE SURVEY

Results are from 1 to 8, with 8 being the top score	Ease of learning	Ease of Installation	Documentation	Customer Support	Ease of Data Input	GUI	Validated Results	Graphical Output	Expectations	Accuracy-Basic	Accuracy-Complex	Productivity	Value	Recommendation	# of Respondents
AISC for AutoCAD	3.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	4.00	5.00	5.00	5.00	6.00	7.00	1
Algor SAP	3.80	5.60	3.40	4.80	3.80	4.60	4.40	4.20	5.20	6.00	5.80	4.80	3.80	3.20	5
BRASS (Wyoming DOT)	6.00	4.00	5.00	5.00	5.00	6.00	5.00	6.00	6.00	7.00	5.00	6.00	5.00	5.00	1
SJI (Floor Vibration)	6.00	7.40	4.80	2.40	6.60	3.80	6.80	4.00	6.40	5.60	4.80	6.20	6.40	5.00	5
CONXPRT	5.75	6.75	4.25	5.00	5.75	5.00	7.25	7.25	5.75	7.00	5.75	7.00	5.75	6.00	4
DESCON	5.66	5.66	5.00	5.00	6.00	5.66	6.00	6.00	5.66	5.66	5.66	5.33	4.66	5.33	3
Descon Brace	2.00	2.00	1.00	2.00	2.00	2.00	1.00	1.00	1.00	2.00	2.00	1.00	1.00	1.00	1
DESCUS	6.00	6.00	4.50	6.50	6.00	5.00	6.50	5.00	7.00	7.00	6.50	7.00	6.50	7.50	2
DetailCAD	7.00	7.00	6.00	8.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	8.00	8.00	8.00	1
Eagle Point Software	5.56	6.26	4.86	6.04	5.69	4.56	5.91	5.52	5.69	6.56	5.00	5.43	5.47	5.65	23
Enercalc	6.31	6.50	5.50	5.43	5.87	5.62	6.43	6.06	5.68	5.81	4.50	6.12	5.75	6.00	16
ETABS	4.30	4.00	4.10	6.10	4.60	4.70	5.10	5.00	4.20	5.70	5.60	5.00	4.40	5.60	10
FloorVib	5.00	7.00	3.00	4.00	4.00	0.00	7.00	0.00	5.00	6.00	6.00	4.00	5.00	5.00	1
FrameMAC	7.50	7.50	5.50	2.50	7.50	7.50	7.50	7.50	7.50	7.00	1.50	7.50	7.50	7.50	2
FrameWorks Plus	6.00	7.00	5.00	3.00	7.00	6.00	5.00	7.00	7.00	8.00	7.00	7.00	7.00	7.00	1
GT STRUDL	5.25	5.31	5.56	5.62	5.81	4.87	6.00	5.81	6.43	7.37	6.75	6.31	5.56	6.37	16
IMAGES-3D	4.00	4.00	4.00	5.00	6.00	4.00	6.00	5.00	5.00	6.00	6.00	3.00	3.00	3.00	1
LARSA for Windows	6.20	7.60	5.20	6.60	6.80	6.80	7.40	7.60	6.20	7.60	7.40	6.20	6.20	6.80	5
MDX Software	5.33	4.33	4.33	4.00	7.00	0.00	5.33	0.00	5.66	3.66	3.00	5.66	4.33	5.66	3
MERLIN DASH	5.12	4.87	4.62	5.50	5.37	6.12	6.25	5.37	5.50	5.50	5.25	6.00	5.25	5.37	8
Multiframe (Macintosh)	7.16	7.66	6.00	5.16	7.33	7.50	7.16	7.33	7.50	7.66	6.33	6.83	7.16	7.66	6
QuickBEAM	7.33	7.66	7.66	5.00	7.66	5.00	7.66	5.00	7.33	7.66	7.66	5.00	8.00	7.66	3
QuickConnect	5.66	5.00	6.00	5.00	6.00	5.66	6.00	5.66	5.00	6.00	5.33	6.00	5.33	5.66	3
RAMFRAME	5.71	6.28	5.35	6.85	6.42	6.07	6.28	6.57	6.42	6.85	5.71	6.57	5.78	6.50	14
RAMSBEAM	6.86	6.47	6.13	6.08	6.73	6.60	6.47	6.60	6.69	6.86	5.82	6.47	6.60	6.65	23
RAMSTEEL	5.85	5.76	5.38	5.23	5.94	5.82	5.82	5.76	5.82	6.32	5.44	6.29	5.55	6.08	34
RISA-2D	6.71	6.56	6.23	5.51	6.35	5.97	6.53	6.51	6.43	6.92	5.17	6.61	6.92	7.00	39
RISA-3D	6.66	6.25	6.05	6.11	6.52	5.88	6.41	6.72	6.58	6.86	6.05	6.69	6.61	6.94	36
RobotV6	6.00	5.00	5.00	5.00	5.00	6.00	5.00	5.00	5.00	6.00	6.00	6.00	6.00	6.00	1
S-FRAME/S-STEEL	8.00	8.00	7.00	8.00	8.00	7.00	7.00	7.00	8.00	8.00	8.00	7.00	8.00	8.00	1
SACS	5.50	6.00	4.50	6.50	7.00	6.00	7.00	6.00	7.00	7.00	7.00	7.00	5.00	5.50	2
SAP2000	5.18	6.72	4.90	5.90	5.27	5.81	6.36	6.90	5.09	7.18	5.81	5.00	5.90	5.81	11
SAP90	4.62	5.62	4.50	3.62	4.62	2.50	5.25	4.75	5.00	6.25	6.00	5.00	5.00	4.62	8
SDI Floor	5.00	6.00	6.00	5.00	5.00	6.00	7.00	6.00	6.00	7.00	7.00	7.00	6.00	6.00	1
SIMON Systems	6.33	4.66	6.33	3.66	6.00	2.00	6.00	2.33	4.00	7.00	7.00	7.00	7.00	6.66	3
SODA	8.00	8.00	6.00	7.00	8.00	8.00	8.00	6.00	8.00	8.00	7.00	8.00	8.00	8.00	1
STAAD-III	5.15	6.03	4.64	4.55	5.50	5.35	6.05	6.14	5.83	6.45	5.78	5.85	5.20	5.57	110
StruCAD*3D	5.50	6.50	4.75	6.00	5.50	6.00	6.50	6.50	5.25	6.75	5.75	4.75	4.00	5.75	4
Structural Analysis, Inc.	4.00	8.00	4.00	1.00	3.00	1.00	7.00	1.00	5.00	8.00	8.00	7.00	8.00	6.00	1
VisualAnalysis/VisualDesign	7.16	7.00	5.50	6.33	6.50	6.83	6.50	7.00	6.16	6.16	3.83	6.50	6.00	6.16	6
WEBOPEN	6.00	6.66	5.00	4.66	6.33	3.66	6.00	3.66	5.66	6.33	6.00	5.00	6.00	6.00	3
WinSTRUDL	6.00	7.00	3.00	4.00	5.00	2.00	6.00	6.00	6.00	7.00	5.00	7.00	6.00	7.00	1

(Source: Modern Steel Construction, January 1998. Available at: http://www.aisc.org/ContentManagement/ContentDisplay.cfm?ContentID=730)

Table 6.4 Comparison of Structural Engineering Software Products

Software Title	Description	Analysis	Design	Building	Framed structure	Bridge	Tower	Material			Analysis Method			Code checking	Specialty
								Concrete	Steel	Others	Static	Dynamic	FEM		
1. SODA	Steel design	X							X						
2. STRAP	Comprehensive analysis and design	X	X	X	X	X		X	X		X	X	X		
3. MicroStation	Bentley's flagship product for the design, construction and operation of infrastructure		X	X	X			X	X						
4. SAM	Bridge design	X	X			X								X	
5. CSI (ETABS, SAFE, SAP)	A wide range of applications	X	X	X	X	X	X	X	X	X	X	X	X	X	
6. ERITOWER	Telecommunication towers design	X	X				X								
7. REAL3D-Analysis	Comprehensive structural analysis program	X	X	X	X										
8. WinSTRUDL	Finite element program	X		X	X			X	X		X	X	X		
9. S-FRAME	Powerful 2D/3D analysis software	X			X				X						
10. MultiFrame	2D/3D static and dynamic analysis of framed structures	X			X						X	X			
11. LGBEAMER	Cold formed steel framing design		X						X						
12. Structural Expert Series (SES)	Multi-purpose analysis and design programs	X	X					X	X						
13.RSTAB	3D analysis software only for frame structure	X						X	X	X	X	X			
14. Dr. Software	Real-time structural modeling software										X	X			X
15. GTSTRUDL	Fully Integrated Software System for General Engineering Design & Finite Element Analysis	X	X	X	X	X	X	X	X	X	X	X			

Table 6.4 <Continued>

16. VisulaAnalysis	A powerful, easy to use, frame and finite-element tool	X		X	X			X	X	X					
17. ROBOT Millennium	**Finite analysis and design software**	X	X	X	X	X	X	X	X	X	X	X	X		
18. Frame Works Plus 7.2	Fabrication and detailing data package														X
19. SpaceGass	General purpose analysis and design program for 2d and 3d frames, trusses, grillages, beams, etc.	X	X	X	X						X	X			
20. MEI	Steel estimating software														X
21. MIDAS	Integrated modeling, analysis and design	X	X	X	X	X		X	X	X	X	X			
22. DesconWin	Connections of steel structures design														X
23. DESCUS	Steel girder bridge design	X	X			X			X					X	
24. RAM International	Fully integrated engineering software, including RAM structural system, RAM Advanse, etc.	X	X	X	X			X	X		X	X			
25. STAAD.Pro	Comprehensive analysis and design software	X	X	X	X			X	X		X	X	X		
26. RISA3D	General purpose three-dimensional analysis and design software	X	X	X	X	X	X	X	X	X	X	X			
27. SAFI3D	Integrated structural analysis, verification, and design program	X	X	X		X	X	X	X		X	X	X	X	
28. Stat-Ease	Statistical software														X
29.Steel Joist	Determine probable vibration characteristics of floor systems using open web steel joists														X
30. WPS Designer	Develop and evaluate welding procedures														X
31.StruCalc 5.0	Analysis and design of light commercial and residential structure	X	X												X
32. ROBOT	Finite analysis and design software	X	X												
33. FloorVibe	Analysis of floors for annoying vibrations	X													X
34. HSS_connex	Design hollow structural section truss connections														X
35. PROKON	Suite of structural analysis and design software	X	X	X	X			X	X	X	X	X	X		

In order to choose most appropriate software for the generality study, some criteria need be specified. Considering the characteristic of SAP2000 and for improving the comparability with the information definitions of other structural analysis and design applications, three criteria of selection are complied with:

(1) They should be the most comprehensive and versatile structural analysis and design software systems available and commonly used in the industry.

(2) They should be integrated and general purpose analysis and design software which can be applicable to any types of structures, buildings, bridges, etc., and are not software specially for the design of bridges, or the design of standard steel sections, etc.

(3) They should have been developed and used for many years.

Besides Tables 6.3 and 6.4, the author also searched the Internet and found out some evaluations of various structural engineering softwares. The most comprehensive and useful forum is Eng-Tips forum (http://www.eng-tips.com), which covers almost all aspects of engineering and where many engineers post their comments and suggestions on structural engineering softwares. As a result of the above investigation and using the three criteria, ten structural analysis and design software were finally selected. They are:

(1) Computers and Structures, Inc. (CSI), which specializes in structural and earthquake engineering software. The products offered by CSI (SAP2000, ETABS and SAFE) cover a wide range of structural applications from high rise buildings to multi-use one- and two-story structures (industrial structures, hospitals) and bridges (suspension and cable stayed bridges, multi-span bridges) to transmission towers. For nearly three decades, CSI software has been used for the analysis and design of major projects in over 100 countries (CSI, 2004).

(2) STAAD.Pro is the world standard for structural analysis and design software with the most intuitive modeling environment, support for most international design codes, multi-material design, automatic load generation (seismic, gravity, wind, wave and moving) and extremely user-friendly reports and result presentations (REI, 2004). As mentioned in Modern Steel Construction (2003), STAAD.Pro is the choice of 46 out of 50 leading Structural Engineering firms, 46 out of 50 state DOTs and 7 out of the top 10 engineering universities. STAAD.Pro features a state-of-the-art user interface, visualization tools, powerful analysis and design engines with advanced finite element and dynamic analysis capabilities.

(3) **RISA-3D** is a general purpose three-dimensional analysis and design software developed to model, solve and optimize 3D structures as fast and easily as possible. Analysis may be done on structures constructed of any material or combination of materials. Design of hot rolled steel, concrete, cold formed steel, and wood is fully supported. The truly interactive nature of RISA-3D is its primary strength. RISA-3D also performs elaborate error checking, and provides context sensitive help every step of the way.

(4) **STRAP** (STRuctural Analysis Programs) is one of the most comprehensive and versatile structural analysis and design software systems available on the market today (MSC, 2003). It's easy to use, due to its superb graphic user interface (GUI) and advanced context-sensitive help system. It offers the engineer a powerful but affordable tool for analysis and design of a wide range of skeletal and continuum structures such as buildings, bridges, shells, towers and more (ATIR, 2004).

(5) **GT STRUDL** is a world class computer-aided structural engineering software system for assisting engineers in the structural analysis and design process (Georgia Tech - CASE Center, 2004). It integrates graphical modeling and result display, frame and finite static, dynamic, and nonlinear analysis, finite element analysis, structural frame design, graphical result display, and structural database management into a powerful menu driven information processing system.

In over 29 years of use, GT STRUDL has become one of the most widely accepted programs for the structural analyst and structural design engineer. GT STRUDL is used on a regular basis by thousands of engineers in over 30 countries.

(6) RAM International has products for every type of project, for every building material, and for every budget. RAM Structural System includes RAM Steel, RAM Concrete, RAM Frame, and RAM Foundation, which provides a fully integrated suite of building design, analysis and drafting software RAM Advanse is a full-featured, general purpose 3D finite element analysis and design software system for wood, steel, cold-formed steel and concrete. It is suitable for analysis and design of any type of structure or structural component.

(7) ROBOT Millennium is the state-of-the-art finite element structural engineering software. It is a recognized system in the analysis and design of various structures including buildings, bridges, industrial facilities, civil and mechanical engineering. The software performs static/dynamic analysis of 2D/3D projects using beams, plates, shells and solids elements. ROBOT Millennium evolved over 20 years of innovative and extensive developments and improvements, as well as a precise study of users' needs and experience of ROBOT V6 and ROBOT 97 (ISS, 2004).

(8) MIDAS Programs for Integrated Modeling, Analysis & Design of Civil/Bridge & Building Structures will change the way of engineering practice (MSC, 2003). MIDAS/Gen is a Windows-based, general-purpose structural analysis and optimal design system (MIDASoft, 2004). MIDAS/Gen offers conventional analysis capabilities as well as other analyses such as Geometric nonlinear analysis reflecting Large Displacement, Boundary nonlinear analysis, Pushover analysis, Construction simulated analysis reflecting time dependent material properties, Heat of hydration analysis, etc. MIDAS/Gen has been used for over 10 years and applied to over 4,000 projects successfully, thereby, exhibiting its credibility and stability.

(9) REAL3D-Analysis is a comprehensive frame and finite element structural analysis program that provides accuracy, reliability and ease of use to structural engineers (CGI, 2002). It incorporates the latest technologies from the fields of finite element analysis, numerical computation and computer graphics. It is a true 32-bit, fully integrated Windows program that allows user to visually analyze any practical 2D & 3D structures reliably, in an unsurpassed user-friendly manner.

(10) The **PROKON** suite of structural analysis and design software is developed by engineers for engineers. It is a large collection of modular engineering programs covering structural analysis, steel design, concrete design, geotechnical analysis and other general calculations including gutter design and wind pressure on buildings. Used worldwide in more than eighty countries, the suite provides quick and reliable answers to everyday structural and geotechnical engineering problems (http://www.prokon.com).

For all the missing information and some derived information identified in previous sections (as shown in Table 6.1), their definitions in above ten kinds of software are investigated and compared with SAP2000's. Table 6.5 shows the results of generality study. In Table 6.5, the "tick" symbol, "✓", means that the information in the software is expressed in the same way as SAP2000. For those defined in different ways, its brief definition is given. Consequently the generality of the definition in SAP2000 for the missing information can be judged. Then the corresponding solutions of IFC extension development are also decided. The detailed explanations are specified in the section following the table.

Table 6.5 Generality Study of the Information Gaps between SAP2000 and Other Software

	Missing Info. Gaps	ETABS	STAAD pro 2004	STRAP	RISA 3D	RAM International	GT STRUDL	ROBOT Millennium	MIDAS /Gen	REAL3D-Analysis 2002	PROKON	Generality	Final Solution
Geometry	Location of Joints	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	Yes	Pset/ Programming
	End offsets	NA	1.Global/Local 2.Start/End 3.X/Y/Z	✔ Start/ End X1/X2/X3	✔	Rigid end offsets	✔	Beginning/End UX/UY/UZ	1. Global/Element 2. RGDXi/Yi/Zi RGDXj/Yj/Zj	No	NA	Yes	Pset/ Programming
	Rigid-end factor	NA	NA	No	NA	K-factor	No	NA	NA	NO	NA	No	No need change
	Length	✔	✔	✔	✔	No	Partially (when by 'start /length / angle')	✔	No (Lu/L)	✔	NA	Already have in Pset	Pset (already included)
	Restraints of Joint	✔	(Support) ✔	✔	✔ (Joint boundary conditions)	✔	✔	✔	✔ (Dx/y/z, Rx/y/z)	✔	✔	Yes	Pset/ Programming
	Releases of Frame Element	Partial	✔	1. Both/one end 2. moment/ shear release	✔	✔ (J/K end M2,M3,V2,V3 , Ax1, Tonly)	✔ (Start/End FX/FY/FZ, MX/MY/MZ)	✔ (Bars,Elastic, damping, unidirectional, nonlinear)	✔ (i-node/j-node; Fx/y/z, Mx/y/z)	Only has moment release for beam	1.Fixity low node 2. Fixity high node	Yes	Pset/ Programming
	Local Axis	NA	✔ (BETA angle)	Give the plane paralleled to or node pointed to	K-Joint and X-axis rotation	✔ (Rotation & Local)	✔ (BETA angle)	✔ (Gamma angle)	✔ (BETA angle)	✔ (Local angle)	✔ (Beta angle)	Yes	New attribute
Load	Load Distance	NA	Absolute	Distance/ Fraction	Absolute / Relative (%)	Relative distance (L1/L)	Fractional / Absolute	Absolute / Relative	Relative / Absolute	Relative	Absolute	No	No need change

Table 6.5 <Continued>

Load	Load Direction	✔	1.X/Y/Z 2.GX/GY/G Z 3.PX/PY/PZ	1. Load type; 2. FX1/FX2	1. Global X/Y/Z 2. local x/y/z 3. Thermal load; 4. Projected X/Y/Z; 5. Moment global/local MX/MY/MZ Mx/My/Mz	1.Gravity point loads; 2. Gravity distributed loads	1. Global / Local; 2. Force / Moment; 3. X/ Y/ Z	1. Global / Local; 2. Projected; 3. X/Y/Z	1. Global X/Y/Z; 2. Local x/y/z; 3. If Projection;	1. Coord-sys 2. Direction	✔	Partly general	Programming
	Load Type	✔	Assign force and moment respectively	Local; Global; Global Projected	If direction =MX/MY/M Z, then is 'moment', others is 'force'	No (same with IFC)	✔ (Joint load is the same with IFC)	No (same with IFC)	✔ (Concentrated force /moment, uniform load, Trapezoidal load / moment, Curved load)	If direction =X/Y/Z, then is force, if = OX/OY/O Z, is moment	✔	No	Programming
	Prestress Load	NA	1. Force (kN) 2. Eccentricity distances: start/middle/ end (m)	(same with STAAD)	Same with Thermal loads	Pre-tension force value	NA	NA	1. Tension (kN); 2. Di, Dm, Dj (m)	NA Out of Scope	NA	Basically Yes	New Class
	Prestressing Pattern		Defined in Prestress load	Defined in Prestress load	NA	NA	NA	NA	Defined in Prestress load	Prestress is out of scope	NA	No	Programming
	Temperature Load	Uniform Temp. change	Directly definition	Temperature change	Member distributed loads: Temperature change	Temperature differences (Temp 1/2/3)	Temperature change (Axial / Bending)	Temperature change (X/Y/Z)	Temperature change (Initial & end temperature)	NA Out of Scope	Tempera-ture change (dT)	Existed	No need change
	Joint Pattern	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	No	Programming

Table 6.5 <Continued>

Load	Combo type	✔	SRSS/ABS	Only additive	SRSS	ADD	Only additive	ULC / SLS/ ACC Seismic: CQC/ SRSS/ 2SM/ 10% quadratic	✔ (ADD/ ENVELOP/AB S/SRSS)	Only additive	Only additive	Partly	New Attribute
Material	Type of Material	✔	Isotropic & Orthotropic	Isotropic & Orthotropic	Isotropic	Linear & Nonlinear	Isotropic	NA	Isotropic & Orthotropic	No.	Isotropic	Yes	Future
	Weight per Unit Volume	✔	No.(mass density)	✔	✔	No	✔ (only Density)	✔	✔	✔	No.(mass density)	No	Programming
	Concrete Shear Stress	No	No	No	No	No	Ult. shear stress / Max. ultimate Concrete shear stress	No	No	NA (only do analysis)	No	No	Programming
Member Section	Radius of Gyration	✔	No	No	Calculated from dim.	No	NA	No	No	No	No	No	Programming
	Plastic Modulus	✔	No	No	Calculated from dim.	✔		✔	✔	No	No	No	Programming
	Shape Type	✔	No	No	Shape type + Dimension: w14x109	No	1. Prismatic 2. Table 3. Pipe	✔ (1-100)	✔	No	No	No	Programming
	Material	✔	✔	✔	✔	✔	Same with IFC (assign to member)	✔	Same with IFC (assign to member)	✔	✔	Existed	Inferred (programming)
	Double angle/ Double channel –	✔	✔ (sp: space between angles / channels)	✔ (Distance between angles / flanges)	✔ ('Spacing')	✔ (Separation)	Standard specifications for these kind of shapes	✔ ('Spacing')	Partial ✔ 1. Standard specifications; 2. User-defined	No	NA	No	Programming
Results	Shell Element Stresses	✔	± Sx / Sy /Sxy / Sxz / Syz Max / Min / Max Shear	1. ±Sx / Sy / Sxy; ±Max / Min; 2. Principal stresses	σ_1 / σ_2 (normal); τ max (shear); Von Mises (plane)	SH, SV, SVH, Smin, Smax	1. MXX /MYY /MXY /VXX /VYY 2. Principal stresses	1. sxx, syy, sxy, txx and tyy 2. Principal S1, S2, t12	✔	Differenc e: Sxx/yy/zz Sxy/yz/xz	✔	Partly	New class (future)

Note: "✔"—the corresponding information gap is defined in the same way as SAP2000

6.5.1 Geometry

1. Basically the location of joint or element in the databases and input tables generated by all software is shown as absolute global displacement. The user has three ways to create a joint: (1) by directly providing the coordinates as input values, (2) by referring to the grid intersection, and (3) by defining the frame or shell elements. Then the software calculates and saves the absolute coordinates automatically. Similarly in IFC models, by *IfcObjectPlacement* the object placement can either be given (1) absolute (relative to the world coordinate system), (2) relative (relative to the object placement of another product), or (3) by grid reference (the virtual intersection and reference direction given by two axes of a design grid).

The current view of IFC models is more coincident with reality. So here no extension is considered. Since it is needed by all softwares, a piece of program could be written to generate the inputs.

2. Regarding the end offsets about frame elements, six out of ten softwares have this function. In SAP2000, the offsets on 'I' and 'J' joints are directly specified by user. But some software require more detailed information including the direction (Global/ Local), the joint assigned (Start/End), and offsets (X /Y/Z).

3. Almost all the database files of every software would include the information of the frame element's length. However, this value is mostly calculated by the software automatically unless the user selects to define the frame element by giving its starting point, its length and angle, such as in GT STRUDL. Therefore, although it is a general requirement, it is not necessary to modify current IFC models.

4. Basically, the way to define supports and restraints of joints or releases of frame elements are the same in all softwares. Normally, if the check box is checked, it means that the joint is restrained and vice versa. For each end of frame element, six types of release are specified individually. In SAP2000, they are Axial, Shear Force 2 (Major), Shear Force 3 (Minor), Torsion, Moment 22 (Minor) and Moment 33 (Major). Each kind of release includes Start and End two ends. In SAP2000, the

values for each type of release are either "I" (released in "Start" end), or "J" (released in "End"), or "IJ" (released in both ends). In other software, maybe the value is expressed by 0 or 1. Regardless of what kind of value is used, the essential meaning is the same. As mentioned in Section 6.4.1, this part of information can be inferred from the attribute *AppliedCondition* for *IfcStructuralConnection* or *IfcRelConnectsStructuralMember*. An instance of *IfcBoundaryNodeCondition* is used to define the joints properties. So this information can be considered add into current IFC models by Pset.

5. Usually the default local axes are given automatically when an element is defined. The local axis is needed only when the section of element rotates about its axes. In this case, six out of ten kinds of software define an angle named Beta angle or Gamma angle to express the difference from the default local axes. STRAP is different by given the plane local axis paralleled to or node local axis pointed to. Anyway, IFC models provide sufficient definition to this information which is implied and can be calculated by the direction ratios of *IfcDirection* (please see Section 6.4.1). Anyway a derived attribute can be considered to entity *IfcDirection* to express the angles of the direction vector. And a function is also developed to calculate the angles. Please see Section 6.6 and Appendix D for the details.

6.5.2 Load

1. Basically, most software provide users two ways to enter the location of load either by relative distance or by absolute distance, for the users' convenience, like STRAP, RISA 3d, RAM, GT STRUDL, ROBOT and MIDAS. However, this parameter is not applied to all load cases. Only the point loads and trapezoidal loads to frame elements have this property. Furthermore, it can be concluded that basically current IFC models provide explicit definition for the location of point action and linear action as described in Section 6.4.2. Thus no change is needed and translation during the implementation is enough.

2. Referring to Table 6.5, by and large, "Load Direction" includes three parts of information. One is coordinate system, local or global. The other one is the detailed

direction in different axis. The last one is whether this load is projected load. The minor difference between different softwares is on the classification or combination of the coordinate system and detailed directions.

As described in Section 6.4.2, SAP2000 provides a total of 11 kinds of load direction. The value for it can be from the attributes "GlobalOrLocal" and "ProjectedOrTrue" of entity *IfcStructuralAction*. The mapping between them is given in Table 6.6. This information is already included in the current IFC models. It is not necessary to add new classes or property sets.

Table 6.6 Mapping of Load Directions between SAP2000 and IFC Model

SAP2000	Attributes Values of IfcStructuralAction	Detailed Direction in 3 Axis
Local 1/2/3	GlobalOrLocal: LOCAL_COORDS	Derived from the value of *IfcStructuraLoad.*
Global X/Y/Z	GlobalOrLocal: GLOBAL_COORDS	
Global X/Y/Z	GlobalOrLocal: GLOBAL_COORDS	
Project	ProjectedOrTrue: PROJECTED_LENGTH	
Gravity	GlobalOrLocal: GLOBAL_COORDS	
Gravity Projects	GlobalOrLocal: GLOBAL_COORDS ProjectedOrTrue: PROJECTED_LENGTH	

3. Different software has different meaning for "Load Type". For example, in SAP2000, it means 'Force' or 'Moment'. But in STRAP, it represents the direction of load, 'Global/Local/Global Projected'. In MIDAS, the load types include 'Concentrated force', 'Concentrated moment', 'Uniform load' etc. However, there is still some software, like RAM, ROBOT Millennium, to define the static loads in the same way with *IfcStructuralLoad.*

Furthermore, it is found that IFC schema is still followed when SAP2000 saves the information on the load types into database. It is not necessary even in S2K format which will be later used in the implementation of prototype system. The value of *IfcStructuralLoad* need be decomposed to the forces in 3 directions and the moments about 3 axes and then assigned to related element individually.

4. As mentioned in Section 6.4.2, the definition of prestress load involves developing a new entity for current IFC models, but the way SAP2000 defines prestress load is not common between domains. As shown in Table 6.5, no other software requires

defining "Frame Prestressing Pattern", whose definition is directly contained in the definition of prestress load, such as STAAD pro, STRAP, MIDAS. There is no need to add new class for "Frame Prestressing Patten", and further detailed study is needed. Some new classes may be developed directly, such as the subtypes of entity *IfcStructuralLoadStatic*. The details are given in next section.

5. Similarly, for the way that SAP2000 defines "Temperature Load" by "Joint Pattern", it does not represent the generic method in other software. From Table 6.5, it can be found that the more generic way is to define the value of temperature change directly. At this point, the existing definition for temperature load in IFC is sufficient. Accordingly, the concept of "Joint Pattern" is only specific to SAP2000. It is not necessary to give a new class for this concept. This information can be translated and processed during programming.

6. Besides SAP2000, other softwares, such as MIDAS, STAAD pro, RISA 3D, ROBOT Millennium, also have more than one type of load combination to choose. These four softwares represent the most popular and powerful structural analysis and design software. Considering the future use of IFC model, this new information can be added by attribute to entity *IfcStructuralLoadGroup*.

6.5.3 Material

1. In Table 6.5, half of the softwares listed can define isotropic or orthotropic material. The orthotropic material is inevitable to be used in some types of structure. As the usage of IFC models increases, orthotropic or anisotropic materials and their usage should be considered in future release. It means that the extension is needed. In this research, the new attribute to the existing class *IfcMaterial* will be developed.

2. Mass per unit volume is used for dynamic analysis. While weight per unit volume is used for self weight gravity loading. Normally they are related by the value of gravitational acceleration (386.4in/s^2, 9810mm/s^2). It does not matter which one is needed by the software, as long as one of them is defined and the input value is

entered. Here there is no necessity to extend any new information about this to current IFC models.

3. Most softwares do not require the definition of concrete shear stress. It is processed and calculated from the input data during analysis.

6.5.4 Member Section

1. As described in Section 6.4.4, "Radius of Gyration" and "Plastic Modulus" can be directly derived or calculated from the six basic attributes of *IfcStructuralProfileProperties*. In other softwares, it is not necessary for them to be defined. Therefore, any new attribute or property set is not needed. Just calculate this information during generating the inputs for SAP2000.

2. Similarly, "Shape Type" is not a generic property needed by all structural analysis software. It is not qualified to be a new attribute for IFC models. It only can be considered as a special requirement of SAP2000.

3. Although most structural analysis softwares require the material property for the sections of structural elements to be defined. In IFC models, they are two independent parts which can be connected by the common assigned structural member. It is very easy to infer the material property of section in current IFC models. From the concept of object-oriented, IFC definitions are more logical and reasonable.

4. In other softwares, the specifications of some composite sections like "Double Angle" and "Double Channel" come from either the standard database or users' input. Regardless of the approach, the "Back to back distance" is always needed which is known as "Spacing" or "Distance between angles" in RISA 3D, STRAP and ROBOT millennium. However, as "Double Angle" and "Double Channel" usually consist of two symmetrical angles or channels, their specification depends on the dimension of one angle or channel and the distance between angles or channels. Generally this approach is adopted by almost all softwares including ETABS, STAAD pro 2004, STRAP, RISA 3D, ROBOT Millennium, and MIDAS. This means that "Outside width" is not one common requirement for defining these special sections. And as

shown in Table 6.2, it can be easily computed by the basic dimension and the distance between angles or channels. Thus new attribute for the property "Back to back distance" can be considered. The property "Outside width" is just calculated for SAP2000 during programming.

6.5.5 Structural Responses

Basically all softwares provide the function to calculate the stress of shell element. It is obviously that the new classes will be needed in a future extension of the model. Although we have done the analysis on information requirements for shell elements and identified the missing information, considering the complexity on the express of elements' stresses, the new extensions related to the stresses results will not be proposed in current stage.

6.6 Recommendations for Further Development of the IFC Extension Model for Structural Analysis

From the generality study in Table 6.5 and the investigations carried out in last section, it can be concluded that the different extensions to IFC models need to be developed for the following information:

1) New Pset for:

- End offsets to frame elements;
- restraints of joints and releases of frame elements;

2) New attributes for:

- Angles of local axis;
- Types of load combination;
- Types of material;

- Properties of composite sections;

3) New classes for:

- prestress load of frame elements;
- Shell element stresses.

The following section introduces the extensions for above information from an information technology viewpoint in EXPRESS-G diagrams. The detailed definitions in EXPRESS are provided in Appendix D.

(1) Expression of Restraints of Joint or Release and End Offsets of Member through Use of Property Sets

With reference to the different scenarios, for concepts that existed in the IFC model, viz. restraints information of joints or release information and end offsets information of frame members, property sets are used for adding this information to existing IFC structural items. This approach has the advantage of coexistence and cooperation with other domain's schemas. Figure 6.11 shows the expression of structural items in IFC and the relationship with the extension. Figure 6.12 shows the expression of information by property sets. The detailed expression of restraints information or release information by property sets respectively is presented in the following section.

Figure 6.11 Expressions of Structural Items in IFC

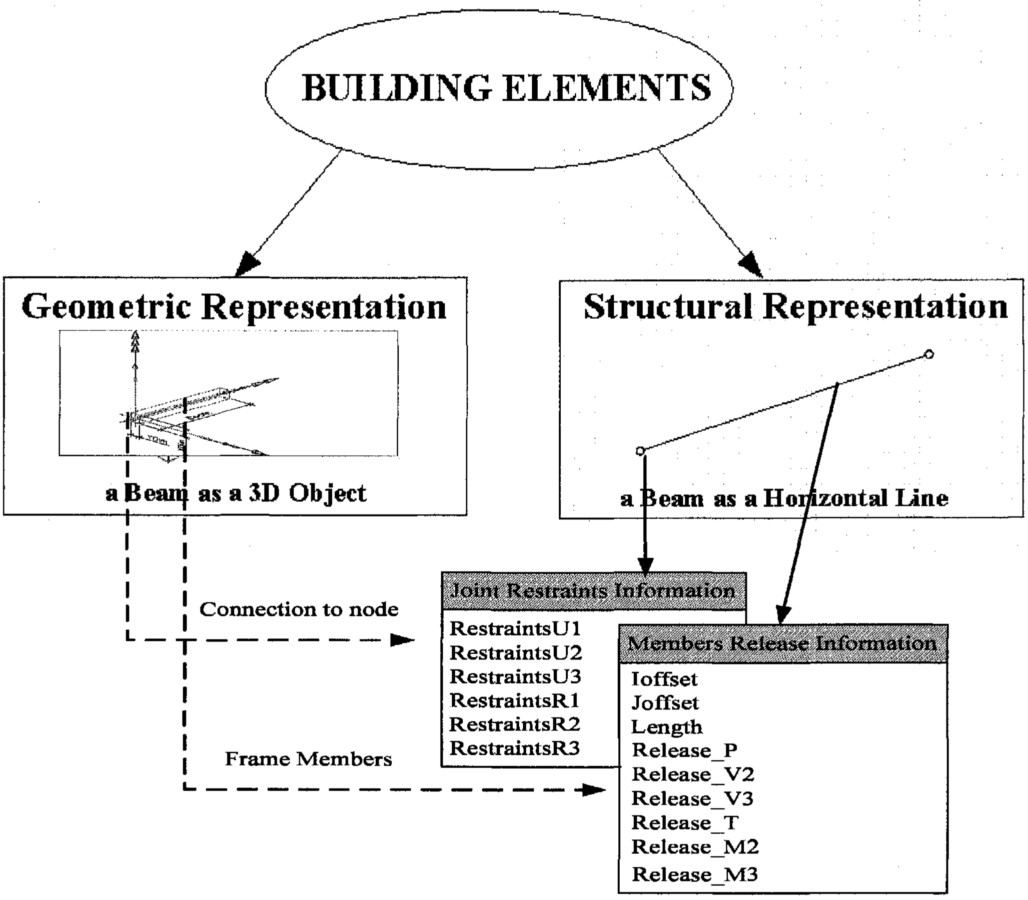


Figure 6.12 Expressions of Restraints or Releases and End Offsets Information by Property Sets

(2) New Attributes for Local Angles, Combo Types, Types of Material and Spacing of Composite Sections

Both the angles of local axes, combo types and material types belong to the second scenario of concepts extending the IFC model, i.e., they need extension to fully capture additional information requirements. For such case, some data types, function or new attributes to existing classes are needed. Figure 6.13 gives the new derived attribute *Angles* added to class *IfcDirection.* The calculation of angles involves developing a new function *IfcLocalAngles* which is not shown in its EXPRESS-G diagram, but is defined in Appendix D. Figure 6.14 illustrates the new attribute *MaterialType* added to class *IfcMaterial* for describing the material types. And a data type *IfcMaterialTypeEnum* is developed to express the domain of values. Similarly, a new attribute *ComboType* is added to class *IfcStructuralLoadGroup* as an optional definition of specify the type of local combination (Figure 6.15). The enumeration data type *IfcLoadCombinationTypeEnum* is developed which contains four load combination types, and is used to appoint the method to combine load cases. The detailed expressions about classes, two data types and one function are shown in Appendix D.

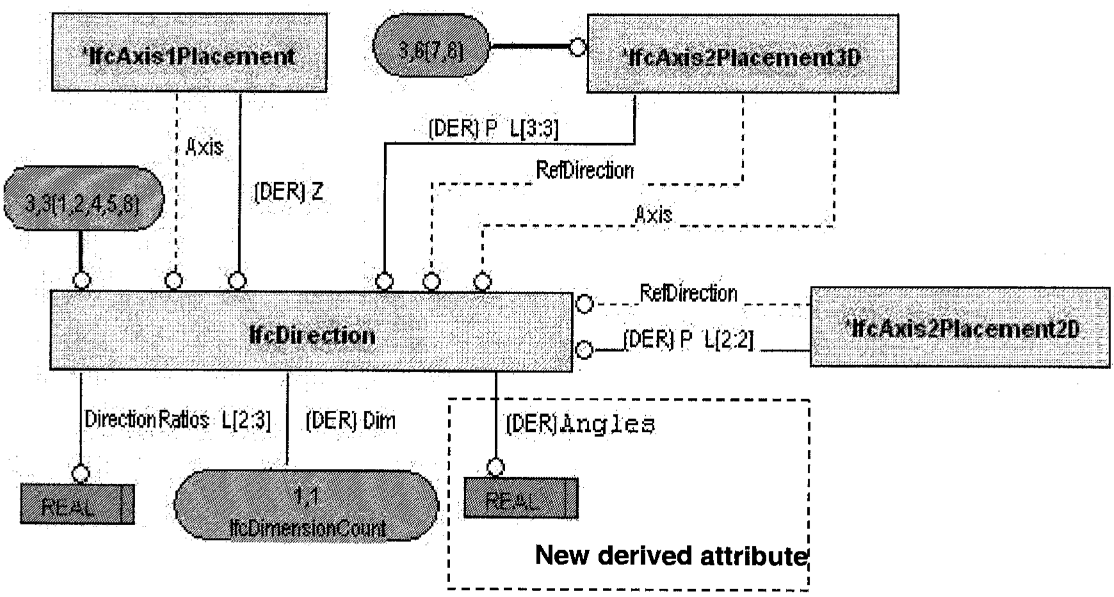


Figure 6.13 Expression of "Angle" by New Derived Attribute

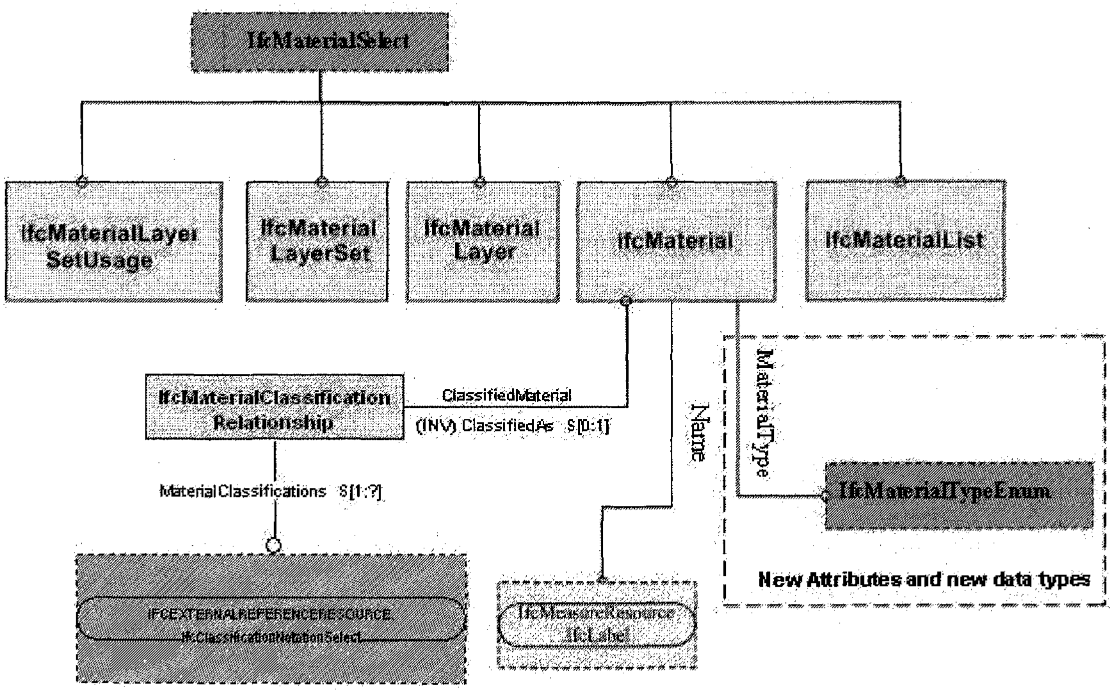


Figure 6.14 Expression of "Type of Material" by New Attribute

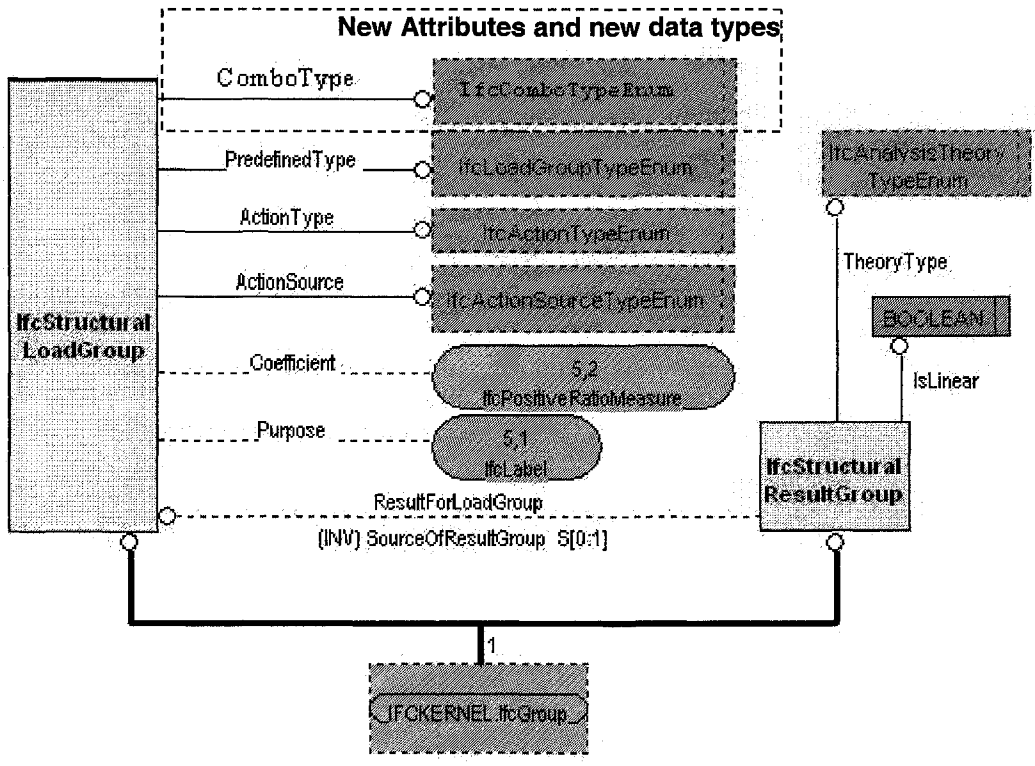


Figure 6.15 Extension of "Types of Load Combination" by New Attribute

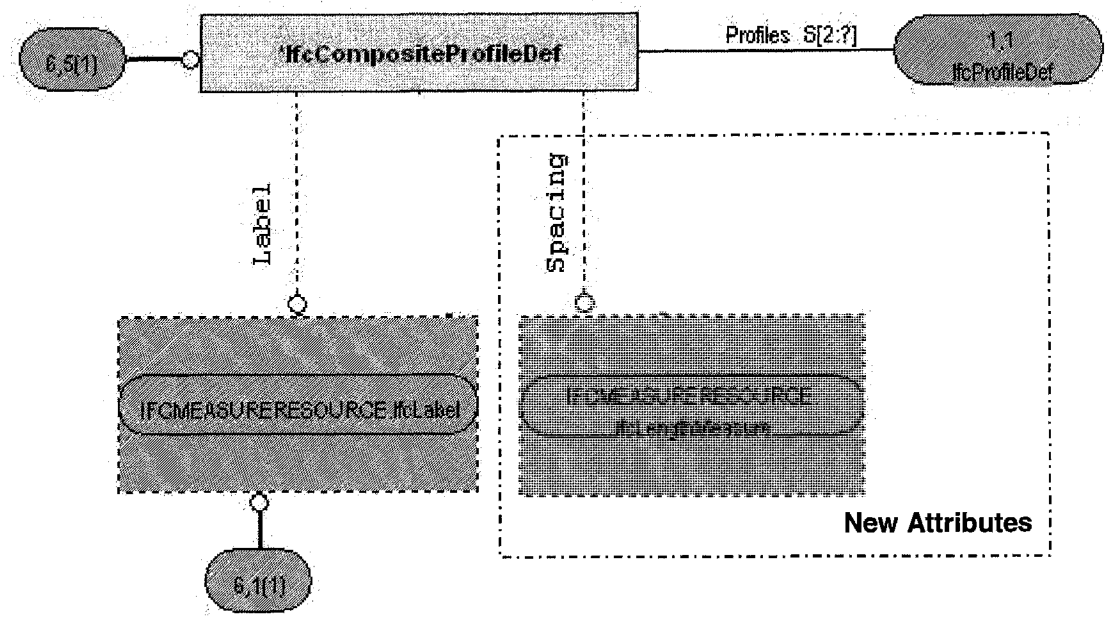


Figure 6.16 New Attribute for "Spacing" of Composite Profiles

(3) New classes for Prestress Load & Shell Element Stresses

As described before, new classes for prestress load have to be specified that get support from the fundamental ideas within the resource layer and the core layer of current IFC models. Although the principle is to minimize the required number of new classes, a new class is required to extending the IFC load resource.

However, prestress load is very complex and cannot be explained in few sentences. And modeling prestressing forces is not so simple. That is the reason why it is left out of the ST-4 project's scope. Only one new class may be not enough to express it accurately.

Basically prestress load is simplified to one load type and defined through same properties with SAP2000, such as STRAP, STAAD pro 2004, and MIDAS/Gen (please refer to Table 6.5). Each prestress load includes the following specifications: (1) tension; (2) eccentricities (Start, Middle, and End). Each prestressing cable produces a set of self-equilibrating forces and moments that are proportional to the cable tension, such as tensile forces acting on joints and the moments acting on joints that are proportional to the drapes respectively, etc. The sum of these forces and moments for all prestressing cables acting on a frame element form the unscaled prestress load for that element.

According to the definition in software, one new class is enough to model prestress load as the subtype of *IfcStructuralLoadStatic* to support the practical need. Figure 6.17 shows the definition suggested for prestress load. This is only a tentative extension. The details will be left for further study in the research.

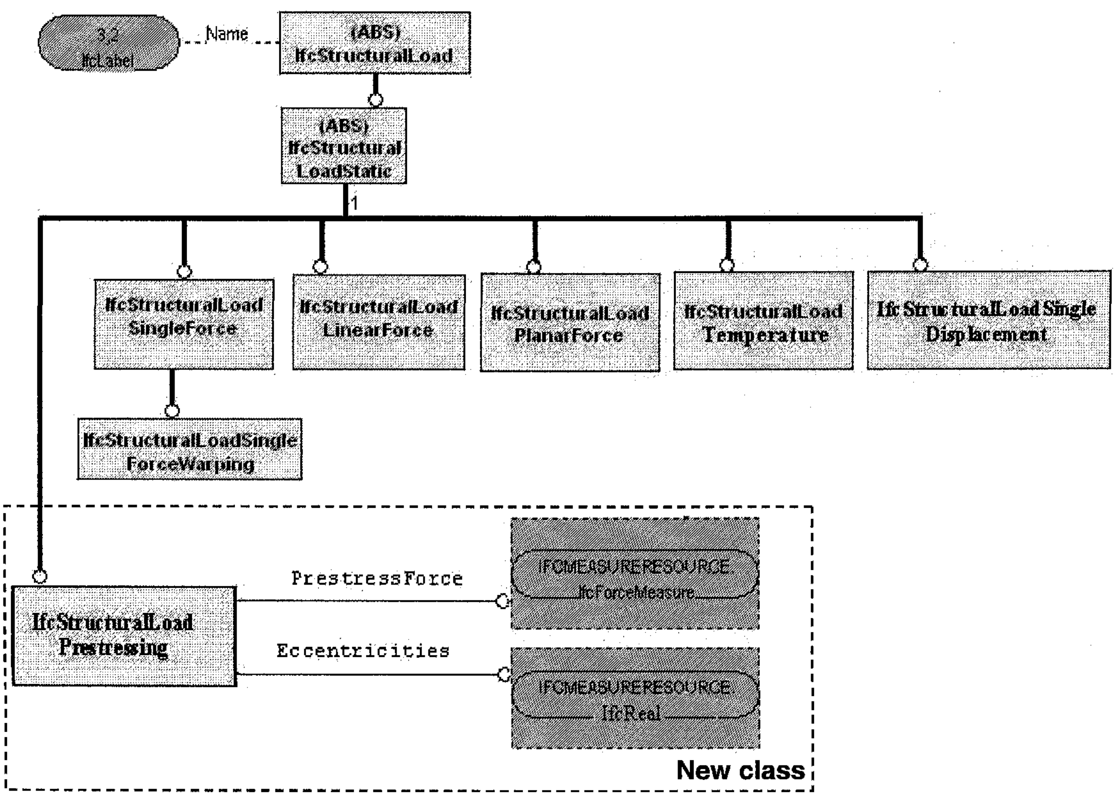


Figure 6.17 New Class for "Prestress Load"

In IFC2x Edition 2 and its addendum, the definition of actions (such as forces, displacement, etc) and reactions (supports and deformations) are combined as the subclasses of abstract entity *IfcStructuralActivity* which are specified by using the basic load definitions from the *IfcStructuralLoadResource*. The abstract entity *IfcStructuralLoad* is the supertype of all loads which can be defined (actions or reactions, as well as dynamic or static). Therefore, the new class developed for the stress reactions of shell elements should be the subtype of abstract entity *IfcStructuralLoad* which may be named ***IfcStructuralStress***. Whereas different categories of stresses are calculated in different software and there are no uniform expressions among them, the detailed attributes of the new class need further review and will not be provided here.

6.7 Summary

The emphasis of this chapter is on using PoIM methodology to analyze the information requirements of SAP2000. The usefulness and capabilities of IFC product models to support structural analysis at multiple levels of detail are assessed from software's point of view. After comparing the information requirements with current IFC models, it can be found that most of information needed by SAP2000 to do structural analysis can be explicitly supported by the current IFC models. Some have their corresponding definitions directly in IFC. Some need inference using the existing data from the IFC model. However, IFC still does not capture explicitly and provide a representation for some information, such as prestress load, types of load combination and types of material etc., which means that some improvement to current IFC models may be necessary. In order to select appropriate approach to develop IFC extensions, a generality study is conducted by investigating other ten popular structural analysis and design software in current market. Some suggestions on IFC extension model development for these information gaps are then proposed in the research. A more comprehensive view of the information needs for structural analysis is derived in this chapter, and it generates a better foundation of requirements for the software systems development.

These extended developments of IFC represent some problems which may exist between different definitions of software and IFC models during the implementation activities. These extensions will have little influence to the current release of IFC.

And some of them are much more from software's perspective and only supporting the requirement of real applications, such as the new class development for prestress load. Therefore to some extent they are only some recommendations which need IAI members to have a further review.

Chapter 7 IFC-based Web-enabled Integrated Building Design System*

7.1 Introduction

This chapter describes the development of an IFC-based web-enabled integrated building design (IWIBD) system where a model server is developed to support both IFC-based data integration and transaction-based interoperability between architectural design and structural analysis processes by taking advantage of the Internet, distributed computing and other advanced network technologies. All IFC-based information is managed and stored in an online server.

This chapter provides an overview of the requirements and the framework for this integrated system. The descriptions about its modular design and the interactions among the modules are provided. The user interaction interfaces are then presented with example usage. Details of core component modules will be described in subsequent sections.

This chapter is organized as follows:

- Section 7.1 gives a brief description of the content and structure of the chapter.
- Section 7.2 introduces the methodology used in developing the system, including the development life cycle and UML diagrams.

* Part of this chapter has been published in the paper "Implementation of IFC-Based Web Server for Collaborative Building Design between Architects and Structural Engineers", in January 2005 on the Journal of Automation in Construction, Vol. 14, No. 1, pp. 115-128, Elsevier Ltd, UK (Please see Publications (Page 308) for details.

- Section 7.3 mainly produces functional requirement analysis of the system, expressed by use case diagram and use case description. The non-functional requirements are also described.

- Section 7.4 gives an overview of the integrated system. The architecture and mechanics of the integrated framework are presented in this section.

- Section 7.5 introduces the modular design of the integrated system. The integrated framework consists of four distinct component modules. The functionalities of the component modules, the interactions among them and their implementation are briefly discussed.

- Section 7.6 gives the detailed illustration about the implementation of domain related models (i.e. the extended IFC models for structural analysis domain) in the prototype system.

- Finally section 7.7 concludes this chapter with a summary.

7.2 System Development Methodology

7.2.1 Development Lifecycle

The development lifecycle of an object-oriented application, shown in Figure 7.1, is similar to the lifecycle of any software system development. It goes through the following phases: requirement analysis, system architecture and design, implementation, validation and test, and maintenance. And depending on the complexity of the application, it may go through many cycles or iterations.

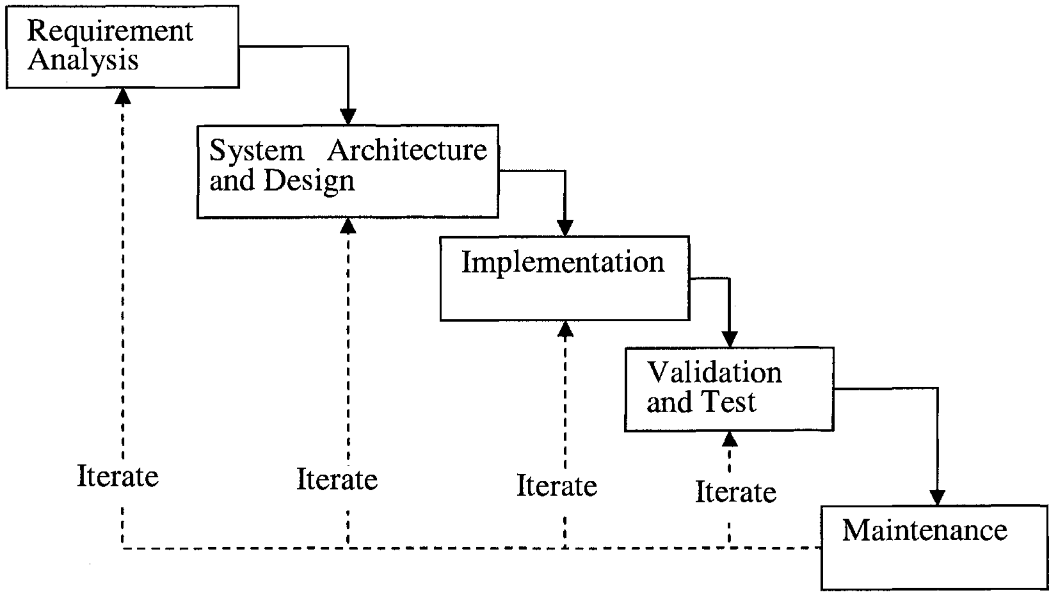


Figure 7.1 Software Development Lifecycle

(Adapted from Hamilton, 1999)

i) Requirement Analysis – Gathering and agreeing on requirements is fundamental to a successful project. This does not necessarily imply that all requirements need to be fixed before any architecture, design, and coding is done, but it is important for the development team to understand what needs to be built (Wiegers, 1999). The software requirements serve as the basis for all the architecture definition, the future design, coding, and testing that will be done on the project (Hamilton 1999, Garland and Anthony 2003). Each top level requirement is assigned to one or more subsystems within an application. Subsystem level requirements are further refined and allocated to individual modules. As this process points out, requirements definition is not just a process that takes place at the start of a development project, but is an ongoing process (Hamilton, 1999).

ii) System Architecture and Design – The focus of this phase is to design an ideal or logical system that satisfies the requirement statement without being overly concerned with implementation considerations. In this phase, the software's overall structure and its nuances are defined. In architecture, developers describe the system at a high level, and decompose the system into smaller parts, such as subsystems. Technology selections are clearly shown as part of the architecture. During design and implementation, the architecture serves as an invaluable high-level guide to developers as they struggle to understand the system as a whole (Arrington and Rayhan, 2003). Analysis and Design are very crucial in the whole cycle. Any glitch in the design phase could be very expensive to solve in the later stage of the software development. Much care is taken during this phase (Raiser, 2003).

iii) Implementation – In this phase, the main task is just writing code. Once the design is complete, it serves as a valuable foundation for implementation. Developers are free to focus their efforts on the details of the implementation technologies, without constantly worrying whether their efforts will fit within the larger system (Arrington and Rayhan, 2003). Different high level programming languages like C, C++, Pascal, Java are used for coding. With respect to the type of application, the right programming language is chosen (Raiser, 2003).

iv) Validation and Test – Once the code is generated, the program testing begins. This phase involves testing the code you have developed to see if it functions properly.

v) Maintenance – Software will definitely undergo change once it is delivered to the customer. There are many reasons for the change. In addition, the changes in the system could directly affect the software operations. The maintenance phase deals with changes that need to be made to the service over its lifetime because of new of changed requirements.

7.2.2 The Unified Modeling Language (UML)

Developing a model for an industrial-strength software system prior to its construction or renovation is as essential as having a blueprint for a large building. Good models are essential for communication among project teams and to assure architectural soundness. We build models of complex systems because we cannot comprehend any such system in its entirety. As the complexity of systems increases, so does the importance of good modeling techniques (OMG, 2004)

The UML is now a well-recognized graphical modeling language for Object-Oriented software engineering. UML has been widely used by software engineers for the specification, construction and documentation of software systems. It was based on the work of three most reputable modeling experts: Grady Booch, Ivar Jacobson and James Rumbaugh on Object-Oriented software engineering over the past decade. UML provides a systematic way of describing a system's architecture, capturing its static, functional and dynamic views in detail. Using UML, system analysts, designers and programmers can build and maintain a complex software system much more easily and, at the same time, ensure that the system will hold up to requirement change (Visual Paradigm, 2002).

There are twelve standard diagram types defined in UML, Class Diagram, Object Diagram, Component Diagram, Deployment Diagram, Use Case Diagram, Sequence Diagram, Activity Diagram, Collaboration Diagram, Statechart Diagram, and three model management diagrams including Packages, Subsystems, and Models (OMG, 2004). They can be divided to different groups which offer different ways of looking at the same problem (Booch, Rumbaugh and Jacobson, 1999). These diagrams provide multiple perspectives of the system under analysis or development. The underlying model integrates these perspectives so that a self-consistent system can be analyzed and built. In this research the use case diagram and static structure diagram are used.

Use case diagrams are used to provide a functional description of a system and its major processes, the interactions between the processes (use cases) and place a boundary on the problem to be solved. It also provides a graphic description of external systems or individuals who will use the system, called actors, and what kinds of interactions they can expect to have with system. Use case diagrams address the static use case view of a system. These diagrams are especially important in organizing and modeling the behaviours of a system.

A complete set of UML static structure diagrams is made up of class diagrams and object diagrams. A class diagram shows a set of classes, interfaces, and collaborations that will be included in your application and their relationships. This diagram is the most common diagram found in modeling object-oriented systems. Class diagrams address the static design view of a system. An object diagram shows a set of objects and their relationships. Object diagrams represent static snapshots of instances of the things found in class diagrams. These diagrams address the static design view or static process view of a system as so class diagrams, but from the perspective of real or prototypical cases. UML does not define a specific object diagram but, in fact, uses informal object diagrams. In some cases you create object diagrams to show the interaction of a set of objects. In other cases, objects are added to class diagrams to show how specific objects will be used within the context of the overall class model.

7.3 Requirement Analysis

Quality requirements are broken up into two kinds: functional and non-functional (Wiegers, 1999). The functional requirements relate to the way the object-oriented system will fulfill the business need. Checking the identity and authorization of user is an example of functional requirements. Nonfunctional requirements are technical in nature. Nonfunctional requirements describe the performance and system characteristics of the application (Perks, 2003). It often means: how well some behavioral or structural aspect of the system should be accomplished (Malan and Bredemeyer, 1999). A requirement to state that a response must be returned to the consumer within two seconds is an example of a nonfunctional requirement.

A good way to document requirements is using use cases. It is important to gather them because they have a major impact on the application architecture, design, and performance (Perks, 2003). Use cases are becoming more mainstream as a method for capturing requirements, as evidenced by the endorsement of big companies and methodologists such as Booch, Rumbaugh, and Coad. One benefit of use cases is that each one encapsulates a set of requirements. This encapsulation lets you easily manage and track the use cases individually and provides a better alternative to prose requirements (Wyder, 1996). In use case modeling, entities outside the problem area that are going to use the application are called actors. An actor describes types of users, which may be a person, another software application, or a hardware device. All are represented by a little stick figure of a person. Processes that occur within the application area are called use cases. The use case itself is represented by an oval. The name of the use case is written inside the oval (or, sometimes, below the oval). A use case is not a class or object. It is a generic process that satisfies some need of the user. A line connects the actors and the use cases they interact with.

The following section describes the requirements of the IFC-based web-enabled integrated building design (IWIBD) system for architect and structural engineer. A use case diagram shows the relationship among use cases within the system and their actors. It provides an overview of its functional requirements and nonfunctional requirements.

7.3.1 Use Cases

A use case diagram provides the main processes in the system and the interactions between processes. An application can have one or more use cases. Figure 7.2 provides a high-level use case diagram for the IFC-based web-enabled integrated building design system. An initial use case diagram is an abstract model of the system. Use case diagram can go beyond simply representing isolated processes and can show relationships between processes.

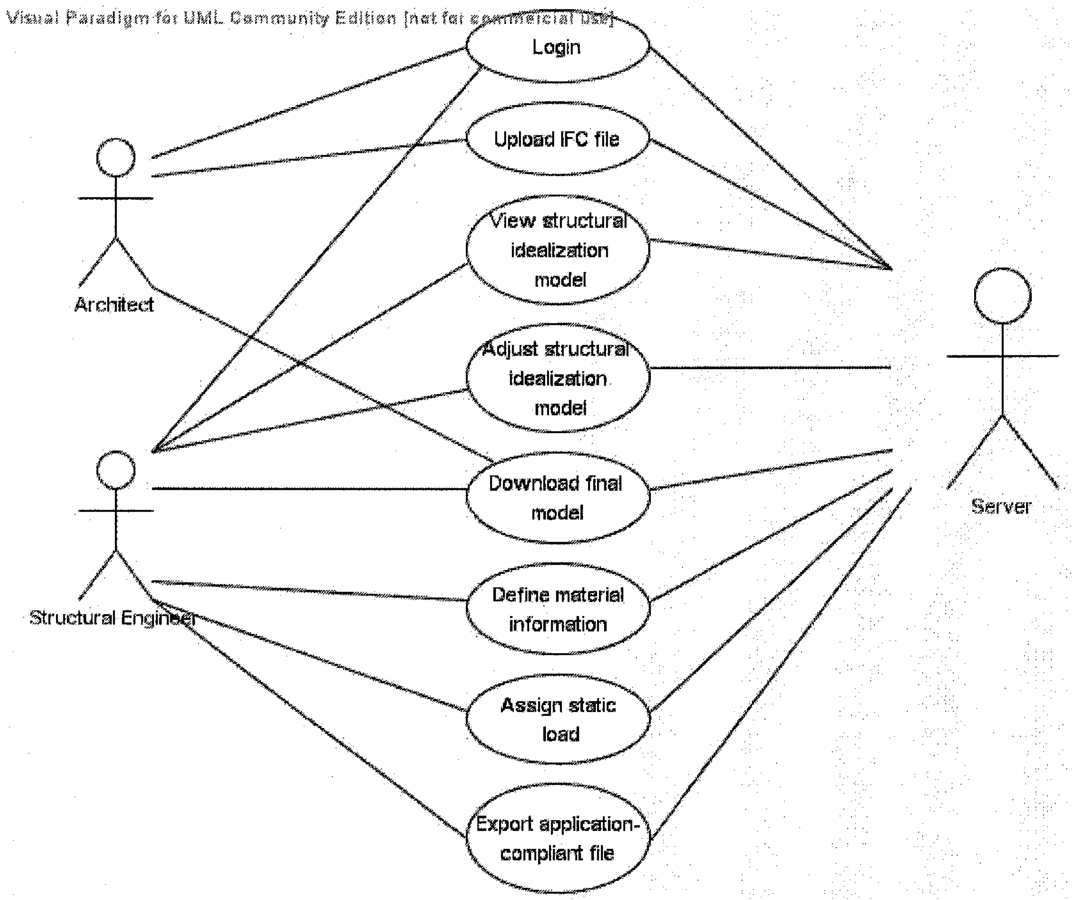


Figure 7.2 Use Case Diagram of the Integrated System

In this diagram, three actors are involved. One is the architect. Another is the structural engineer. The last one represents the model server that architect and engineer will interact with. And eight use cases are shown in Figure 7.2: Login, Upload IFC files, View structural idealization model, Adjust structure idealization model, Download final model, Define materials information, Assign static loads (load cases), and Export application-compliant files.

7.3.2 Functional Requirements

Besides the use case diagram, a use case description is also needed to provide a generic, step-by-step written description of the interaction between an actor and a use case. Use case descriptions describe basic functions of the system including what the user can do and how the system responds. In Figure 7.2, a total of eighteen interactions are included: three between architect and three use cases, seven between structural engineer and seven use cases, and the server with all eight use cases. These eighteen interactions represent the functional requirements of the system. Table 7.1 illustrates the use case descriptions for all interactions shown in the use case diagram.

Table 7.1 Use Case Descriptions of Eight Use Cases

Step	Description
Use case name:	login
1	The Architect or Structural engineer connects the webpage through the URL of the Server.
2	The Architect or Structural Engineer enters the username and password.
3	The login function should check the client user's ID and autorotation. If the user is not acceptable, he will be refused to enter.
Use case name:	Upload IFC file
1	The Architect requests to upload IFC file.
2	The architectural design is accepted and saved on the Server.
3	The Server reads the architectural information, find the topological information among those elements and generate structural analysis model.
4	The Server saves the structural analysis model information in XML format.
Use case name:	View structural model
1	The Structural engineer requests to view the structural model.
2	The Server invokes the application and displays the 3D structural model in a web browser for the user on client side by Java applet.
3	The Structural engineer selects the structural element and the Server can extract and show its detailed structural information of element.
Use case name:	Adjust structure model
1	The Structural engineer is allowed to give the comments on the selected element and entering the name and value of proposed property.
2	The server should add the comments and additional information submitted by the Structural engineer in property set to the IFC file.
3	The Server can feedback to the Architect.

Table 7.1 < Continued>

Step	Description
Use case name:	Download final model
1	When the Structural engineer agrees with structural model from architect's design, the server should allow both of them to download the IFC file.
2	The Structural engineer is allowed downloading the file for structural model which is in XML format.
Use case name:	Define material information
1	The Structural engineer defines the name and type of material.
2	The Structural engineer inputs the mechanical properties for the defined material.
3	The Server can save the information.
Use case name:	Assign static load
1	The Server invokes the application and display the 3D structural model on the client side.
2	The Structural engineer chooses the element to be loaded.
3	The Structural engineer inputs the load value for corresponding load types.
4	The Server saves the load information into the XML file.
Use case name:	Export application-compliant file
1	The Server writes the S2K file for SAP2000.
2	The Structural engineer is allowed downloading the S2K file as the imported file to help structural analysis.

7.3.3 Non-functional Requirements

Along with the functional requirements for a system, the non-functional requirements must also be defined, to determine the technical level of service the system will support. Use cases merely capture the functional requirements of how the system will be used. They however, do not capture all of the external requirements of a system. There are many other aspects to the requirements that must be captured and addressed (Mcbreen, 1998).

Non-functional requirements define system properties, including constraints and qualities e.g. reliability, response time and storage requirements. Qualities are properties or characteristics of the system that its stakeholders care about and hence will affect their degree of satisfaction with the system. Constraints are I/O device capability, system representations (Malan and Bredemeyer, 2001). In modern software development, it is especially necessary to pay attention to non-functional requirements such as performance, security, modifiability, reusability, integrability, testability, availability, reliability, and portability.

Non-functional requirements are as important as the functional requirements. Table 7.2 lists all the non-functional requirements for the IFC-based integrated building design system.

Table 7.2 List of Non-functional Requirements

Requirement	Detail
Data requirement	Input data from architect should be in IFC format
User interface and interactive input requirement	1. The web page should have one consistent user interface 2. It can pop up new browser windows for uploading file, display structural model 3. The Java applet should pop up frame window for user to input the additional information 4. TextArea should be used to accept the comments 5. TextField should be used to accept names and values of new properties.
External Interface requirements	Not available
Performance requirement	Currently only handle the frame type of structure with its elements (beams and columns) in planar (2D) and spatial (3D) dimension
Operational Requirement	The system is expected to run on personal computer and currently in Window XP operating system
Modifiability	Its receptiveness to change
Reusability	The ability of a software asset to be used in a different application context without modification.

7.4 System Architecture and Design

At macro level, a software architecture defines how different parts of the project can be mapped to the hardware components. The objective of this section is to provide an overview of the system's architecture, its modular design and the interaction among the modules. The user interaction interfaces are then presented with example usage. Details of the core component modules will be described in subsequent sections.

7.4.1 Architecture of the IFC-based Web-enabled Integrated Building Design System

The IFC-based web-enabled integrated building design system is designed to provide architects and structural engineers with easy access to a model server to improve their collaboration by facilitating the information exchange and sharing. The current design collaboration between architects and structural engineers has not fully utilized the existing technologies to gain the maximum advantages. The structural engineer still needs to manually input the geometric information of structure analysis model, which indeed can be deduced from the geometric information in the 3D architecture model.

Now an integrated system is utilized as a common platform for architects and engineers to communicate, exchange ideas, and download useful files. In this system, architects and engineers can have direct access to a model server and upload data file by using a web browser. The information can be extracted and deduced from the IFC file forwarded by architect to the structural engineer. If the structural engineer is not satisfied with the structural model, the server can be used as the medium of interaction between structural engineer and architect. When engineer is finally agreeable with the structural model, the server will list the final architect file in IFC format and structural model file in XML format. For the convenience of engineer to do structural analysis, inputting structural related information for selected elements is allowed and the model server provides a set of application compliant file to download.

The structure of the IFC-based web-enabled integrated building design (IWIBD) system is schematically depicted in Figure 7.3. It involves the following six parts: (a) Model sever; (b) Architectural design application; (c) Structural analysis application; (d) IFC standards and product models; (e) Information editor; and (f) Web-based Interface.

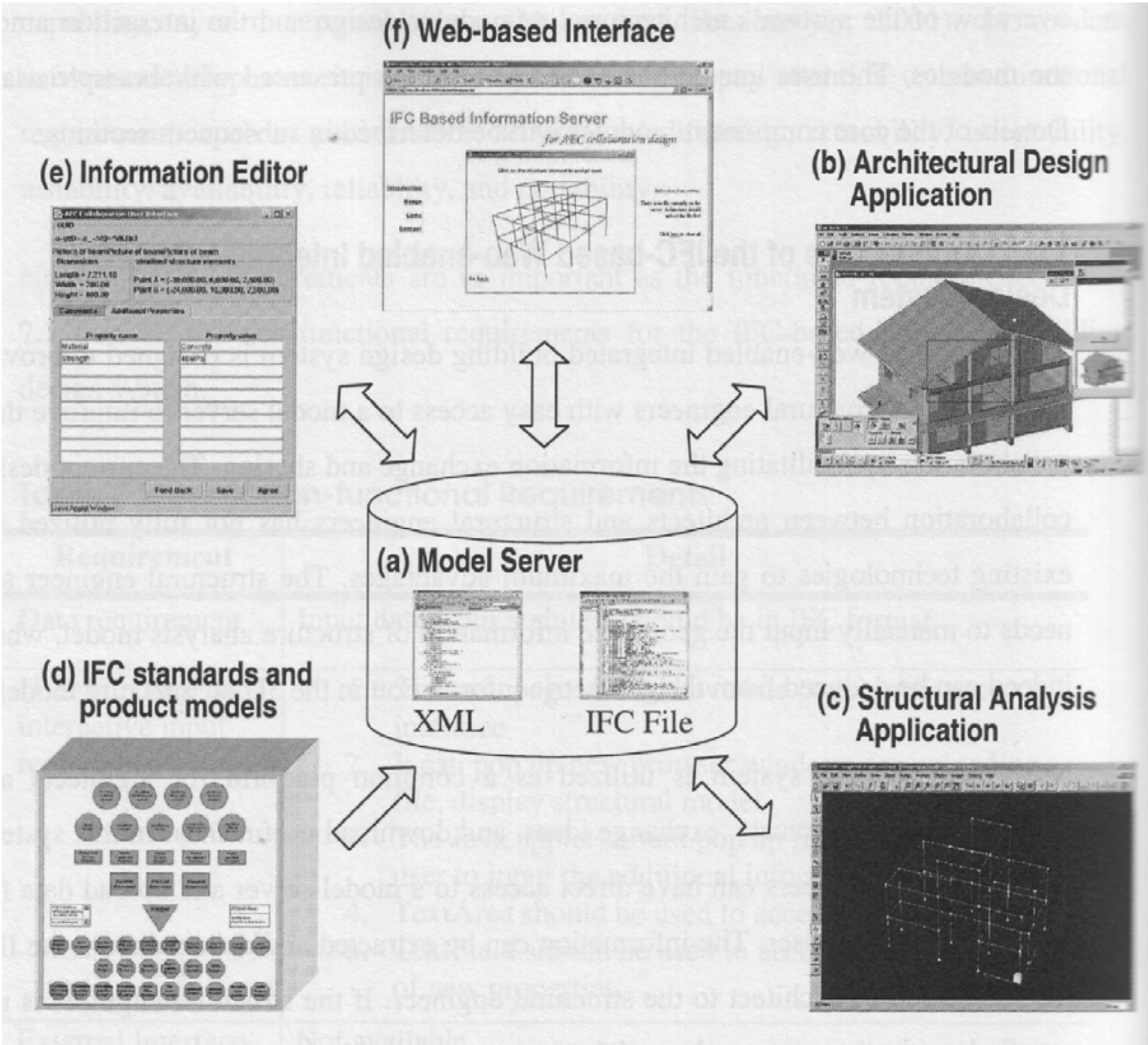


Figure 7.3 Structure of IFC-based web-enabled Integrated Building Design (IWIBD) System

As shown in Figure 7.3, through the online services and interfaces provided by the system, the user can upload and edit the information to the server. The server is responsible for the generating and saving of all architectural and structural information based on IFC standard and models. File transfer is supported by the server in order to achieve the communication between architectural design and structural analysis application. Accordingly, the real integration between these two processes is achieved.

The overall framework and architecture of the IFC-based web-enabled integrated building design system is schematically depicted in Figure 7.4. The architecture defines the dependency and the interaction among the participants. It follows the Java 2 Enterprise Edition standard three-tier model: client, server and data storage. In a three – tier software architecture, the application is broken down into three layers, the data storage on one tier, the business logic in a second tier, and the user interface in a third. The main advantage of three-tier architecture is that it becomes simpler to modify the user interface, business logic, or data storage components without affecting other components. Another advantage is scalability. Since the data storage and business logic are separated, they can each be hosted on their own server.

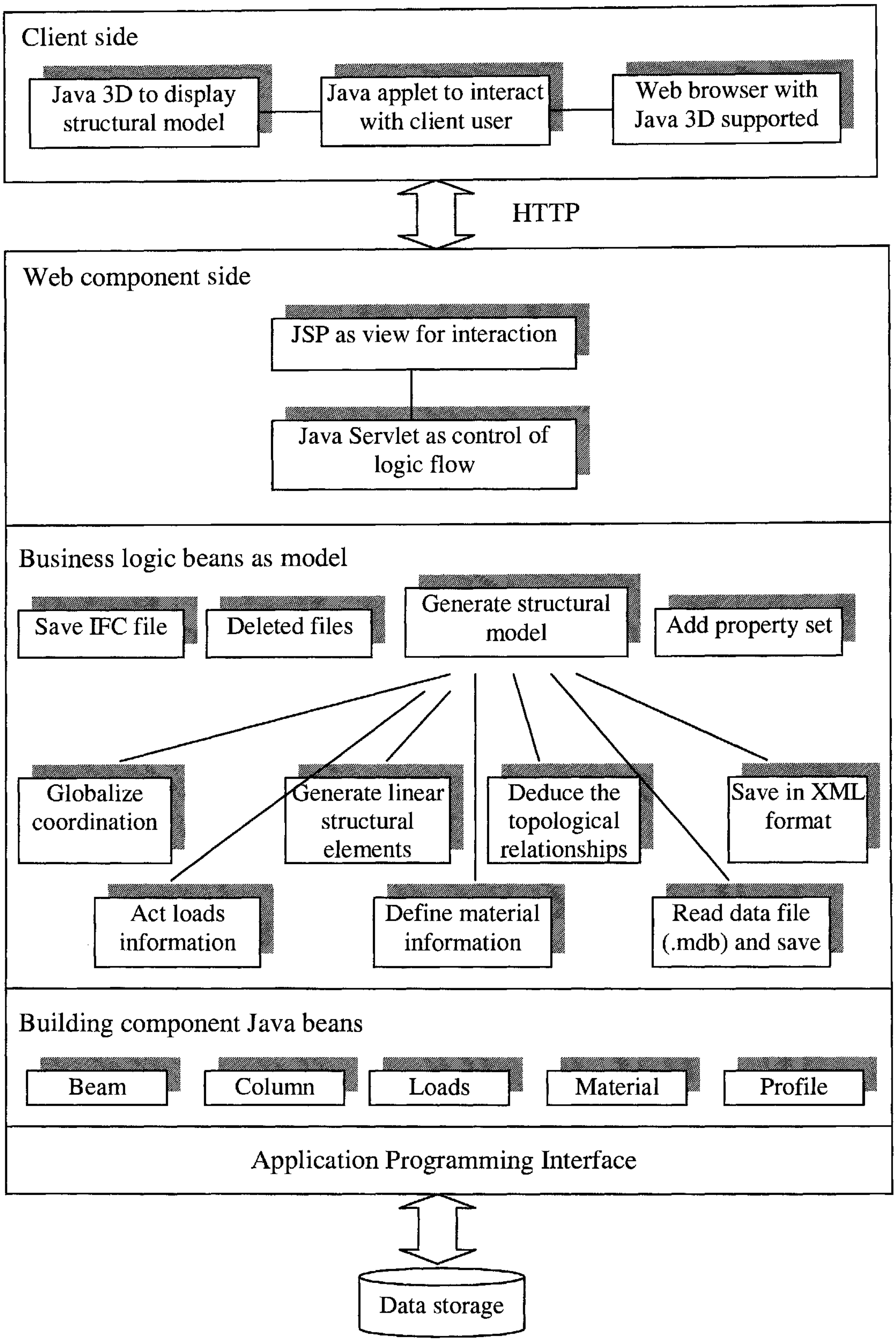


Figure 7.4 The Architecture of the Integrated System

Currently, the client tier only supports Java 3D enabled web browsers. Inside the server, there are three layers, the data access layer, business logic layer and web component layer.

- The data access layer has two sub-layers to achieve data storage independent and IFC release version independent. The application programming interface is to read the data in the data storage. It offers a stable interface for other components in web container to read, write and modify IFC data without knowing how the data are stored. If the data storage method is changed, the only code that needs to be changed is the implementation of the programming interface. The IFC EXPRESS schema is undergoing some major changes at the moment. To protect the re-usable code from those changes, the properties of building component are encapsulated in Java Beans, which are initiated by reading the IFC data via application programming interface layer.

- Business logic beans read the encapsulated information only from those building component Java Beans without knowing about IFC schemas. Thus if the IFC EXPRESS schema has changed, it will only affect the initiation method in those building components Java Beans. Business logic beans contain all the algorithms on processing geometric information. It can idealize the three-dimensional load-bearing building components and deduce connections from spatial locations. It can also integrate the deduced topological information with the adjusted information returned from the end user to generate a final report in the XML format. The topological logic beans are indeed standard independent. Even if the IFC EXPRESS schema has changed, the coding remained in this layer will not be changed.

- Web component layer consists of Java Servlet and JSP. It is in charge of receiving and dispatching the request from the client to the classes on the server side and transmitting the calculation results from server back to the client.

7.4.2 Mechanics

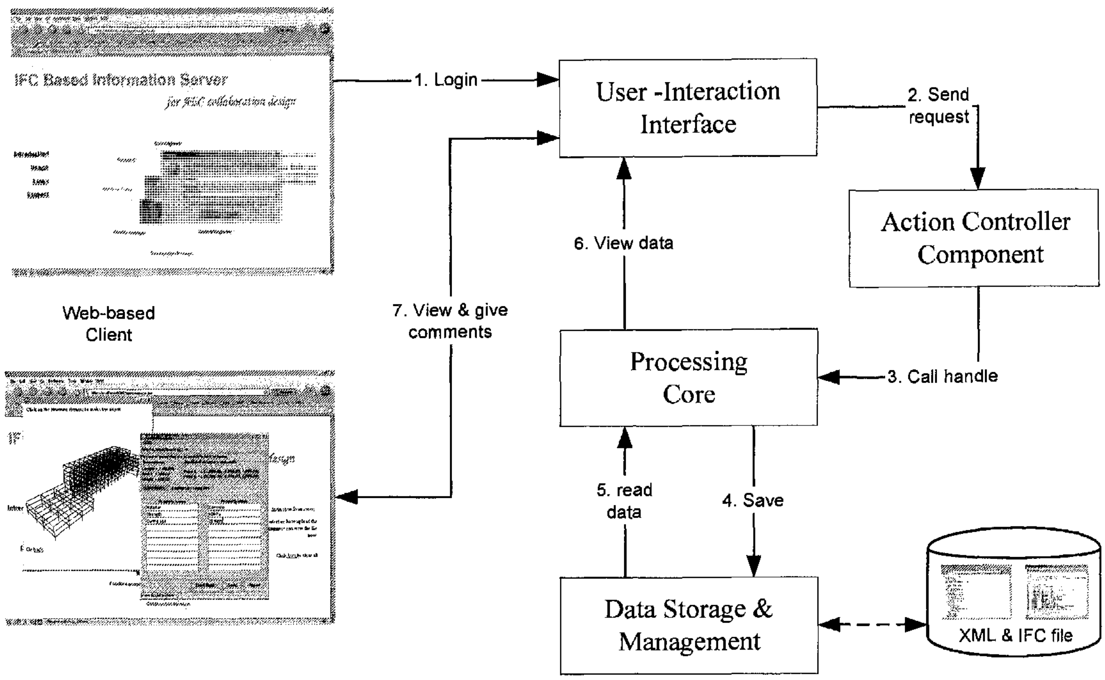


Figure 7.5 The Mechanics of The Integrated System

The mechanics of the IFC-based web-enabled integrated building design (IWIBD) system is illustrated in Figure 7.5, which shows the essential procedures to access the server and to perform integrated operations over the Internet. The architect first builds the architectural design on the client side. After logging in the web site, the architect is assigned a certain role by the server which allows the architect to upload IFC files. Architect can submit the IFC file to the server via a web browser, using the Internet as a communication channel. The core processing applications on the server receives the file and saves on the server. After finding the connectivity of structure elements and idealizing those elements, the core processing applications generate a structural idealization model and save the model in the XML format on the server side.

The structural engineer can query and view the model using a web browser. The process follows almost the same procedures as the uploading of IFC file by the architect. First the engineer signs in the server from a client machine. The core processing applications on the server read the structural idealization model's related information from the database and send back to the engineer. The Java applets and related applications are downloaded on the client side to receive the information and display the 3D structural idealization model by the Java3D technology. The engineer can also check the detailed information by clicking on the idealized structural elements. A window will pop up to let the engineer view the geometric information about selected element and the location of the joints. If the engineer finds discrepancies, he can add new properties and comments to the specific element. After finishing the modification, the engineer can send the feedback to the server. The server receives the feedback, and makes corresponding modification on the IFC models by adding property sets.

After the architect reviews the changes proposed by the engineer, he might review and modify the architectural design. The server can then generate updated structural model for engineer to review. This process ends when the engineer and the architect finally agree with the design. The server then publishes the structural model file in XML format and architecture file in IFC format. Since currently few structural analysis and design applications provide the supports for the IFC formats, the adaptor for specific application is provided by the server. In current prototype implementation only the S2K file, which can be imported by SAP2000, is generated. At this time, the engineer could download the S2K file and directly import it into SAP2000 for structural analysis. The structural analysis model is automatically generated.

Besides the idealized structural elements and their mechanical connectivity, support conditions, mechanical properties and loadings should also be included in the structural model of building for structural analysis (Hörenbaum, 2003). Only the idealized structural elements and connectivity information could be deduced from the 3-D geometric information of an architectural model. In order to improve the future extensibility of the server, other functions are incorporated into the server which could assist engineer in performing additional structural analysis. Four kinds of operations are provided if the engineers want to do more preparations for structural analysis. The primary aim of this part of effort is to provide the foundation for the future incorporation of structural analysis software on the server side even if its benefit is not so distinct in current stage. According to the 3D model of structure, the material and load information is assigned by engineer via the Internet and saved to the server. The new S2K file with material and load information can be generated and downloaded. After performing the structural analysis, engineer can upload the data file of structural analysis results to the server. The server can retrieve the results, like forces and displacements, and save into XML formats. Similarly any authorized user to the server can query and view all related information including the analysis results about structural elements via a browser.

Besides the mechanics, Figure 7.5 has already presented that the IFC-based web-enabled integrated building design system consists of four distinct modules: User-Interaction Interface, Action Controller Component, Core Processing module and Data Access and Data Storage module. The details about modular design and implementation are described in the following section.

7.5 Modular Design and Implementation

As illustrated in Figure 7.5, this system consists of four distinct modules:

- The User-interaction module provides an interface to facilitate the access to and interaction with the software platform for the users and developers.
- The Action Controller Component is provided for online application services to register to the core so that these services can be found and accessed, and routing the incoming request to an appropriate command object that knows how to handle the request.
- The Core Processing module is the main part to process the data, including reading and writing of IFC data, retrieving and manipulating the geometric and structural related information of structural members, storing and querying the data file etc.

- Currently the Data Access and Data Storage module is mainly responsible to process XML related data because in this phase all data are saved as flat files in XML format. As the developing of the system and more and more data generated, a database is needed. At that time, this module is built to link with a database, which can provide efficient data access and facilitate post processing tasks. Project management and version control are also supported by the data management system.

This section documents the modules in terms of its context in the system described in the architectural design. It describes the context, in which the modules will be used, and the services (i.e. functionality) they provide. It also discusses the issues related to the detailed design and implementation in a prototype. The related technologies used during the implementation are also briefly introduced.

7.5.1 Related Technologies

For the prototype implementation and testing in this research work, Java is employed as the programming language to implement most parts of the system architecture. Java's well-designed object-oriented structure and platform independence are the influencing factors in using it. The wide proliferation of the Internet can be attributed to the ease of World-Wide Web access, so taking advantage of this environment is appropriate. When interaction is needed within the Web browser environment, Java applets could be seamlessly integrated into the Java-written distributed architecture. Although the use of a web browser is not mandatory for the functionalities of the integrated framework, using a standard browser interface leverages the most widely available Internet environment, as well as being a convenient means of quick prototyping.

In order for the server to process the HTTP requests from the client, Apache Tomcat 4.0, which is built on Java Servlet based technologies, is employed as the entry point of server's process. In the prototype implementation, Java's Servlet is chosen to handle communication for the distributed element services over the Internet. Java Servlets are Java technology's answer to CGI (Common Gateway Interface) programming. They are programs that run on a web server and build web pages. Java Servlets are designed to extend and to enhance web servers. Servlets provide a component-based, platform-independent method for building web-based applications, without the performance limitations of CGI programs. Servlets have access to the entire family of Java APIs (Application Programming Interface), including the JDBS API to access databases. Thus, Servlets have all the benefits of the mature Java language, including portability, performance, reusability, and crash recovery. Java Servlets are more efficient, easier to use, more powerful, more portable, and cheaper than traditional CGI and other alternative CGI-like technologies.

Java Server Pages (JSP) is a technology that permits mixing of regular, static HTML with dynamically-generated HTML. Many Web pages that are built by CGI programs are mostly static, with the dynamic part limited to a few small locations (Hall, 1999). But most CGI variations, including Servlets, make the user generate the entire page via the user's program, even though most of it is always the same. JSP lets the user create the two parts separately. The user simply writes the regular HTML in the normal manner, using whatever Web-page-building tools he normally uses. He then encloses the code for the dynamic parts in special tags, most of which start with "<%"and end with"%>".

JSP is so easy and convenient that it is quite feasible to augment HTML pages that only benefit marginally by the insertion of small amounts of dynamic data. Previously, the cost of using dynamic data would preclude its use in all but the most valuable instances (Hall, 1999). The dynamic part is written in Java, not Visual Basic or other MS-specific language, so it is more powerful and easier to use. And it is portable to other operating systems and non-Microsoft web servers.

7.5.2 User-interaction Module

The User-interaction module provides an interface to facilitate the access to the IFC-based model server for the architects and engineers. Currently the server can be accessed only by a web-based interface.

The architecture of the integrated system shown in Figure 7.3 implies the essence of model-view-controller (MVC) architecture to some extent. MVC architecture is a popular software architecture used to structure web applications, which separates the application's core business model functionality from the user interface and control logic (Moller and Schwartzbach, 2002-2003). Such separation allows multiple views to share the same data model, which makes supporting multiple clients easier to implement, test, and maintain. It is easier support for new types of clients. To support a new type of client, one simply writes a view and some controller logic, and wires them into the existing application.

Generally the JSP and Servlets are used together to deploy web applications that conform to MVC architecture, as shown in Figure 7.6. The using of JSP makes it easier to develop and maintain the HTML content. Java Servlet technology is employed to implement the server interface, which serves as the wrapper to the core system. Through the combination of JSP and Servlets, a single request will result in multiple substantially different-looking results. It can process complicated data, but with relatively fixed layout (Hall, 2003-2004).

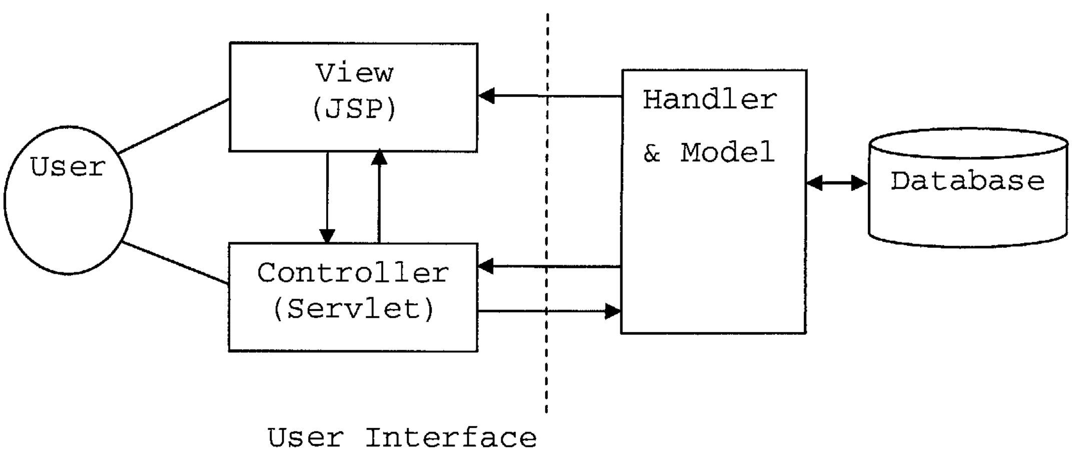


Figure 7.6 Model-view-controller (MVC) Architecture

Following the pattern, a set of JSP pages and Servlets are developed as the interactive interface with clients and to control program flows.

The JSP is considered as the View. The view primarily concerns with presentation and formatting of Model objects which have been placed in scope by the controller (or its delegate) (Hanley, 2004). The Model represents the business logic of an application. It contains all data and operations which are implemented as Java classes. Encapsulating business rules into components facilitates testing, improves quality, and promotes reuse.

The controller is represented by the Servlet. The controller acts as the point of entry into the application, and delegates to various worker classes to fulfil a request. In particular, the controller is a user of Model and View objects (Hanley, 2004). The controller translates interactions with the view into actions to be performed by the model. In a stand-alone GUI client, user interactions could be button clicks or menu selections, whereas in a web application, they appear as GET and POST HTTP requests. The actions performed by the model include activating business processes or changing the state of the model. Based on the user interactions and the outcome of the model actions, the controller responds by an appropriate view. The Servlet plays an important role in this architecture because it takes care of parameter retrieval, instantiation, and bean handling; but it can also handle transfers to different JSPs in terms of user type, carry out processing in relation to user actions, etc. Obviously, this architecture offers better separation of the user interface with regard to processing.

In this prototype implementation, the model part is contained in core processing module, the detailed descriptions of which are in the next section. The focus of this section lies on the view and controller as user interactive interface to implement the server interface and control the logic flow of system. Apache Tomcat is customized to serve as the Servlet server, which is a middleware to enable the virtual link between the web browser and server. Since Servlets have built-in supports for web applications, the communication between the web browser and the Servlet server follows the HTTP protocol standards, which is a fairly straightforward process. And this system aims to facilitate the collaboration between architect and structural engineer; it is obvious that two kinds of interaction exist: Server-to-Architect interaction and Server-to-Engineer interaction. Figure 7.7 represents the related classes used for user interaction, among which six Java servlets are developed to control the flow and cooperation of these operations.

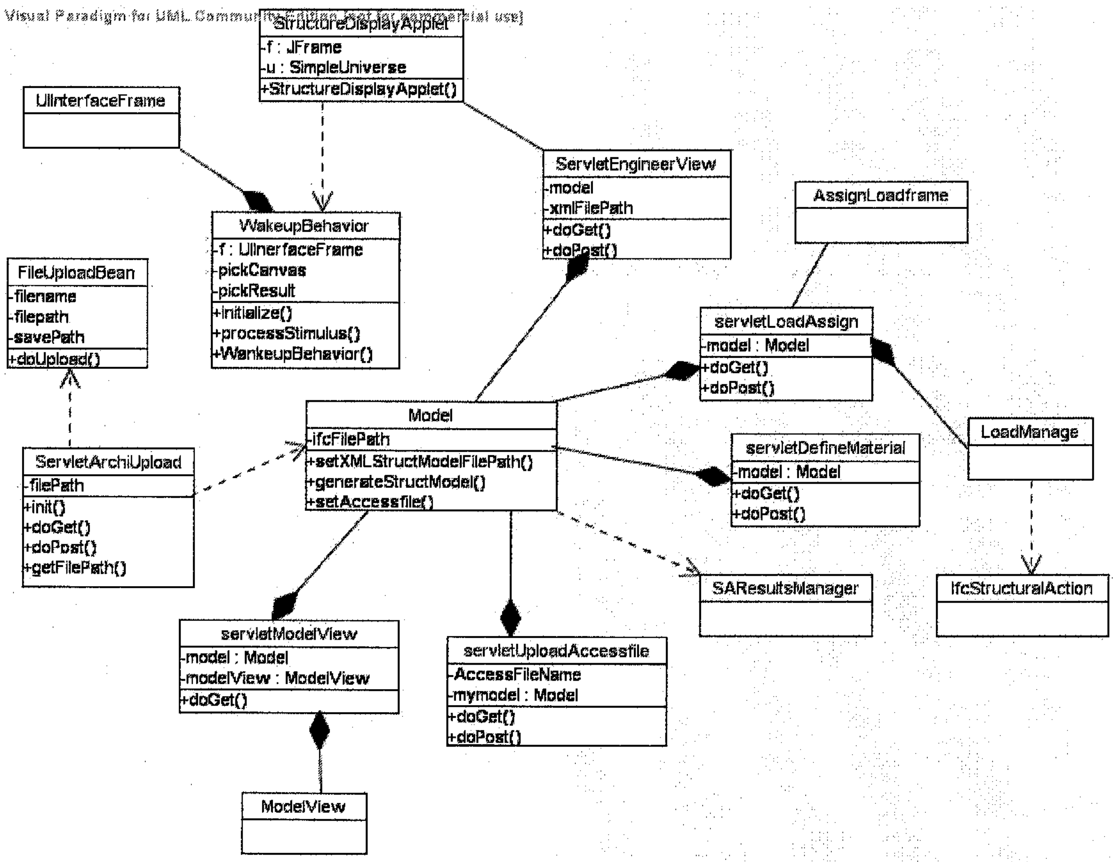


Figure 7.7 Class Diagram for Interfacing

7.5.2.1 Server - to - Architect Interaction

After the architect visits the `JspHomepage` (as illustrated in Figure 8.3) via a web browser, the architect logs in the server and the server checks his identification and authorization. Upon receiving the request from architect, ServletArchiUpload is invoked and used to control the uploading of IFC files. Through ServletArchiUpload, the content of IFC file is provided as an input stream for reading binary data from a client request. The class FileUploadBean is used to read the input stream and write the new IFC file to the local server. The core processing module is then invoked to construct the structural idealization model and save it on the server in a file of XML format by the method setXMLStructModelFilePath () of Model class.

The status of process is prompted by the message on the right of webpage. After the architectural design file is successfully submitted, the message is changed to "*Architect has uploaded the file. Engineer can view the file now.*", so the engineer can log in the server and view the structural idealization model.

7.5.2.2 Server-to-Engineer Interaction

As mentioned above, the engineer can choose to view the model according to the message on the right of homepage. Similarly after verifying the authorization information of engineer, ServletEngineerView is called. In the servlet, the Java applet class StructuralDisplayApplet is invoked to show the structural model in 3-dimension by Java3D on the client side in a browser. When the engineer picks up a specific element from structural model, WakeupBehavior is invoked and the Swing JFrame UIInterfaceFrame is responsible for the displaying of basic geometric information of selected element and allows the engineer adding new properties or comments to the element. The additional properties are sent back to the servlet and added to the architectural IFC data file by the core processing module.

Similarly the architect is notified that structural engineer asks for changes in the design by the message. The server allows the architect downloading the modified IFC file to view the feedback from engineer and make decision on the design modification. Then the architect resubmits the design in IFC format to the server. Another cycle is started.

Until the consensus is achieved, the server generates the application compliant file, such as S2K file, and provides the downloading to the engineer. The link to JspOperations is provided on the right of JspHomepage. Some additional functions are provided to the engineer through this JSP webpage in order to make the server more powerful and extensible for future functions (e.g. integrating structural analysis software) and help engineer to perform analysis. After visiting this page, the engineer can download the S2K file and import the S2K file directly to SAP2000 to do structural analysis. At this point, the integration of architectural design and structural analysis is basically achieved because the communication of geometric information is implemented with the engineer.

Therefore, besides the downloading of application compliant files, other add-on functions are also provided in the prototype, including the operations of defining material information, assigning load information, uploading structural analysis results, and viewing the whole structural model with analysis results.

The engineer defines the material properties through servletDefineMaterial. Upon receiving the request of assigning load by engineer, the servletLoadAssign invokes StructuralDisplayApplet to let engineer choose the structural member which is going to be loaded. The load information is entered by engineer through the web browser built up by AssignLoadFrame class at client side. Then the connection to servletLoadAssign is reconstructed and the object about load is sent to the servlet using serialization in compressed stream. Each input instantiates a new IfcStructuralAction instance. The IfcStructuralAction class is provided object serialization which makes its instances can be serialized. It aims to use ObjectOutputStream and ObjectInputStream to write and read objects. The key to writing an object is to represent its state in a serialized form sufficient to reconstruct the object as it is read. Thus reading and writing objects is a process called "object serialization". Java object serialization has simplified the issues involved with formatting responses. With both applets and servlets written in Java, it's only natural that they should communicate by exchanging Java objects. Therefore, the loads assigned are represented as a Vector of IfcStructuralAction instances and sent to the servletLoadAssign.

After structural analysis is completed, most of structural analysis and design software can export data file to save the input and output for structural analysis, such as the Access file exported by SAP2000. Current trend sees that the commercial database industry is shifting to use the Internet as the preferred data delivery vehicle (Peng, 2002). Considering the collaboration with structural analysis programs and improving the amount of information sharing in the server, the function of receiving and saving structural analysis results to the server is implemented in the prototype. In current stage, only the collaboration with SAP2000 is realized. The file uploaded by engineer is Access data file. With the same process on architect's uploading, the Access data file is uploaded to the server by engineer and saved to the local server through the request for the servlet servletUploadAccessfile. Then JDBC technology is used to establish the connection with relational database and retrieve the corresponding data from result sets. The SAResultsManager class is responsible for reading the data from Access file and saving the structural analysis results, such as frame forces, joint displacements etc., as different Vector objects.

servletModelView is used to give a comprehensive view of structural model, including the basic information of structural members, the loads assigned on the specific member and structural analysis results. This service is not limited to the engineer, but any other involved project participants who may interested in the structural information.

7.5.3 Action Controller Component

The Action Controller Component is provided for online application services to register to the core so that these services can be found and accessed and routing the incoming request to an appropriate command object that knows how to handle the request. Figure 7.8 illustrates all involved classes in Action Controller Component module.

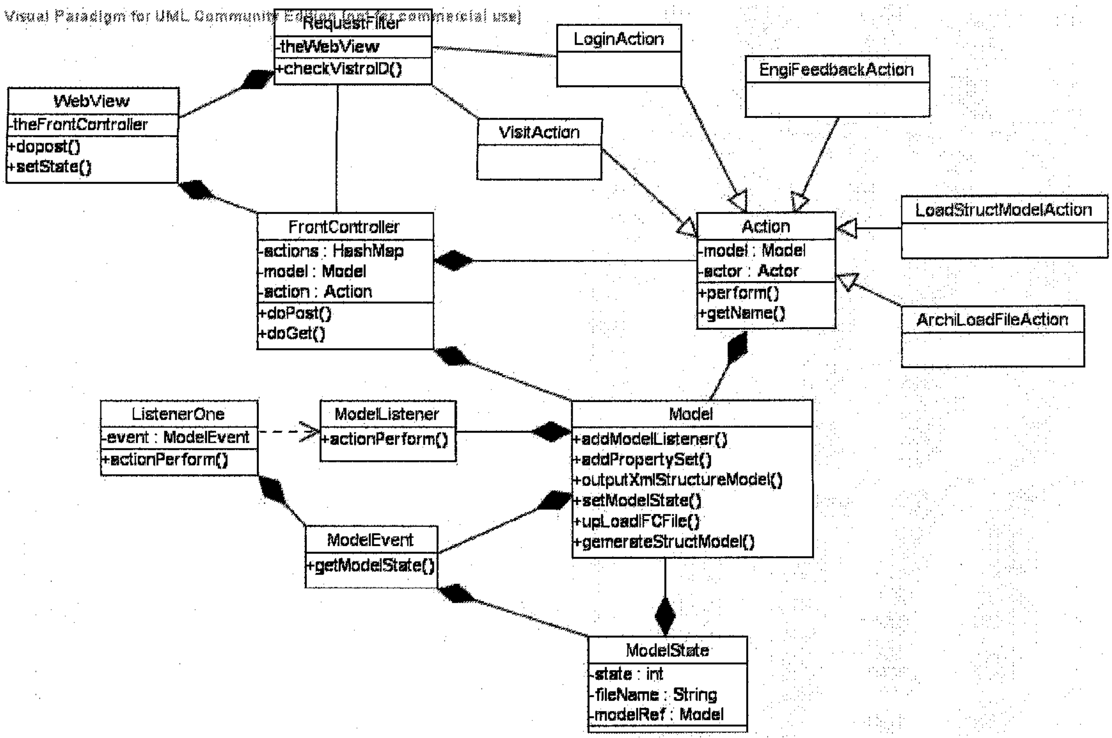


Figure 7.8 Action Controller Component

The client visits the JSP homepage through web browser and send HTTP request to the FrontController. On the first request for a web Application, the FrontController Servlet creates Model Bean and ModelState Bean. The ModelState Bean lives as long as the application is alive in the web container.

All the requests from client send to the FrontController, which in turn will call the corresponding sub class of Action. The corresponding sub class of Action will operate on Model Bean, which might change the state of Model Bean. When the Model state has been changed, it will fire ModelEvent. The ModelListener receives the event and do corresponding operations, one of which is to refresh the JSP homepage to reflect the appropriate model state.

The responsibility of this component is to route the incoming request to an appropriate command object that knows how to handle the request. The command-object further delegates the request to other appropriate object that will execute the appropriate business logic on Model Bean. The Model Bean has the event-firing mechanism that can fire the event according to the state change. The event listeners that are attached to the model will behave accordingly.

The ModelState Bean is the object that controls access of web application. It might be necessary to incorporate more complicated pattern to control the access if there are more than one architect or engineer involving in the design process. But as a prototype, it only considers one architect and one engineer.

7.5.4 Core Processing Module

The Core processing module is the main part to process the data, including retrieving the geometric data from uploaded IFC file, computing and generating the basic information of structural members and connections, as well as processing the data input by the engineer, reading and querying the structural analysis results from database file.

7.5.4.1 Algorithm of Constructing Structural Models

In order to construct the structural model, the deduction is needed from geometric representations of building elements (beams and columns etc.) in architectural design to topological representations of structural elements as lines or points following some algorithm. CuiLu et al. (2003) carried out the study on how to deduce the topological relationship from the geometric representation of product in IFC. In this research, Cui's algorithm is utilized to generate structural model.

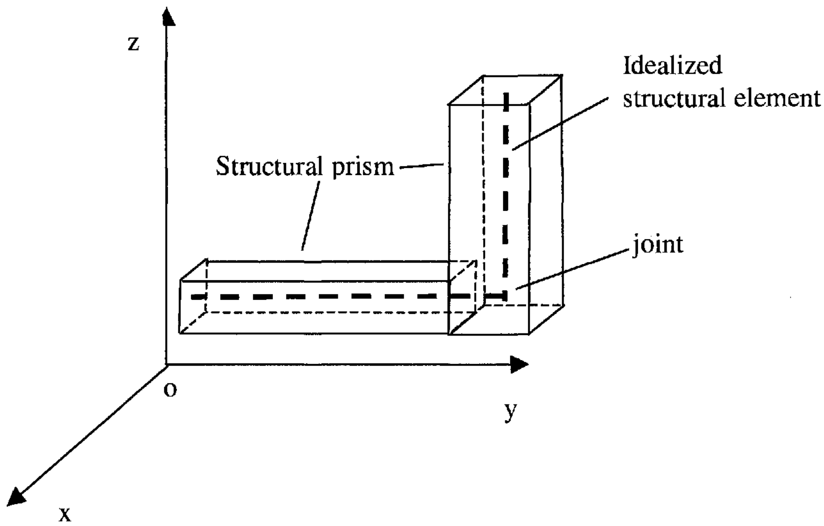


Figure 7.9 The Illustration of Idealized Structural Elements and Joint of Two Structural Prism

According to Nguyen (2001) there are five categories of topological relationships between building elements and space: adjacency, separation, containment, intersection and connectivity. For the purpose of structural analysis, only two relationships (intersection and connectivity) are considered in Cui's study. He proposed that the prism connectivity checking is based on the checking of collision between the edges of a prism and the surfaces of another. If two prisms are connected, an edge of one of prisms must intersect with the surface of another. Thus, the basic point of connectivity checking algorithm is to find whether a spatial line segment has a common point with a planar three-vertex facet. The collision between more complicated polygons can be found by first triangulating them into three-vertex facets. Therefore, a simple algorithm could be proposed to deduce the connectivity between prisms, which have the most common 3-dimensional shape of the structural elements.

Cui (2003) mentioned that the idealized structural elements and connectivity information could be deduced from the 3D geometric information of an architectural model by following the steps below:

1. Finding the connectivity between structural elements;
2. Defining the idealized structural elements;

3. Finding the joints between two connected structural elements.

For a prism, its corresponding idealized structural element is the line segment in between the centroids of two base surfaces (Figure 7.9). The joint can be defined as the intersection point of two idealized structural elements if they are in one spatial plane or the nearest points on each segment if they are not in one spatial plane. In the prototype implementation, a structural element includes the location and index of its two joints.

7.5.4.2 Implementation

In the prototype implementation, a series of classes are defined to complete the main functions of the server, including information read from IFC files, deduction of structural model, as well as the other tasks. The class diagram for core processing module is shown in Figure 7.10.

When the architect uploads the IFC file via the web page, the server receives the file and saves it on the server. An instance of Java class Model is created synchronously to record the information of saved IFC file and all the other generated information during the whole process. The method setIfcFilePath () is used to record the path of saved IFC file. By invoking the method generateStructureModel of class Model, an instance of IfcStructManager is created. IfcStructManager is mainly responsible for reading the geometric information in IFC files, extracting the geometry information of structural elements, and deducing the idealized structural elements and their topological relations. Joints are calculated between connected elements according to above algorithm. Other classes, such as IfcStructGeoManager and IfcStructTopoManager are also needed during the deduction. The structural elements of structural model are saved as the instances of classes StructLinearElement and joints are represented as the attributes (startPoint and endpoint) of corresponding StructLinearElement. All the structural elements are stored as a Vector of StructLinearElement. Subsequently the whole structural idealization model with the information about idealized structural elements and joints on them is saved on the server in a file of XML format by the method setXMLStructModelFilePath (). During the course, SimpleXMLOutput class is called to write the content of Vector into XML format. In this way, a flat file of structural information is kept on the server as a back up for future data retrieve. At this point, the cycle for architect uploading IFC file is hereto finished. It waits for the engineer to review and comment on the structural idealization model.

For another use case of adding property set to structural model, all the feedback of the engineer is stored as property set in PSetBean. IfcPropertySetManager is used to add property set to the target IFC file. Furthermore, the engineer is also allowed to define material properties, assign load information or upload structural analysis results which are needed for the extended functions to perform structural analysis and share analysis results with others. After the engineer enters the information via Java applets, MaterialManager, LoadManager and SAResultsManager are designed to manage the creating and saving of material properties as well as activities including actions and reactions. All the materials, actions and reactions are represented as the Vector of IfcMaterial, IfcStructuralAction, and IfcStructuralReaction instances respectively. Basically the development of these kinds of domain-related classes is based on IFC models for structural analysis domain encapsulating part of extensions developed in previous chapter, which will be described in Section 7.6 in detail.

As mentioned before, in order to truly implement the integration between different disciplines, the system should enable its services to different types of client applications. In current prototype, it points to structural analysis applications, which are mostly not IFC-compliant. They are written in different programming languages and implementing different data access paradigms. To put this into practice, the function of generating the imported file for different applications is needed. In the prototype implementation, when generating structural model, all related structural information is also written into a S2K file for the benefit of SAP2000 by ExportSAPfile class in data storage module.

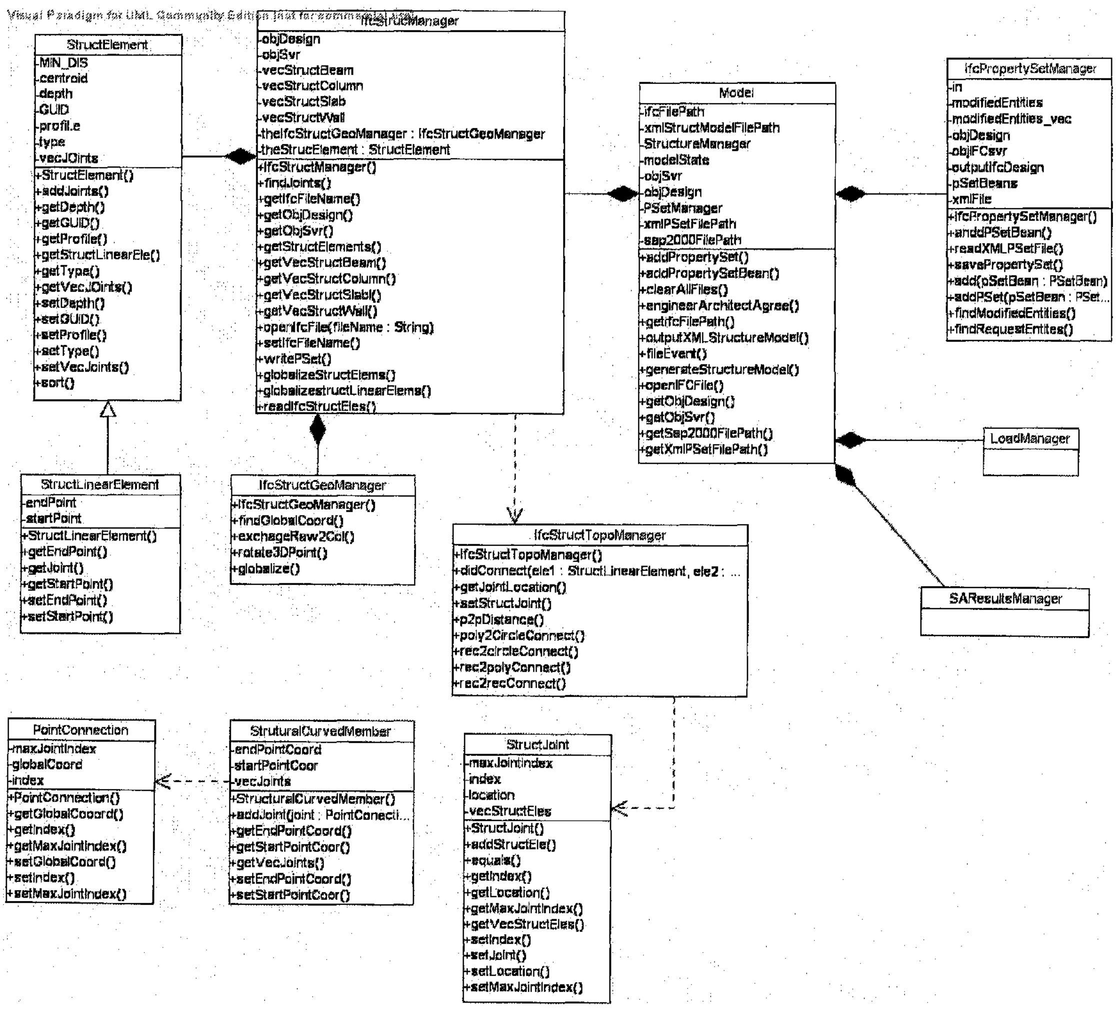


Figure 7.10 Class Diagram of Core Processing Module

7.5.5 Data Access and Data Storage Module

The primary objective of data access and data storage module is to set up an engineering database which will provide users the needed engineering information from readily accessible sources in a ready-to-use format for further manipulation. Modern engineering programs are increasingly required to be linked to other software such as CAD, graphical processing software, or databases. Software applications collaborate by exchanging information. Data integration problems are mounting as engineers confront the need to move information from one computer program to another in a reliable and organized manner. The lack of a reliable, simple, and universally deployed data exchange model has long impaired effective interoperations among heterogeneous software applications.

The handling of data shared between disparate systems requires the definition of persistent and standard representations of the data, and corresponding interfaces to query the data. Data must be represented in such a manner that they can facilitate interoperation with humans or mechanisms that use other persistent representations. XML format is thus selected as the standard representation for the data. In the system, the data storage supports only a flat file system and the primary responsibility of this module is to process XML files.

7.5.5.1 Data Representation

In the data access sub-system, Extensive Markup Language (XML) is chosen as the standard for representing data in a platform independent manner for the data exchange between collaborating applications. XML is an emerging protocol that allows devices to exchange data efficiently. XML was enthusiastically adopted by programmers who needed a robust, extensible, standard format for data (Harold, 2002). XML is a textual language quickly gaining popularity for data representation and exchange on the Web (Goldman et al., 1999). Unlike HTTP, XML defines a class of data objects called XML documents and partially describes the behaviour of computer programs which process them. XML lets developers define complex data structures and developers can share this information across a variety of applications, clients and servers. Using the XML parser, developers can create applications that enable their web server to exchange XML-formatted data. XML provides an effective means for the data exchange of different applications and accessing the database on the Internet. XML can alleviate many programming problems associated with data conversion.

XML is a set of rules for defining semantic tags that break a document into parts and identify the different parts of the document. It is a meta-markup language that defines a syntax used to define other domain-specific, semantic, structured markup languages (Harold, 1999). An XML element is made up of a start tag, an end tag, and content in between. The start and end tags describe the content within the tags, which is considered the value of the element. In addition to tags and values, attributes are provided to annotate elements. Thus, XML files contain both data and structural information.

7.5.5.2 XML Related Component

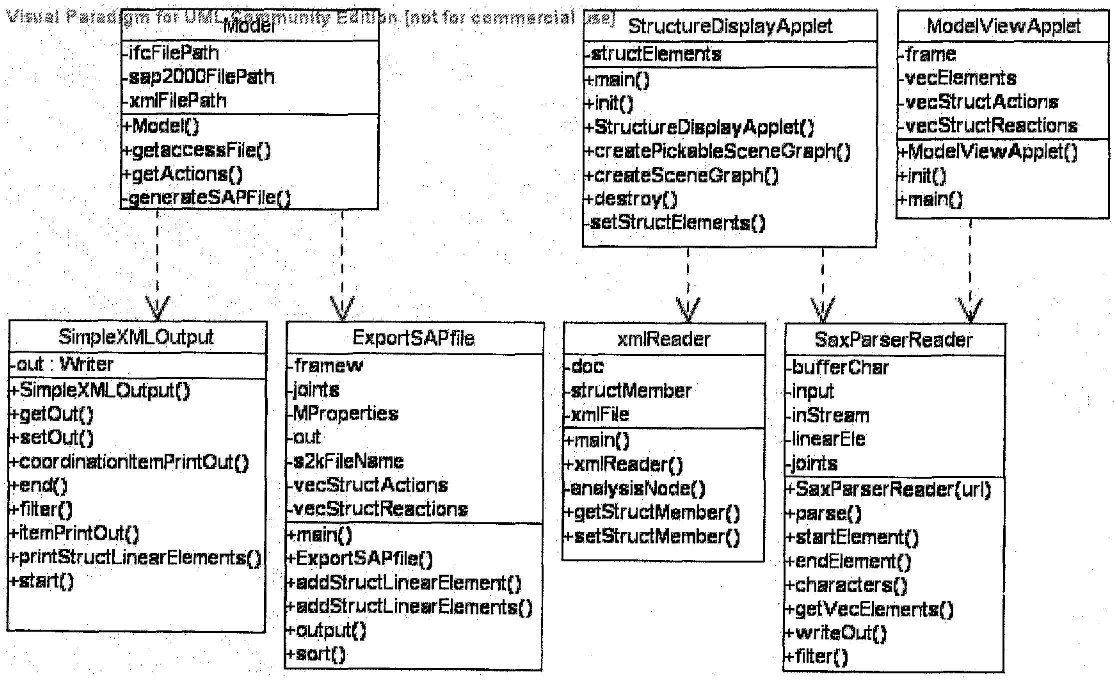


Figure 7.11 Sample Classes and Related Components of Data Storage

Figure 7.11 shows the sample classes involved during data storage. The responsibility of SimpleXMLOutput class, xmlReader class and SaxParserReader class is to read and write structural information (geometric information and topological information of structural elements) in XML format. Simple API for XML (SAX) is used to process XML documents with Java. SAX is the first and gold standard API shared across different XML parsers. It is the most complete and correct by far (Harold, 2002). As an operation on the server, it is designed to consume only a small amount of memory.

In the application server, the structural model information is recorded and transmitted in XML format. When the application finishes the uploading of IFC file from architect, the IfcStructManager is used to analyze and generate the structural model. It will generate a Vector of StructLinearElement, which is stored in memory. The SimpleXMLOutput is called then to convert and save the geometric information and topological information of every StructLinearElement instance into XML representation on the server. SimpleXMLOutput does not use JDOM or DOM, as these two consume too much memory on the server. It is just a simple writer that writer the structural information in XML format, and it is much lighter. As shown in Figure 7.11, the setOut () method is used to define the file path of XML file saved onto the server. Then the methods itemPrintOut (), coordinationItemPrintOut (), start (), end () and printStructLinearElement () are responsible for converting and writing the structural linear elements' data into XML representation.

When engineer on client side wants to view the structural model in browser, the server transmitted the XML data file to the Java Applet StructureDisplayApplet. A SAX program, SaxParserReader is used to parse the XML data file and read it from beginning to end. Once an instance of this class is obtained, XML can be parsed from a variety of input sources. These input sources include InputStreams, Files, URLs, and SAX InputSources (Java Sun, 2003). In this case, it is invoked by the StructureDisplayApplet from the client side. The XML data file on the server side can be read and parsed through the connection to its Uniform Resource Identifier (URI). A vector vecElements is constructed which stores the structural elements information as the vector of StructLinearElement. Similarly, the xmlReader is also a SAX parser. But it only reads in the XML file directly coming from local computer. It can not parse the XML from InputStreams, URLs etc. The function analysisNode () is used to read the structure and data of XML file and save to the vector of StructLinearElement.

7.5.5.3 The XML DTD design

The acronym DTD stands for Document Type Definition, which focuses on the element structure of a structure of a document. It says what elements a document may contain, what each element may and must contain in what order, and what attributes each element has (Harold, 2002). A DTD provides a list of markup declarations for the elements, attributes, notations, and entities contained in a document, as well as their relationships to one another. DTDs specify a set of rules for the structure of a document. For example, the XML file of saved structural elements and its corresponding DTD diagram are shown in Figure 7.12.

```
<?xml version="1.0" encoding="UTF-8" ?>
<!ELEMENT StructureModel ( StructLinearElement+ ) >
<!ATTLIST StructureModel xmlns CDATA #REQUIRED >
<!ELEMENT StructLinearElement ( Type, GUID, Profile,
Depth,
StartPointGlobalCoordinatin,
EndPointGlobalCoordinatin, JointCollection ) >
<!ELEMENT Type ( #PCDATA ) >
<!ELEMENT GUID ( #PCDATA ) >
<!ELEMENT Profile ( Width, Height ) >
<!ELEMENT Width ( #PCDATA ) >
<!ELEMENT Height ( #PCDATA ) >
<!ELEMENT Depth ( #PCDATA ) >
<!ELEMENT StartPointGlobalCoordinatin ( X, Y, Z ) >
<!ELEMENT EndPointGlobalCoordinatin ( X, Y, Z ) >
<!ELEMENT JointCollection ( Joint+ ) >
<!ELEMENT Joint ( Index, GlobalCoordination ) >
<!ELEMENT Index ( #PCDATA ) >
<!ELEMENT GlobalCoordination ( X, Y, Z ) >
```

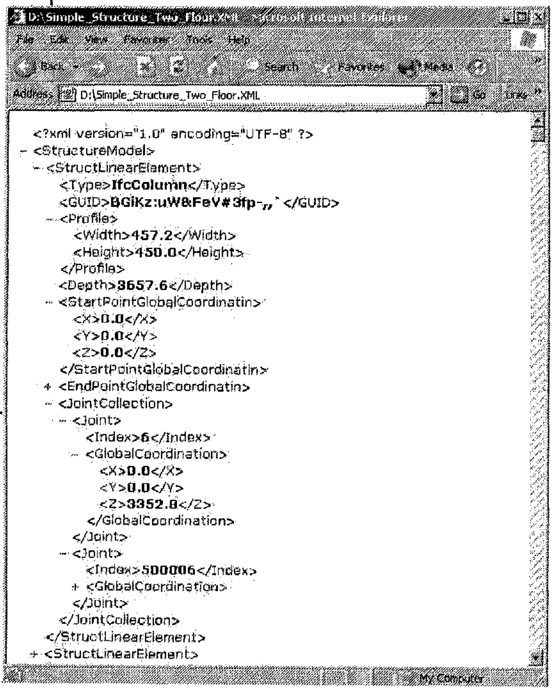


Figure 7.12 Samples of XML File and Its DTD

7.5.5.4 Application-Specific Data Adaptor for SAP2000

In current stage the only and easy way to achieve the essential integration between architectural design and structural analysis applications is by creating a physical file of information that may be shared across a network. However, presently most of structural analysis software cannot accept or generate IFC file or XML file which is the common schema of the prototype system to save the data. Therefore, "adaptors" are needed to map the common data schema to different applications' specific schema. Generally this mapping is carried out by an application-specific adaptor software component.

SAP2000 works around a central database created for the structural model. The database is maintained in a binary format and does not operate with text input files. However, text input files may be read or written using the Import/Export facility. The supported formats mainly include text file, DXF file and Enhanced Metafile. The DXF file import is intended to facilitate importing model geometry from AutoCAD and other DXF compatible programs. However, only the DXF for AutoCAD r12, r13 and r14 is supported. The Enhanced Metafile is a vector file format that can be read by many graphics programs as well as some office tools like word processors. A text file with an extension "S2k" is saved at the same time as the model database is saved (as a file with .SDB extension). This text file is good for analysis purposes. The analysis and design information provided in the SDB file is also saved in the S2K file. This gives the user the ability to modify the model using a text editor like WordPad.

The text file provides a feasible way for the system to interact with SAP2000, since it is easiest to generate. Thus the adaptor for SAP2000 is implemented to write S2K text file and provide the link of download via Internet to engineer as the input of structural analysis. In this implementation, one class is enough for one kind of application. It can be noticed that in Figure 7.11 another class ExportSAPfile is used except the SimpleXMLOutput to write the whole structural model, including the structural geometric and topological information, even material properties and load information assigned by engineer, to a text file in accordance with the format of the S2K file.

7.6 Implementation of Extended IFC Models in System

The prototype implements the augmented IFC models in the context of distributed, model-based, integrated AEC/FM system architecture. When the core processing module reads IFC file, IFCsvr ActiveX component is used which is an off-the-peg ActiveX component for handling IFC data. IFCsvr is a software component for the development of IFC compliant application with Visual Basic, Visual Basic for Application (VBA), VC++, and so on. IFCsvr has IFC model data input/output function as STEP Part21 file or XML file and provides additional operations, such as IFC object searching, changing, and creating.

Till now IFCsvr has transited from version R200 to the latest R300. The new features of R300 include the support to IFC 2x and strengthening XML import and export function (BLIS-XML stream with MSXML or string data). Whereas R300 is still under improvement and most of IFC compliant CAD architectural design software can successfully provide IFC R151 or R2.0 file and a few can support IFC 2x, IFCsvr.R200 is more stable by contrast with R300 and is selected to be used in current prototype implementation.

7.6.1 IFCsvr. R200

Figure 7.13 gives the object model of IFCsvr. R200. The IFCsvr.R200 object is a root object of IFCsvr, which can load the IFC model data from following formats: STEP Part 21, BLIS XML format, ROSE binary, and ROSE ascii. The Design object manages IFC model data file. Design object can write the IFC model data. This object has also instantiating and searching Entity object functions. The Entities object is a collection of Entity object. The Entity object manages IFC object instances defined by EXPRESS. Each Entity object contains its ENTITY TYPE name and a pointer to its own attributes. The Attributes object is a collection of Attribute object. The Attribute object can set and get values of each attribute which are contained by an Entity object. More detailed information is available at http://cic.vtt.fi/projects/ifcsvr/ifcsvrr200/obj_r200.html.

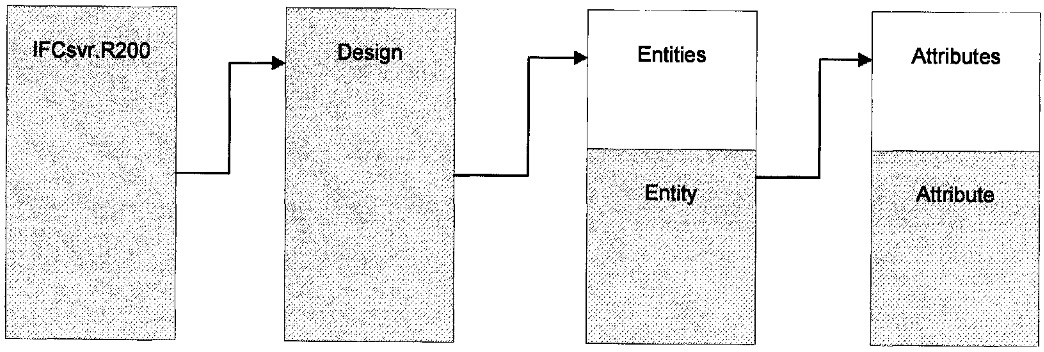


Figure 7.13 IFCsvr. R200 Object Model

(Source: http://cic.vtt.fi/projects/ifcsvr/ifcsvrr200/obj_r200.html)

7.6.2 IFC Models Implementation

The data structure of IFC models is complicated and has to be represented in Java objects to fully utilize the advantages of object-oriented approach. During the implementation of prototype system, a set of Java classes is designed to represent the geometric information from IFC architectural design file, as shown in Figure 7.14. Any object in IFC with a geometric representation has two attributes: ObjectPlacement and Representation. ObjectPlacement, which has the type of IfcObjectPlacement, stores the placement information of an object. Representation, which has the type of IfcProductRepresentation, stores the shape representations of the object. Its location is defined within the context of ObjectPlacement. Each Entity read by IFCsvr such as IfcBeam, IfcColumn and so on, are stored as one instance of class IfcProduct. The values of attributes ObjectPlacement and Representation of each Entity are extracted and saved into corresponding attributes of the IfcProduct by types of IfcLocalPlacement and IfcProductRepresentation.

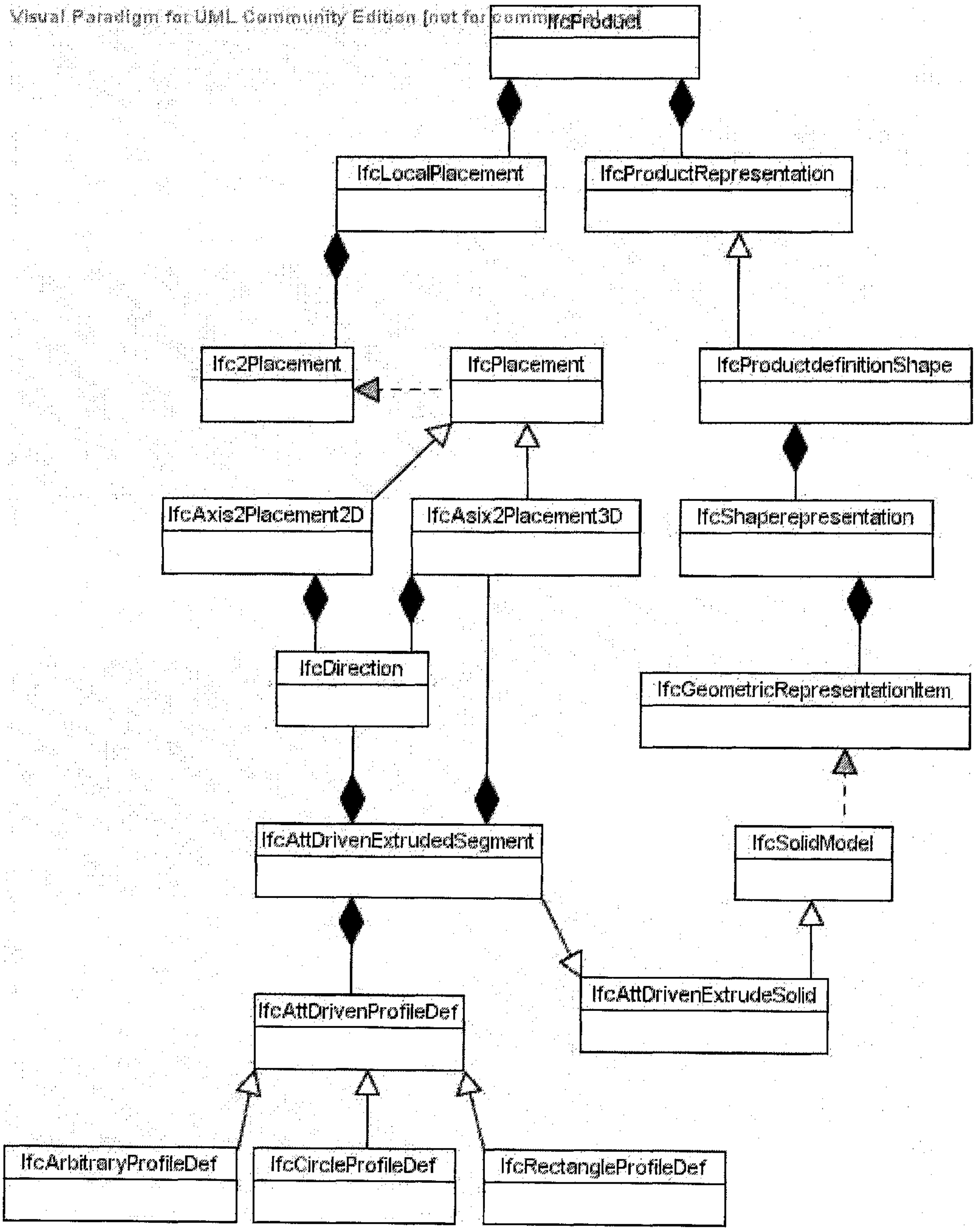


Figure 7.14 IFC-compliant Java Classes for Geometry Information

Besides the geometric information, other Java objects are also needed, such as the material information and load information assigned by engineer, as well as structural analysis results. Basically they still follow the data structure of IFC schema which aims to make it easy to cooperate with or transfer to IFC schema in the future.

Because of limitation of IFCsvr R200, presently the system cannot write these kinds of information into original IFC file after the server get them from engineer. In the future, it can be considered to write this information into the original IFC architectural design file and provide a more complete file to download for query and view. As more and more applications provide the support for IFC models, a complete IFC file is a more useful and effective way for future communication and information sharing. Figure 7.15 illustrates the developed Java classes for material and load information. It is apparent that it is very similar with the data structure of latest IFC Release 2x Edition 2 and its addendum.

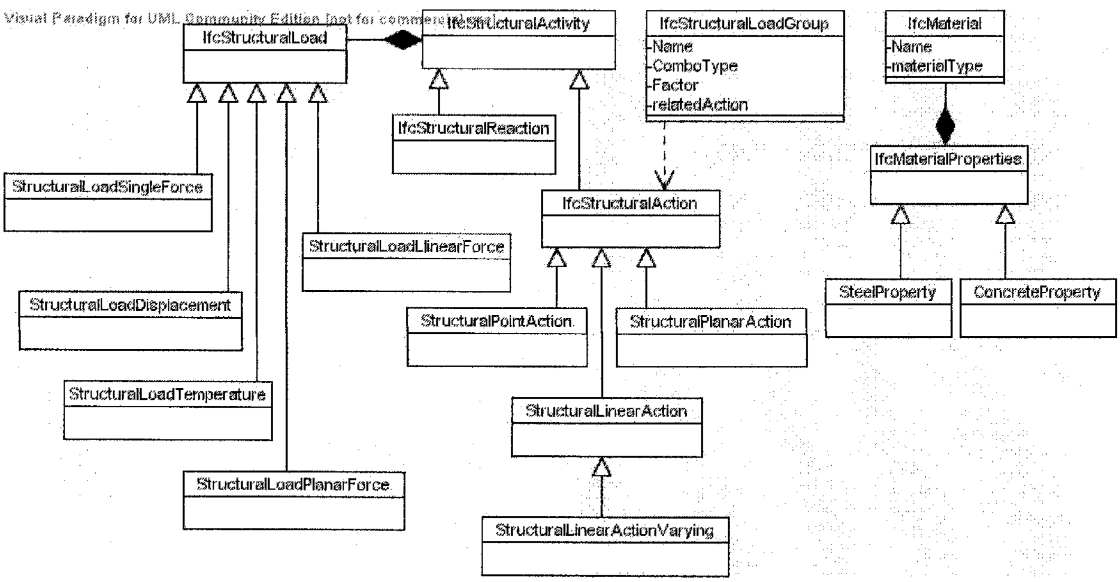


Figure 7.15 Java Classes for Material and Load Information

7.6.3 Implementation of Proposed IFC Extensions

As described in previous chapters, current IFC models cannot support complete requirements of structural engineering software to perform structural analysis. According to Table 6.5 in Chapter 6, some new extensions are developed. Small revision is necessary in some minor respects or some information need deduction. However, these new extensions to IFC models proposed in this research cannot be written into IFC files before they are finally incorporated into the new Release of IFC models.

New property set can be included in IFC files at any time and it has already been implemented in the prototype system by PSet beans. With regard to other information, no matter the new extensions or new attributes to objects, their Java classes which are basically compliant with IFC data structure are developed in the prototype implementation. On the other hand, new classes or new attributes for the information that applications require are also incorporated and processes. In the prototype, the following respects are implemented to process the related information gaps with IFC Release 2x Edition 2 and its addendum which can be referred in Table 6.5.

(1) For the gaps on geometry information, referring to the sample of the definition for StructLinearElement class in Figure 7.16 and its XML representation in Figure 7.12, it can be investigated that the global locations of joints are always provided. In class StructLinearElement, the attribute vecJoints is inherited from class StructElement to save the related joints by the type of StructJoint. In XML, The information of joints is included under the child element JointCollection of element StructLinearElement. For each joint, its Index and GlobalCoordination are saved. Moreover, the length of the structural element is represented in the child element Depth.

```
public class StructLinearElement extends StructElement {
  // Fields
    private double[] startPoint;
    private double[] endPoint;
  // Constructors
    public StructLinearElement() { }
    public StructLinearElement(StructElement structElement) { }
  // Methods
    public StructJoint getJoint(double[] doubleArray) { }
    public boolean hasJoint(double[] doubleArray) { }
    public void setEndPoint(double[] doubleArray) { }
    public void setStartPoint(double[] doubleArray) { }
    public double[] getStartPoint() { return null;}
    public double[] getEndPoint() { return null;}
}
```

```
public class StructElement implements Serializable {
  // Fields
    private String GUID;
    private double[] depth;
    private String type;
    private double[] centroid;
    private Profile profile;
    private Vector vecJoints;
        protected final double MIN_DIS = 0.01;
  // Constructors
    public StructElement() { }
  // Methods
    public void getStructLinearEle() { }
       public void setDepth(double[] doubleArray) { }
    public void setProfile(Profile profile) { }
        public double[] getDepth() { return null;}
    public Profile getProfile() { return null;}
    public void addJoints(StructJoint structJoint) { }
    public Vector getVecJoints() { return null;}
    public void setVecJoints(Vector vector) { }
    public String getGUID() { return null;}
    public void setGUID(String string) { }
    public String getType() { return null;}
    public void setType(String string) { }
    public void sort() { }
}
```

Figure 7.16 Part Definition of StructLinearElement Class

(2) The developments related to load information include:

- The load distance saved is always relative distance. As shown in Table 7. 3 which is the load definition in generated S2K file, the load position of this instance of IfcStructuralAction, is relatively at the 0.25 of the length of element expressed by the value of parameter RD.

- As described in Chapter 6.5.2, 'Load Type' is not needed to be described in S2K file. Only the values of IfcStructuralLoad should be wrote into S2K file separately. In S2K file, the 'TYPE' of load stands for the kind of load assigned, concentrated load or distributed load etc.

- The load values in different directions or axes are divided and wrote respectively into S2K file by ExportSAPfile. For example, StructuralLoadSingleForce has six values for three forces in different directions and three moments about different axis. If all values are not equal to zero, then they will be expressed to six loads in 'TYPE' of "Concentrated Span" respectively in S2K file. As shown in the following example (Table 7.3), in fact these six values just represent a point action acted on a structural element named 28. And the assigned load is a StructuralLoadSinglForce with the value (3, 4, 5, 6, 7, 8). The value of 'Load Direction' is implied in the left operand expressed by 'UX, UY, UZ, RX, RY, RZ' etc.

- As shown in Figure 7.15, the attribute ComboType of entity IfcStructuralLoadGroup reflects the combination types. The default value is "ADD".

Table 7.3 Example of Load Denotation in S2K File and Corresponding IfcStructuralAction Class

<table>
<tr>
<td rowspan="2"><pre>...
LOAD
 NAME=DL SW=1 CSYS=0
   TYPE=CONCENTRATED SPAN
     ADD=28 RD=.25 UX=3
     ADD=28 RD=.25 UY=4
     ADD=28 RD=.25 UZ=5
     ADD=28 RD=.25 RZ=6
     ADD=28 RD=.25 RY=7
     ADD=28 RD=.25 RX=8

...</pre></td>
<td><pre>public class IfcStructuralActivity implements
Serializable {

  private String GUID;
  private String GlobalOrLocal;
  private IfcStructuralLoad AppliedLoad;
  private String LoadCase;
  private String AssignedtoElement;
  private String Position;
  private String Name;
  public IfcStructuralActivity() {
  }
}</pre></td>
</tr>
<tr>
<td><pre>public class IfcStructuralAction extends
IfcStructuralActivity{
        private Boolean DestablizingLoad;
        private String ProjectOrTrue;
}</pre></td>
</tr>
</table>

(3) Regarding the types of material, the new attribute materialType to class IfcMaterial is developed as shown in Figure 7.15. Although it provides the choices of types for the engineers currently, it is still recommended that isotropic material is used. Moreover, the material properties "weight per unit volume" and "mass per unit volume" are currently both defined in the class IfcMaterialProperties which aims to support different requirements for different software. As long as one value is provided, the other one can be calculated during generating the application-specific file, such as the S2K file generated by class ExportSAPfile.

(4) On section information, "Shape Type" is deduced by the value of attribute Profile of class StructLinearElement. For example, if its value is an instance of RectangleProf, then the value of "Shape Type" in S2K file equals to "R". Following the IFC schema, material is assigned to the selected structural elements. Through this, the relationship between section and material can be inferred.

(5) Whereas the conditions and definitions for the Prestress load and the elements' stresses are a little complicated, and the shell elements have not been included in this simple prototype implementation in this stage.

In conclusion, in the prototype system, for those information required to be processed during programming and no new corresponding extensions developed, they are computed or deduced from the existing values of classes during the writing of S2K file through the class ExportSAPfile, such as Shape Type and profile properties of member sections, etc. Other new extensions are realized during the classes generated. However, it can not represent the final implementation. As the possible development of IFC for these gaps, the structure or extensions have to be adjusted accordingly.

7.7 Summary

This chapter presents the development of the IFC-based web-enabled integrated building design (IWIBD) system, which provides a collaborative environment whereby the diverse participants can perform online collaboration via the web. It aims to support the communication and cooperation of architects and structural engineers, and to facilitate the incorporation of their design into the framework. The integrated framework can offer users access to the core server, as well as the associated supporting services via the Internet. An overview of the system architecture framework is provided. The architecture follows a three –tier software architecture and consists of four distinct modules. The detailed design and implementation of modules are described in this chapter. This system is based on the internationally recognized IFC models and the implementation of extended IFC models is also illustrated.

A prototype system has been implemented to prove the validity and concept. It provides web-enabled services for practical use of this framework in representation, exchange and sharing of interoperable design information between architectural design and structural engineering applications. It is capable of importing and exporting IFC information. For the prototype implementation and testing in this research work the J2EE technology is utilized as the basis. A standard World Wide Web browser is employed to provide the user interaction with the core server. Apache Tomcat 4.0 is employed to process the HTTP requests from the client. Java's Servlet is used to handle communication for the distributed element services over the Internet.

The prototype system is designed and implemented as a generic prototype application for the purpose of demonstrating software interoperability through the use of IFC data standards. It provides a means of integrated services in a modular and systematic way. The modular service model helps the integration of legacy code as one of the modular services in the infrastructure. Each component of the system can be added or updated without substantial amount of modification to the existing system. The application is not limited to architectural design and structural analysis only. Similar scenarios can be generated for demonstrating data exchange among the whole life cycle processes. The utilization of standard query language and popular query interfaces, as well as the deployment of the Internet for delivering data, makes the system flexible and extendible.

Chapter 8 Prototype Application and Case Studies

8.1 Introduction

In Chapter 7, a prototype of the IFC-based Web-enabled integrated framework is implemented. This chapter uses two cases and describes how the prototype of integrated building design system works. It is organized as follows:

- Section 8.1 gives a brief description of the content and structure of the chapter.
- Two case studies are carried out in Section 8.2 and Section 8.3 as illustrative examples for the application of the integrated building design system. The first case is used to illustrate the interoperability with architectural design, the user interface browsing and editing capabilities. The useful information for structural analysis in architectural design is extracted and automatically translated to structural information. The second shows the data transfer and interoperability with structural analysis and design software.
- Section 8.4 gives an assessment for this new way of communication between architects and structural engineers. The advantages and problems of the usage of integrated system are both described.
- Finally section 8.5 concludes with a summary.

8.2 Case Study I: Seven - Storey Building

The first case is a seven - storey building shown in Figure 8.1. Figure 8.1 is the three-dimensional architecture of the building with a total of 741 beams and 442 columns which can be summed up from its IFC file (Figure 8.2) by IFCTreeView. In this case study, the focus is to illustrate the processes of extracting the architectural information from the IFC file uploaded by architect and how to display the idealized structural model to engineer after deducing the structure-related information.

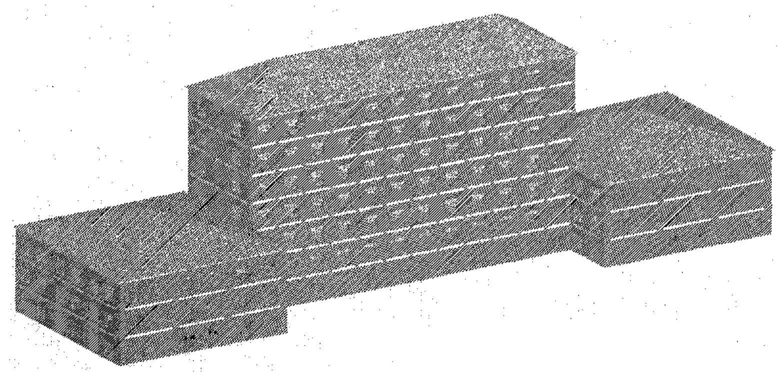


Figure 8.1 The Architecture of 7-storey Building as Input Data

8.2.1 Uploading IFC File

The architect first logs in the web site using Internet Explorer 6.0 in a remote computer (Figure 8.3). The server checks the identification and authorization of the architect. After the validation, the server will generate a JSP page that allows the architect to upload the architectural design file in IFC format. Figure 8.2 gives a fragment of the IFC file for this building. And Figure 8.4 shows the screenshot of the uploading JSP page.

The application on the server receives the file and generates the structural analysis model, which is saved on the server in XML format. The architect can then log off.

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION (('ArchiCAD generated IFC file.'), '2;1');
FILE_NAME ('For Strucure analysis.IFC', '2003-01-24T13:30:45', ('Architect'), ('Building Designer Office'),
'PreProc - IFC Toolbox Version 2.0 (99/07/01)', 'Windows System', 'The authorising person.');
FILE_SCHEMA (('IFC20_LONGFORM'));
ENDSEC;
DATA;
#100036=IFCADDRESS($,(),$,$,$,$,('555-87654321'),('555-
12345678'),('jiri.hietanen@solibri.com'),$,'www.solibri.com',$,$);

#2 = IFCDIRECTION ((0., 1., 0.));
#6 = IFCPERSON ('FamilyName', $, $, $, $, (), ());
#7 = IFCORGANIZATION ('OrganizationName', (), (), $);
#8 = IFCORGANIZATION ('Graphisoft', (), (), $);
#9 = IFCAPPLICATION ('ArchiCAD', 'ArchiCAD 7.0 (Graphisoft)', '7.0', #8);
#10 = IFCPERSONANDORGANIZATION (#6, #7, ());
......

#51004 = IFCTABLEROW ((IFCDESCRIPTIVEMEASURE  ('Concrete Block'), IFCINTEGER (0),
IFCINTEGER (65), IFCINTEGER (34), IFCINTEGER (20), IFCINTEGER (8), IFCINTEGER (20),
IFCINTEGER (34), IFCINTEGER (65), IFCINTEGER (-128)), .F.);
#51005 = IFCTABLEROW ((IFCDESCRIPTIVEMEASURE ('Structural Concrete'), IFCINTEGER (0),
IFCINTEGER (2), IFCINTEGER (32), IFCINTEGER (14), IFCINTEGER (68), IFCINTEGER (0),
IFCINTEGER (17), IFCINTEGER (64), IFCINTEGER (-24)), .F.);
#51006 = IFCTABLE ('d?n`<vE4~YQeDWuB?8Pb', 'Fill-Material Table', (#51003, #51004, #51005));
ENDSEC;
END-ISO-10303-21;
```


Figure 8.2 Fragment of Building's IFC File

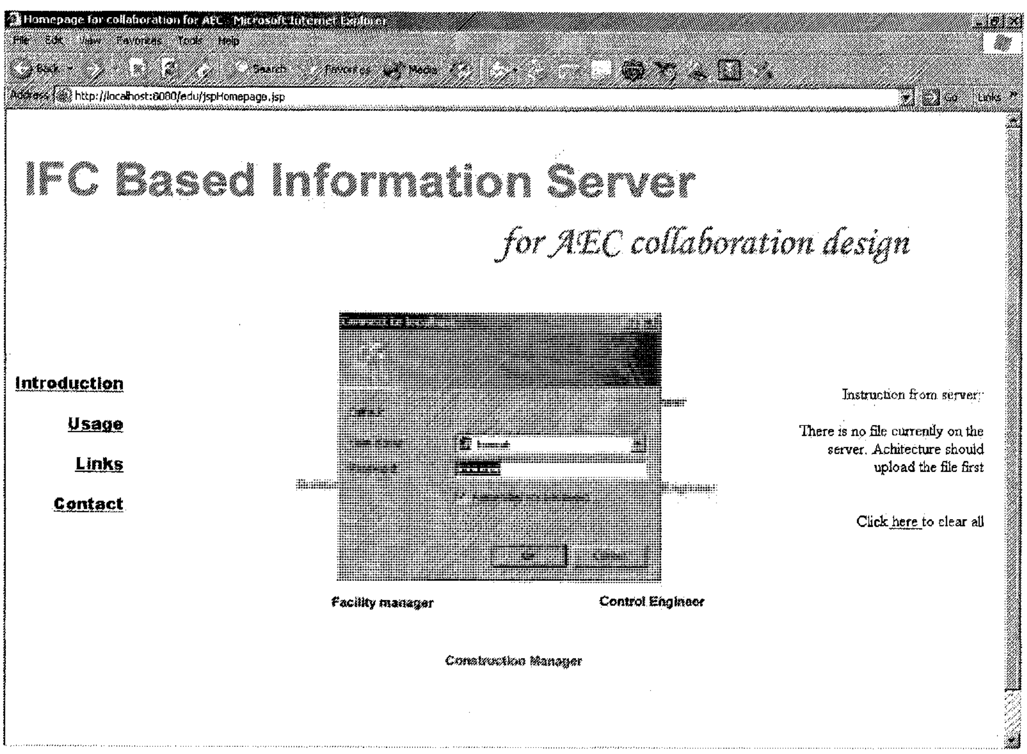


Figure 8.3 Screenshot of Architect Logging in JSP Page

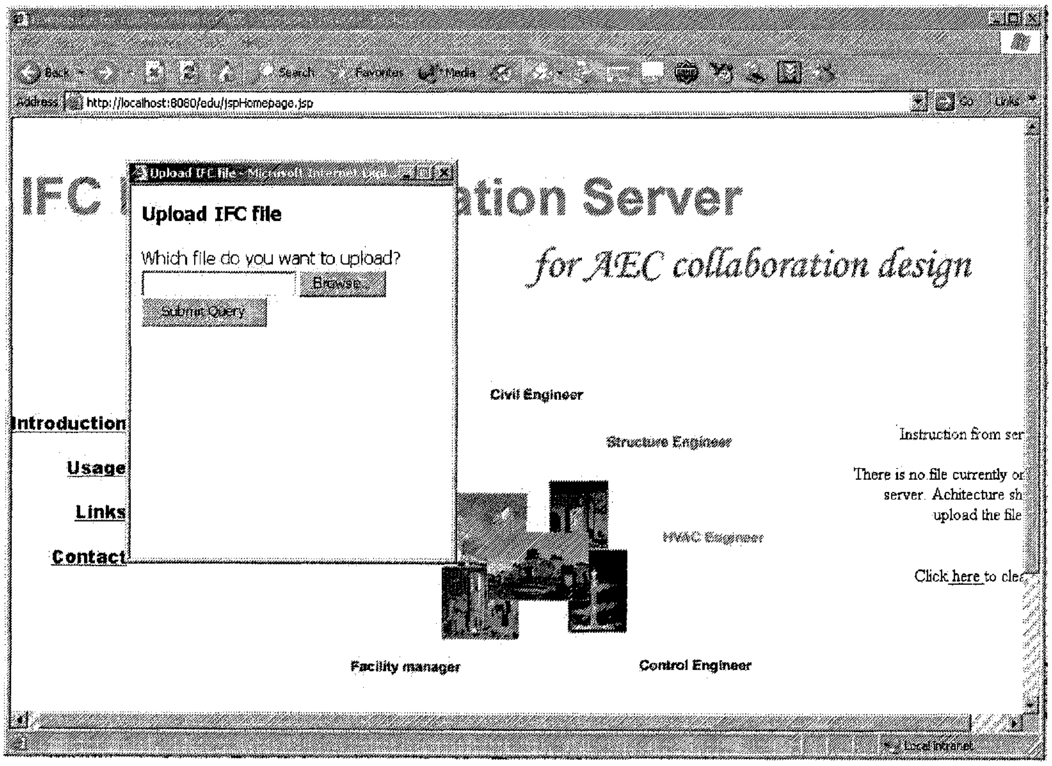


Figure 8.4 Screenshot of Architect Uploading IFC File

8.2.2 Viewing and Editing 3D Structural Idealization Model

The structural engineer involved in the project can then, at another location, log in the server. After successfully logging in, the engineer can view the 3D idealized structural model in his browser. Though he cannot directly change the structural model, he can pick any element and add new properties or comments (Figure 8.5). Figure 8.5 presents the overall picture of the model viewing and editing.

The structural idealization model in Java applet (on the left of Figure 8.5) allows the client engineer to rotate, zoom in, zoom out and walk through the structural model to have a close view. The pop-up window (on the right of Figure 8.5) shows the basic information of selected element, including the dimension, the location of the idealized structural element and joints. Currently the information of element comes from the XML file saved in the server.

Besides the basic information, the system also allows the structural engineer to add new properties to the selected element as name-value pairs. For example, if the engineer has some suggestions about the location or dimension of the element, he can add the comments in the TextArea. These are written back to the server after clicking feedback button and are saved as Property Sets into the IFC data file on the server, after clicking the save button. After receiving the feedback from engineer, the server generates the JSP page that gives notice to the architect and allows him to log in and download the adjusted IFC data file with the property sets added by the engineer. After downloading, the architect can use his CAD software to view and edit the design. After editing, the architect logs in the web and once more uploads the revised architectural design as an IFC data file again. The server receives the file and automatically generates a structural idealization model and a JSP web page that only allows the engineer to log in and view the revised model.

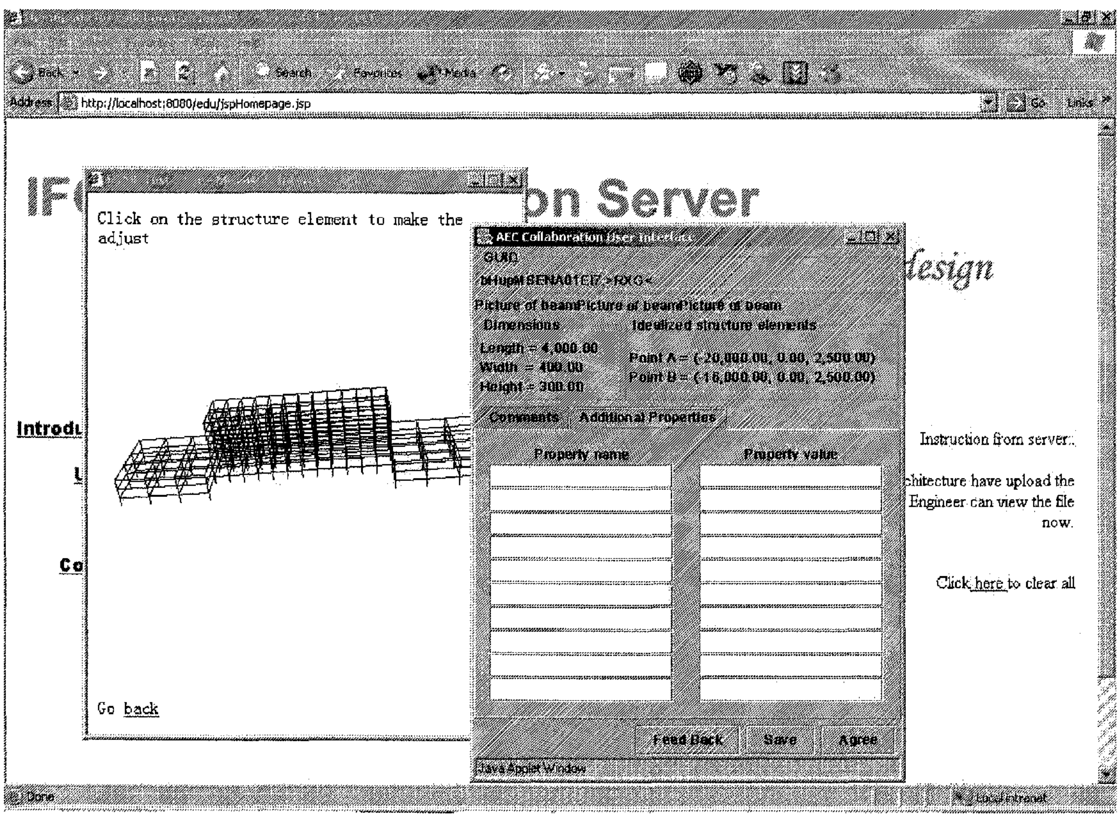


Figure 8.5 The Screenshot of Structural Engineer Logging in Server and Adds some information to Idealized Structural Model

8.2.3 Downloading the Agreed Model File

If the engineer is satisfied with the structural model, the server will generate a web page to close the information feedback process and allow the architect and structural engineer to download the architectural model as an IFC data file and the structural idealization model as a XML format file (the message is shown on the right of Figure 8.6). If the engineer is still not satisfied with the structural model, he can feedback his suggestion and server will repeat the above process until the agreement is achieved.

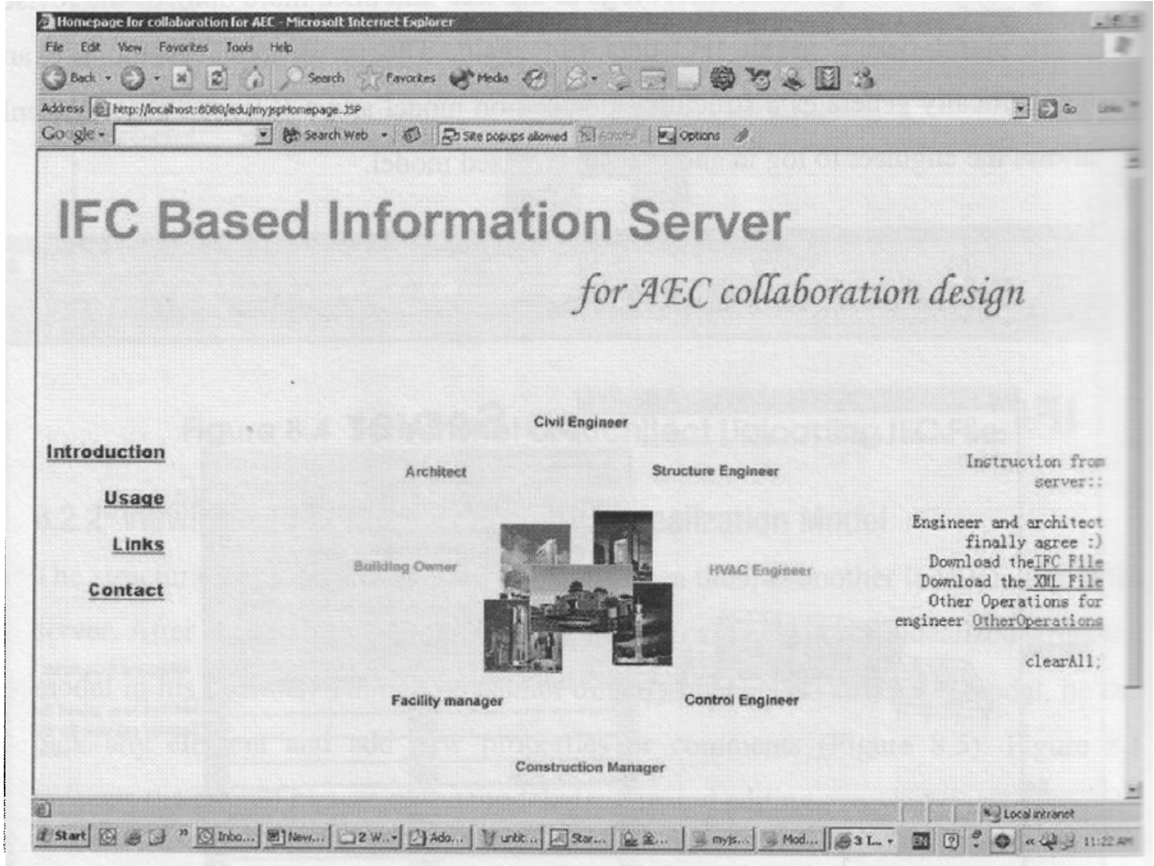


Figure 8.6 The Screenshot of Final JSP Page that Allows Architect and Structural Engineer to Download Files

As the output is in XML format, it can be easily transferred to the other data formats required by the structural analysis software. The IFC2.0 Release does not include the structural analysis domain. Thus, the structural analysis information and analysis results generated by structural engineering software cannot merge with the IFC model at the moment. It would be changed in the near future with the coordinated in improving on the IFCsvr ActiveX component and the capabilities of structural engineering software to support IFC.

8.2.4 Information and Data Transformation

The above sections provide the general picture of the whole process of the collaboration between architect and engineer. They also illustrate that how their communications are implemented by the model server via the web.

However, they cannot show the information transformation during the process and cannot prove that the information is exchanged consistently. In this section, one beam element labelled "Beam#2138" in IFC file is selected as an example to show the process of information and data transformation. For the same element's information, different definitions are generated during the different phases. Some definitions are visible for users, such as IFC file, XML file, while some are invisible which are only generated during the running of program and act as kind of transitional results.

There are four kinds of formats for the definition of the element. Starting from the definition in IFC file, it is then extracted, deduced and saved as the instance of StructLinearElement class. As the backup saved in the server, the data is saved into XML format. In order to support the use of SAP2000, the information is finally written into S2K file. The following section investigates into these four different formats of information.

Figure 8.7 shows the original definition of Beam#2138 in the IFC file uploaded by architect. It is a text file and all related information is in textual representations. Figure 8.8 is the browsing of the #3044 IfcBeam object by IFCTreeView. This tool can show the object reference diagrams on a tree view and is an application for a programmer who implements IFC compatible software. From the tree view, it can be shown that the geometry-related information in IfcBeam's definition lies on the value of Representations and LocalPlacement.

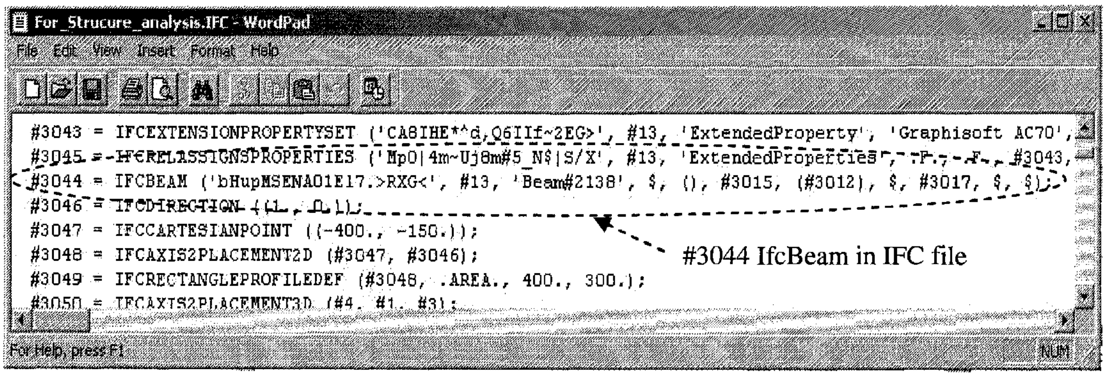


Figure 8.7 Definition of Beam#2138 in IFC File

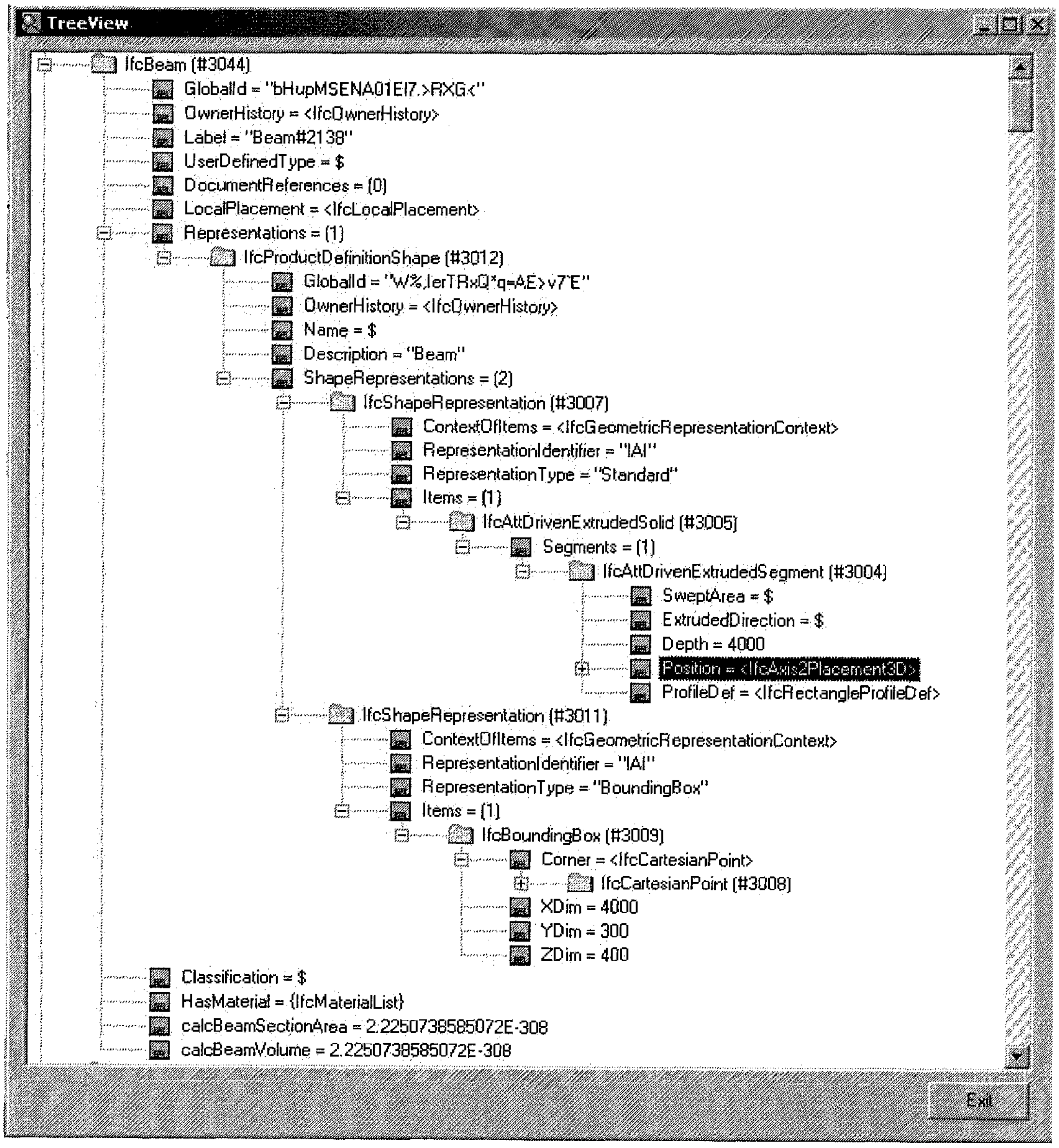


Figure 8.8 TreeView of the Value of Beam#2138

After the server receives the IFC file, it can extract the geometric information of IfcBeam and deduce the topological information of corresponding structural element. The deduced structural element is saved as one instance of StructLinearElement class. According to the definition shown in Figure 7.15, Table 8.1 lists the values of attributes deduced.

Table 8.1 Primary Values of Entity StructLinearElement for Beam#2138

	Attribute Name	Data Type		Value
	GUID	String	:	bHupMSENA01El7.>RXG<
	depth[ ]	double	:	(4000.0, 0.0,0.0)
	type	String	:	IfcBeam
	centroid	double[ ]	:	(-20000.0, 2.4442670110147446E-12, 2500.0)
	vecJoints	Vector		Two instances of StructJoint
	startPoint	double[ ]	:	(-20000.0, 2.4442670110147446E-12, 2500.0)
	endPoint	double[ ]	:	(-16000.0, 2.4442670110147446E-12, 2500.0)
	profile	Profile	:	An instance of RectangleProf
RectangleProf	centroid	double[ ]	:	(-20000.0, 2.4442670110147446E-12, 2500.0)
	Heightwidth	Double [ ]	:	(300.0, 400.0)
	Criticallength	double	:	250.0

Figure 8.9 is the close view of engineer's viewing on the selected element, which is the 'zoom-in' of the example in Figure 8.5. Here the element selected is just the same element as the example element which is used to explain the information transformation, i.e. Beam#2138. This beam is located in the middle of first storey as indicated on the left of Figure 8.9. After the engineer clicks the beam, a window is popped up as the right picture of Figure 8.9. It can be found that all the basic information of selected element is shown in the window, including the dimension of the element, the location of the idealized structural element and deduced joints. From the pop-up window, it can be seen that the basic information is identical with the values of previously-generated instance of StructLinearElement class (Table 8.1).

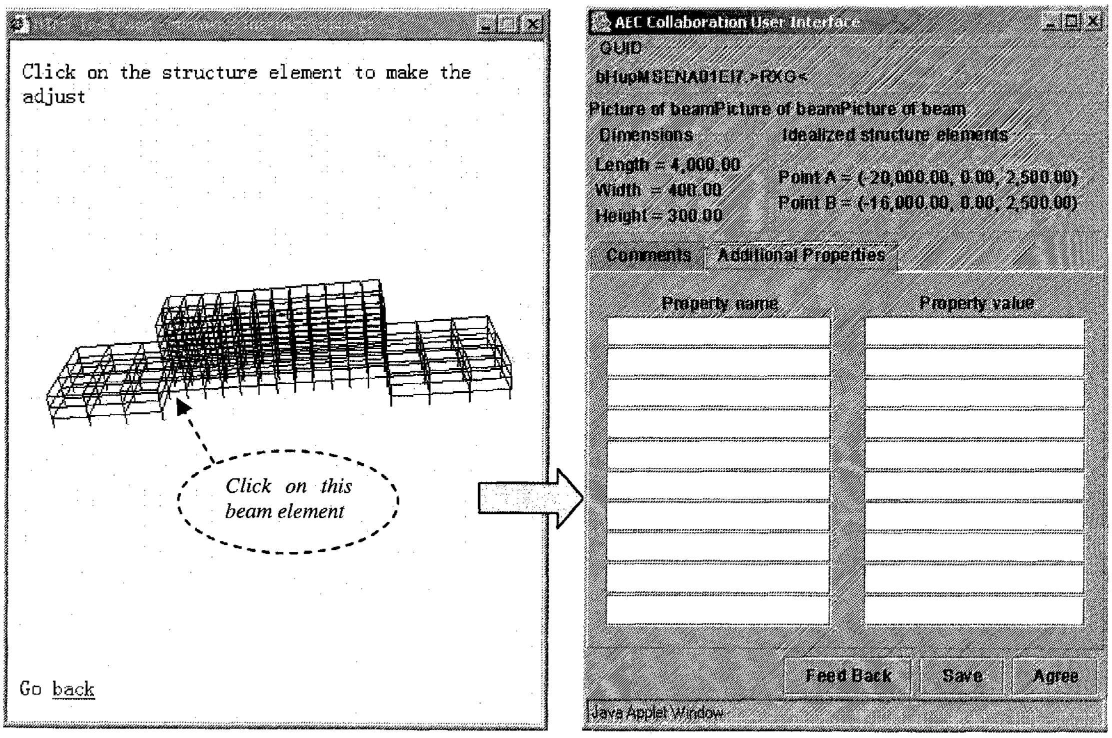


Figure 8.9 The Screenshot of Engineer Viewing Information of Selected Element

Currently the information of the element is read from the XML file saved in the server. Figure 8.10 represents the information of Beam#2138 in the XML file. Figure 8.11 shows the related information in S2K file. In S2K file, Beam#2138 is expressed as no. 1 frame. The joints of this frame element are no. 1 and no. 3 joints. The frame section is a rectangle with the dimension of 400.0 x 300.0 mm. All this information comes from the XML file and is written into this text file. Therefore, the value in S2K file should be certainly equal to that in XML file. Comparing Figure 8.10 and Figure 8.11, it can be seen that all the values are identical except for the indices of joints. The reason is that the index of expression in S2K file usually starts from 1, so the indices of joints in XML file are added by 1. This S2K file can then be imported by SAP2000 directly for further structural analysis, which will be illustrated in details in the next case study.

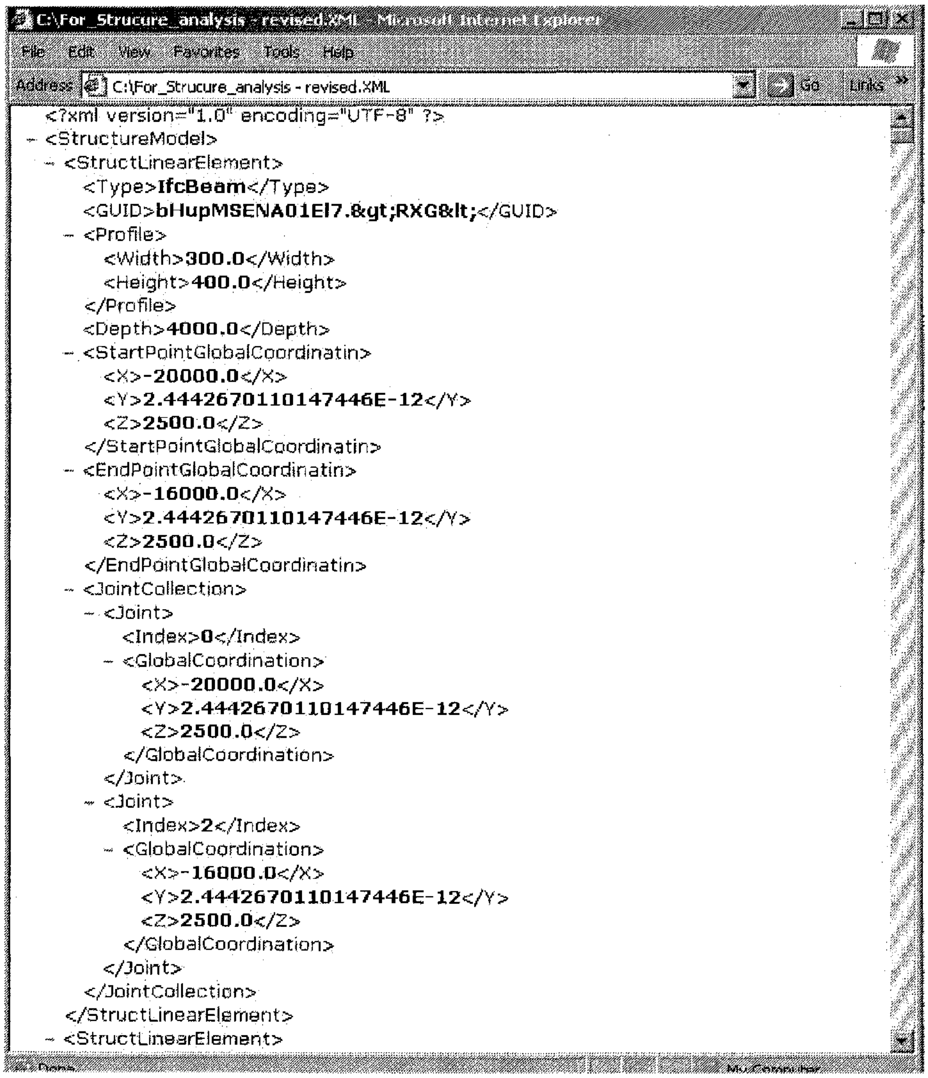


Figure 8.10 Definition of Beam#2138 in XML File

```
JOINT
  1    x =-20000.0    y = 2.4442670110147446E-12      z = 2500.0
  ...
  3    x =-16000.0    y = 2.4442670110147446E-12    z = 2500.0
  ...

FRAME SECTION

  NAME=1    SH=R    T=400.0, 300.0    MAT=CONCRETE
   ...

FRAME
  1    J=1, 3    SEC=1
   ...
```

Figure 8.11 Related Structural Information for Beam#2138 in S2K File

Table 8.2 contrasts the different definitions of related information for Beam#2138 in IFC file, by StructLinearElement class, and in XML file respectively (Figure 8.8, Table 8.1, and Figure 8.10). The expression in S2K file is not covered in this table because this part of information directly comes from XML file without any change. It can be seen that the basic information of the beam, such as GUID, element type, and profile information, is extracted and saved in a consistent way during the whole course. However, the values of GUID have some minor differences in XML format. This is because some symbols are reserved for a certain format, such as "<" and ">" symbols to XML format. Therefore, modification is needed for these symbols. The information of element's joints is deduced from the Representations and LocalPlacement of IfcBeam in the IFC definition according to the algorithm described in Chapter 7.5.4.1. Although Table 8.2 cannot show the correctness of deduction, it can be basically illustrated from the 3D model constructed (Figure 8.9). Therefore, it can be concluded that the architectural definition for Beam#2138 has been successfully transformed to its corresponding structural element. The topological information of structural element is accurately deduced from the beam's geometry information. The information and data transformation during the whole process is thus found to be consistent and accurate.

Table 8.2 Comparison of Three Definitions for Beam#2138

IFC Definition		StructLinearElement		XML Definition	
Attribute	**Value**	**Attribute**	**Value**	**Element**	**Value**
GUID	bHupMSENA01E17.>RXG<	GUID	bHupMSENA01E17.>RXG<	GUID	bHupMSENA01E17.>RXG<
Representations: IfcProductDefinitionShape (#3012): IfcAttDrivenExtrudedSolid: Depth	4000	depth[ ]	(4000.0, 0.0,0.0)	Depth	4000
Label *(Entity Name)*	Beam#2138 *(IfcBeam)*	type	IfcBeam	Type	IfcBeam
Representations:- IfcRectangleProfileDef (#3002)	XDim: 400 YDim: 300	RectangProf: -Heightwidth	(300.0, 400.0)	Profile (Width & Height)	300.0, 400.0
No directly definitions for element's joints. All are deduced from the information of Representations and LocalPlacement.		startPoint	(-20000.0, 2.4442670110147446E-12, 2500.0)	StratPointGlobalCoorination	(-20000.0, 2.4442670110147446E-12, 2500.0)
		endPoint	(-16000.0, 2.4442670110147446E-12, 2500.0)	EndPointGlobalCoordination	(-16000.0, 2.4442670110147446E-12, 2500.0)
		vecJoints	Two instances of StructJoint	Joint Collection	Two Joint elements
		StructJoint: Index	0	Joint: Index	0
		StructJoint: location	(-20000.0, 2.4442670110147446E-12, 2500.0)	Joint: Global-Coordination	(-20000.0, 2.4442670110147446E-12, 2500.0)
		StructJoint: Index	2	Joint: Index	2
		StructJoint: location	(-16000.0, 2.4442670110147446E-12, 2500.0)	Joint: Global-Coordination	(-16000.0, 2.4442670110147446E-12, 2500.0)

8.3 Case Study II: Erection of a 2-storey Corner Terrace Dwelling House

The second example is a proposed project to erect a 2-storey corner terrace dwelling house with an attic. This case aims to illustrate the process of inputting additional structural information and how to use it to perform the structural analysis, as well as the integration with structural analysis applications.

In this case, it is assumed that the architect uses ArchiCAD to perform the architectural design and export the IFC 2.0 file for the house (Figure 8.12). After finalising the architectural design between architect and structural engineer using the same procedures as in Case 1, the engineer can begin the work for structural analysis. As the message shows in Figure 8.6, except for the choice to download IFC file and XML file, engineer can choose to continue the work of structural analysis. After the click on "Other Operations", a new JSP page is connected with five buttons which represent the five different kinds of online services provided to structural engineer (see Figure 8.13). These services include: (i) defining material properties, (ii) assigning loads, (iii) exporting S2K file, (iv) uploading and saving the structural analysis results, and (v) viewing the whole model.

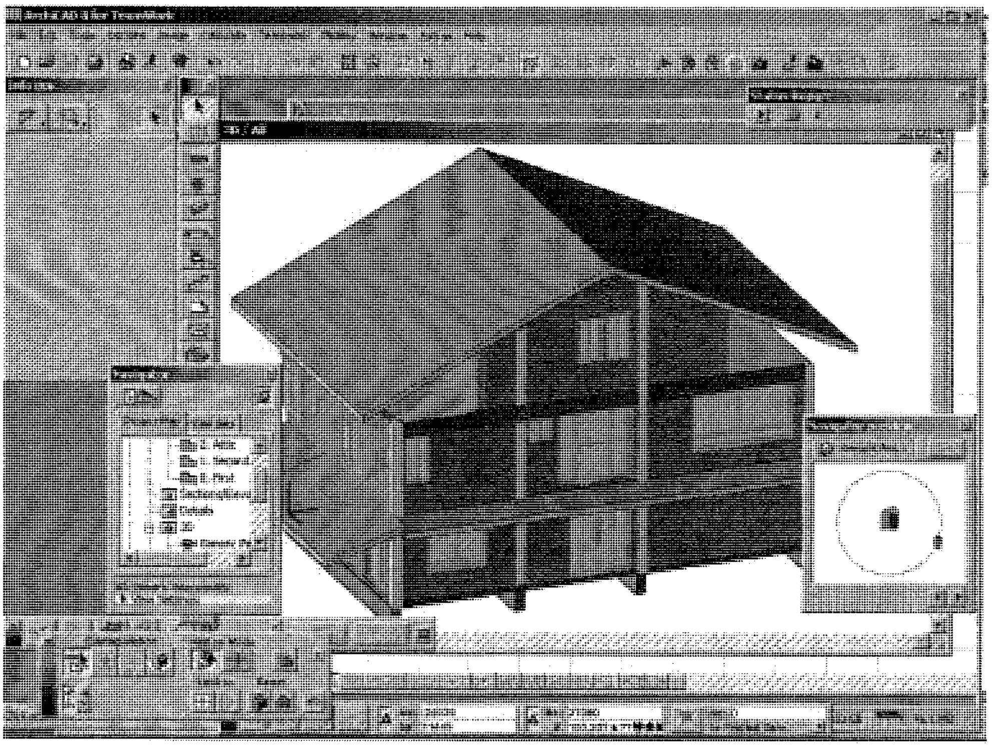


Figure 8.12 Architectural Design in ArchiCAD

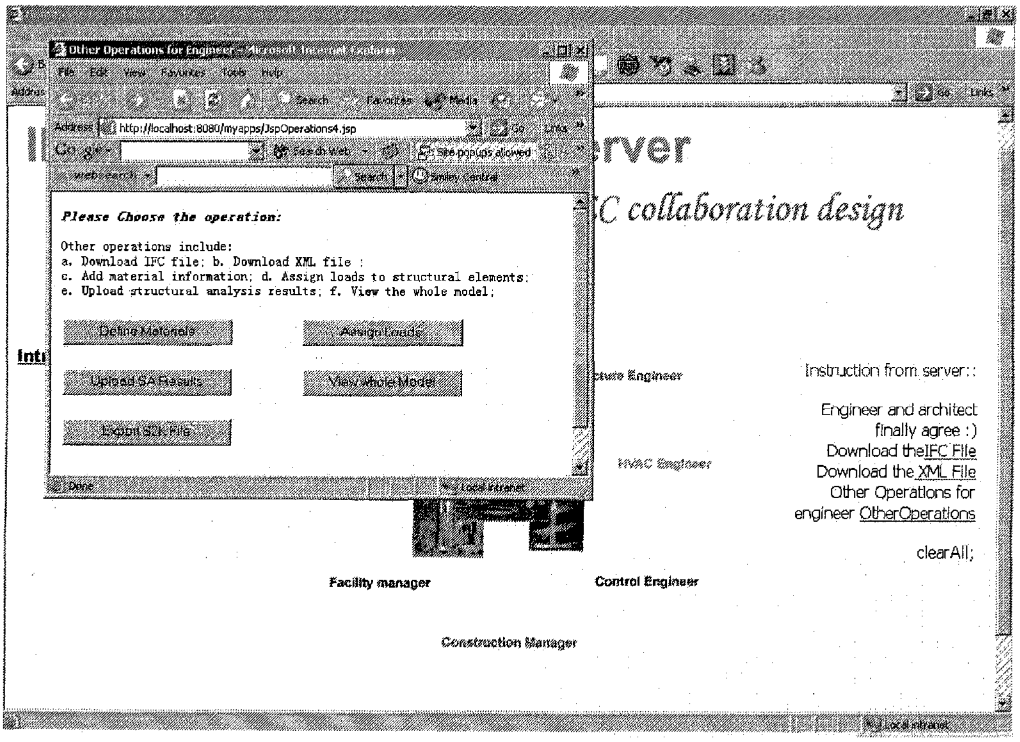


Figure 8.13 Screenshot of JSP Page for Engineer's Operations

8.3.1 Defining Material

For the purpose of structural analysis, the properties of the material need to be defined. By clicking on the "Define Material" button (Figure 8.13), a window is popped up for the engineer to input the properties online. As shown in Figure 8.14, a type of concrete material named "Cont1" is defined. The material information is then saved to sever and later used to export SAP2000 compatible files. It should be noted that the choices of material types are provided. It reflects the new attribute MaterialType extended to IfcMaterial (Figure 6.14). Although the structural engineering softwares usually provide two choices of isotropic and orthotropic to the value of MaterialType, here the choices are decomposed to more detailed level, such as concrete and steel etc., which aims to provide more convenience to the engineer. For each choice, the default values of the material properties are given.

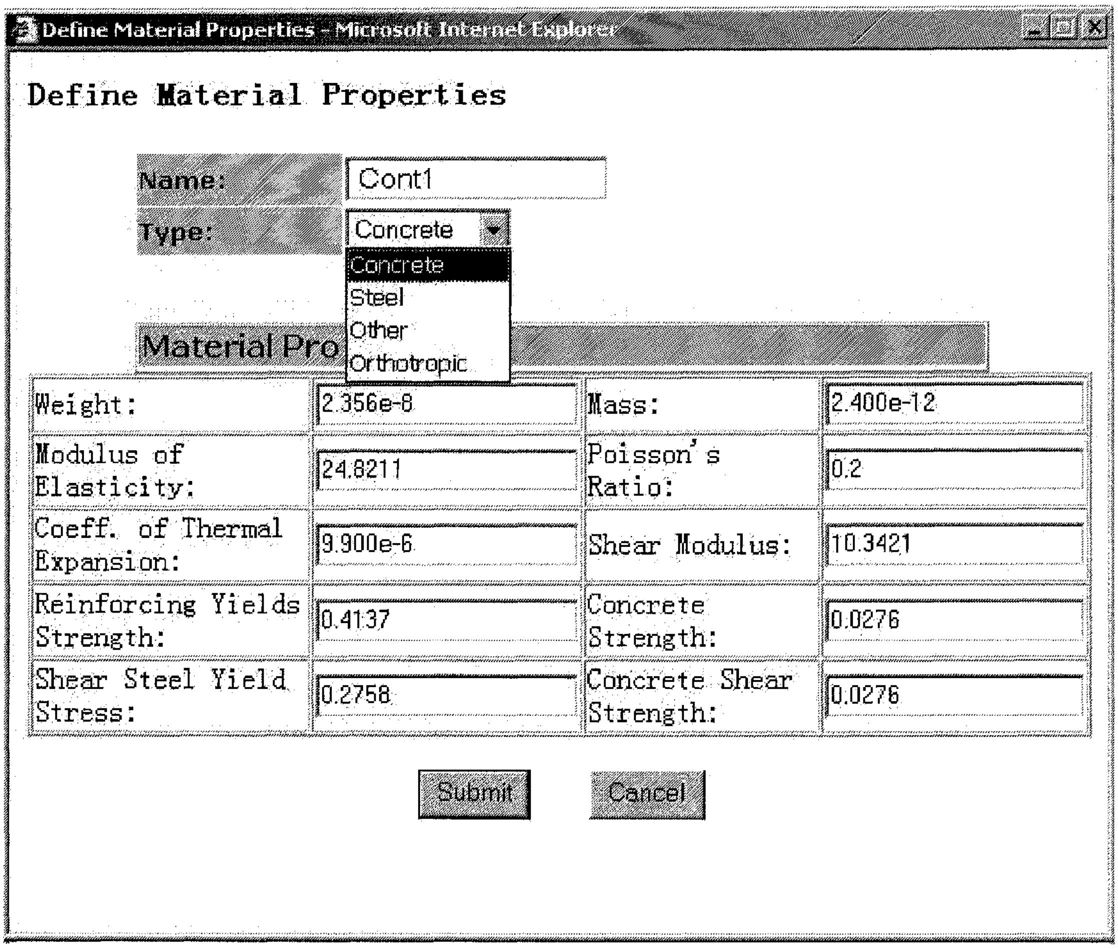


Figure 8.14 Define Material Properties

8.3.2 Assigning Loads

With a Java 3D enabled browser, any structural analysis models generated by the prototype from architectural IFC files can be displayed. The engineer can select elements to assign member static loads or joint loads. Figure 8.15 shows the 3D structural analysis model and one of interface for assigning the load to the selected element through a browser.

Structural Idealization Model

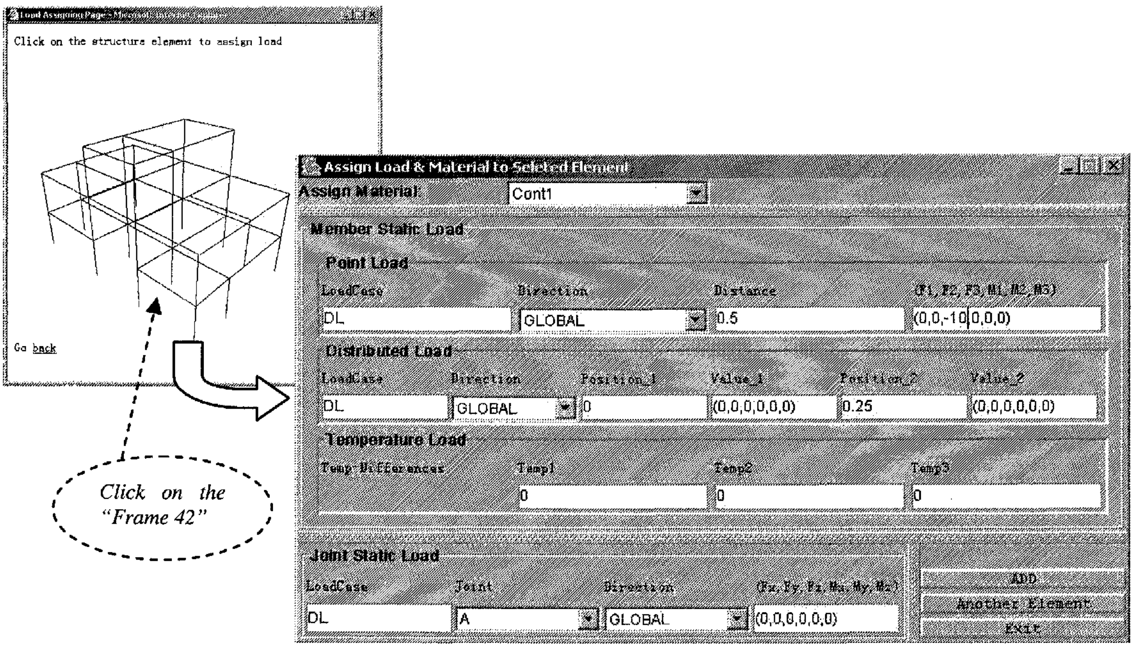


Figure 8.15 Selecting Element and Assigning Loads

As shown in Figure 8.15, after the engineer clicks the beam (which is named as Frame 42), a JFrame is popped up to let the engineer enter the information for loads. In this frame, four primary types of static loads are listed, namely point load, distributed load, temperature load and joint static load. The engineer can input the value for a certain load type and keep the default value of zero for those load types which have no inputs. In this figure, it can be seen that a point load is added to the selected element. The relative distance equals 0.5 which means the load is acted at the middle position of this beam element. Its value is minus 10 for "F3" and "Direction" is GLOBAL. That represents 10 units of force is applied in the negative direction of axis Z in global coordinate system.

8.3.3 Exporting S2K File

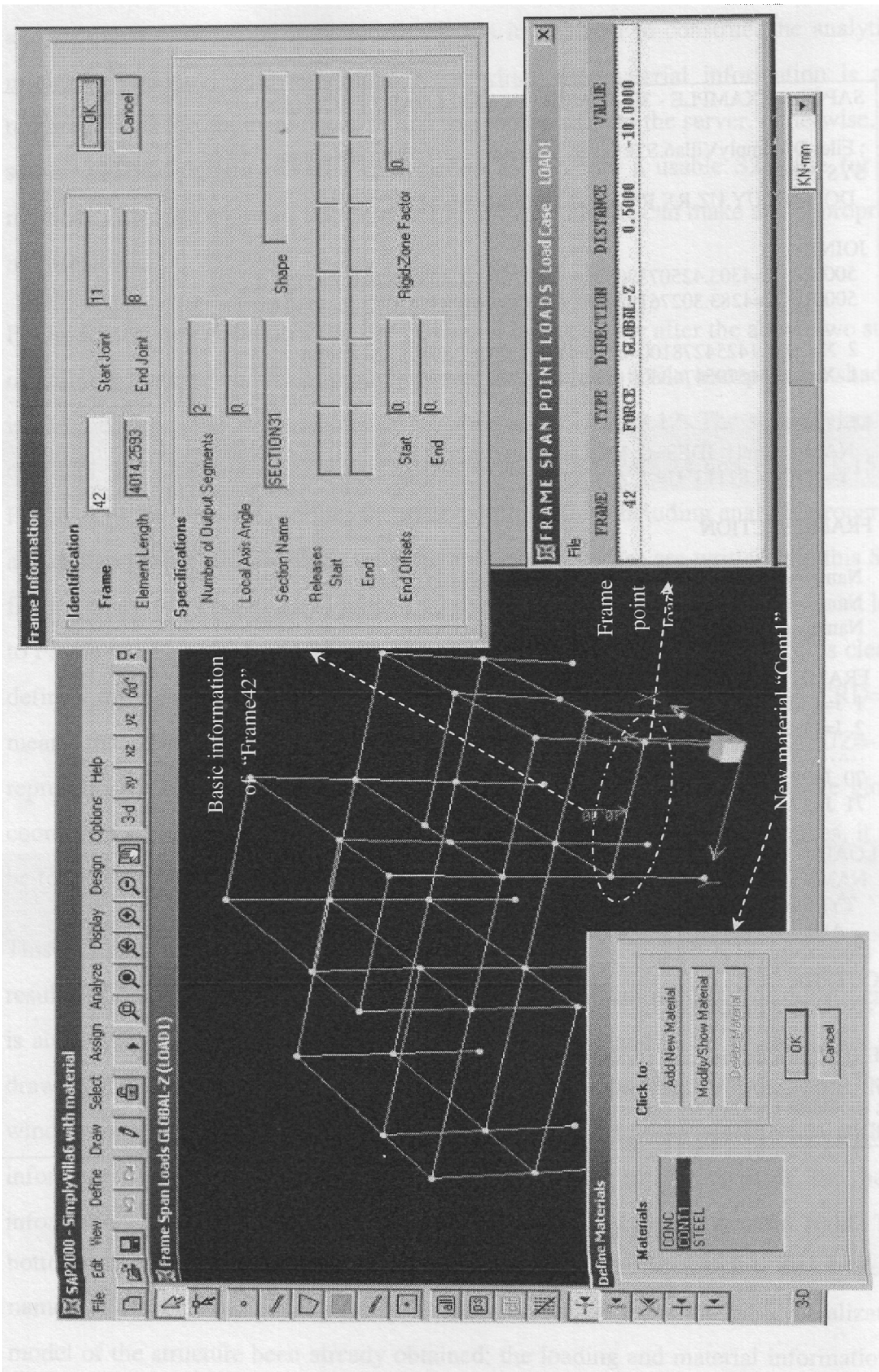
As the application adaptor, the server will provide engineer the application compliant file in order to lighten the work of engineer for structural analysis. If the engineer does not define the material properties or assign the loads, only geometry information and sectional information is included. That is insufficient to construct the analytical model in structural analysis software for which the material information is also required. Thus the engineer needs to add this information to the server. Otherwise, the server will use default material information to generate a usable S2K file for the moment. After the engineer imports the file to SAP2000, he can make any appropriate modification.

Figure 8.16 shows a sample S2K file generated by the server after the above two steps of defining material and load assignment. All the data in this file, except those shaded, is obtained from the architectural design shown in Figure 8.12. The shaded data are obtained from the engineer's input to the server in Figure 8.14 and Figure 8.15. In Figure 8.14, the engineer defines the material properties, including analysis properties and design properties. Currently only the analysis properties are written into this S2K file for analysis purpose. And Figure 8.15 shows that the engineer assigns a point load to Frame 42. Therefore, in S2K file, the part of load information is added. It is clearly defined through "ADD=42" to stand for the load is added to Frame42. "RD=.5" means the relative distance of action is at the half length of element. "UZ=-10" represents 10 unit of load is acted at the negative direction of Z axis in the global coordinate system. Comparing these three figures and investigating the values, it can be found that the values are accurately saved and written into S2K file.

This S2K file can then be imported to SAP2000 directly. Figure 8.17 represents the result of importing the S2K file. In SAP2000, the idealization model of the structure is automatically generated. The engineer saves the time and effort on idealizing and drawing the model. He can do any modification on it as he wants. Furthermore, three windows are also provided in Figure 8.17 to show the reloading of material and load information defined through online services. On the top right, it is the basic information of Frame42 and the load table is displayed on the bottom right. The bottom left is the window for defined materials. It can be seen that a new material named "CONT1" has already been loaded and not only has the basic idealization model of the structure been already obtained; the loading and material information is also imported.

```
SAPCON EXAMPLE - 3D FRAME - STATIC LOADS - ACI318-89

; File  D:\SimplyVilla6.S2k saved 13/1/2005  15:7:59  in KN - mm
SYSTEM
  DOF=UX,UY,UZ,RX,RY,RZ   LENGTH=mm FORCE=KN

JOINT
  500023  X=4303.425073905688  Y=4136.102403158708  Z=5750.0
  500016  X=4283.30276153106  Y=4135.761285761072  Z=5750.0
  ......
  2  X=2931.1425427810045  Y=4133.722308369695  Z=2750.0
  1  X=8459.157954743609  Y=4143.1238424485555  Z=2750.0

MATERIAL
   NAME=Cont1  IDES=C  M=2.400E-12  W=2.356E-08
    T=0  E=24.82113  U=.2  A=9.9E-06

FRAME SECTION

  Name=section1 MAT=Cont1 SH=R T=300.0,300.0
  Name=section13 MAT=Cont1 SH=R T=300.0,200.0
  Name=section31 MAT=Cont1 SH=R T=250.0,500.0

 FRAME
  1  J=13,500013 SEC=section1
  2  J=11,500011 SEC=section1
  ......
  70  J=28,30 SEC=section31
  71  J=27,30 SEC=section31

LOAD
  NAME=LOAD1  SW=1  CSYS=0
   TYPE=CONCENTRATED SPAN
    ADD=42  RD=.5  UZ=-10

OUTPUT
 ; No Output Requested

END; The following data is used for graphics, design and pushover analysis.
; If changes are made to the analysis data above, then the following data
; should be checked for consistency.
END SUPPLEMENTAL DATA
```

Figure 8.16 Case II Exchange S2K File Fragment


SAP2000 - SimplyVilla6 with material
File Edit View Define Draw Select Assign Analyze Display Design Options Help
Frame Span Loads GLOBAL-Z (LOAD1)
Frame Information
Identification
Frame 42
Element Length 4014.2593
Start Joint 11
End Joint 8
Specifications
Number of Output Segments 2
Local Axis Angle 0
Section Name SECTION31
Shape
Releases
Start
End
End Offsets
Start 0
End 0
Rigid-Zone Factor 0
OK
Cancel
FRAME SPAN POINT LOADS Load Case LOAD1
File
FRAME TYPE DIRECTION DISTANCE VALUE
42 FORCE GLOBAL-Z 0.5000 -10.0000
KN-mm
Basic information of "Frame42"
Frame point load
New material "Cont1"
Define Materials
Materials
CONC
CONT1
STEEL
Click to:
Add New Material
Modify/Show Material
Delete Material
OK
Cancel

8.3.4 Uploading and Saving SA Results

Sometimes users from different design disciplines need to view the results of structural analysis. Or other engineer may want to check the results and investigate the structures of buildings. After performing structural analysis, the server allows the engineer to upload the outputs through Internet and saves in the server's repository. Currently, only Access database file is allowed which is applicable for SAP2000. The uploading process is very similar as the uploading of IFC files by architect. The server can extract and save the analysis and design results, and then provide for other project participates to query and view.

8.3.5 Viewing Whole Model

The online services allow the engineer to query and view the structural analysis results for the whole structural model. Similarly as in "Assign Loads", the structural analysis model is displayed to user through a Java 3D enabled browser. The user can select the element concerned and its related information will be extracted and shown online by the server through a browser (Figure 8.18).

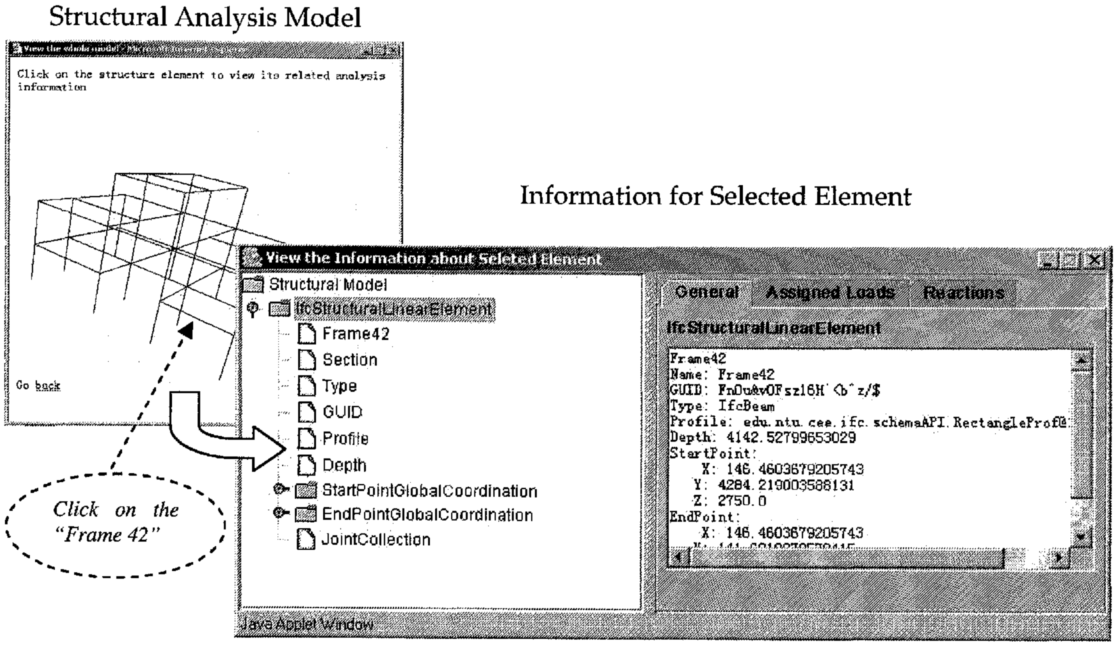


Figure 8.18 Viewing Structural Analysis Information

8.4 Assessment of Prototype's Implementation and System Architecture

Through the two case studies carried out in previous section, the functionalities of the IWIBD system have been demonstrated. It shows the feasibility and practicability of the collaboration between architects and structural engineers. The first case tests the interoperability with architectural design, the user interface browsing and editing capabilities. The useful information for structural analysis in architectural design is extracted and automatically translated to structural information. The second shows the interoperability with structural analysis and design software. The data exchange and sharing between two different disciplines and different applications based on IFC models is successfully executed. In addition, through the investigation on the processes of data transformation, the information is proven to be transformed and transferred accurately and consistently.

Furthermore, it proves the capability of IFC models to allow project participants to share project information across different application packages and building upon existing data, while eliminating the inefficiencies and inconsistencies associated with conventional practices of data re-entry. It must be stressed that the focus of the implementation is not to develop software with features already available in commercially available software. The focus is rather to implement a web-based integrated prototype application that is capable of exchanging and transforming data based on IFC standard models.

With respect to level of integration, there are three stages identified on the way to a full integration: data exchange, data integration and process integration (Sun and Lockley, 1995). Data exchange is the first stage where design tools still operate independently. At this level, data can be exchanged between the tools when the user decides to do so. The next target is to carry out the data integration where several design tools are incorporated into one system. Each tool interacts with this model when invoked by the system, and the interaction between the tool and the model is seamless. The highest level of integration is process integration when the system will have sufficient knowledge on the built environment and the design process, which is used to provide intelligent support to designers. In this research the lowest level of integration, data exchange, has been implemented.

The model-based system and architecture combine both data interoperability and system integration. Interoperability is defined as the ability for tools to exchange data, and it offers one solution to the problem of integration. Integrated system is defined as multi-purpose tools that combine many different views (both data and functionality) (Froese, 2003). With interoperability, it is difficult to manage the collective body of information since each tool works with only a limited view in its specialized domain. Furthermore, the "business logic" associated with each view resides in different tools and cannot interact. This would be possible within integrated systems, yet no integrated system can support all the views and users required for an AEC/FM project. It would be difficult to impose one specific system on all projects users, or to enter all the necessary information within one tool. Therefore, the IFC-based integrated system is one general and better effective solution for the integration. The interoperability is provided by the adoption of IFC, a standard data model approach. Through the integrated system, existing applications are able to exchange information through the data exchange standards, while new integrated tools are used for overall information management and functional integration.

Although only two disciplines and two kinds of applications are involved in current prototype implementation, the concept of model-based integrated system has been successfully validated. It not only provides a platform for the information exchange between different users. It also incorporates the information transformation into information exchange which is its special feature. It implements the real integration and shows that the structural model can be derived programmatically from architectural model. The use case, Architectural design ← → Structural analysis and design is carried out in this integrated system which is not fully considered in other existing IFC – related collaborative implementation projects, such as BLIS, Intelligent Services and Tools for Concurrent Engineering (ISTforCE), eConstruct, VERA, iCSS, CORNET, and so on. For example, the use cases supported for the project BLIS include: Architectural design ← → HVAC design, Arch/HVAC Design

→ Quantities take off / cost estimating, Arch/HVAC Design → Thermal load calculations / HVAC system design, Arch/HVAC Design → Construction management/scheduling (BLIS, 2002).

In order to summarise the benefits of web-enabled integrated system, the integrated system with conventional practice with respect to the organization of the project team, quality of design, decision support, information sharing, and project collaboration is compared in Table 8.3.

Table 8.3 Comparison between Conventional Practice and the IFC-based Integrated Building Design System

	Conventional Practice	IFC-based Web-enabled Integrated Building Design (IWIBD) System
Information sharing	Paper-based or electronic-based without interoperability, transmittal through postal delivery, facsimile, or e-mail	Product modeling approach using IFC interoperability standards and XML
Design quality	Design according to code requirements, personal experience, rules of thumb Redundancies in the design due to simplification of loads and assumptions	Dynamic analysis engines, and automated production of structural information
Project collaboration	Collaboration occurs in meetings with static drawing sets and light-tables	The project team worked with a "live" product model and related visualizations in meetings

Traditionally, design drawings, technical specifications and standard forms of contract are all paper-based documents which provide formalised methods of communication. By using the IFC-based web-enabled integrated building design (IWIBD) system, the performance is improved in terms of the time saved during communication, the accuracy of data-reentry, standardised paper-based models, and the cost saved on documents.

For the end user allowing data exchange by neutral files and eventually via a central database where all common data is stored; this represents essentially a gain in time and quality because the time-consuming and error-prone task of re-entering data in an application is eliminated or at least minimised. For example, it could also mean the possibility of more time in studying and comparing several solutions at the design stage. The benefits of IFC-based integrated system are summarized in terms of quality, costs, risk, and time in Table 8.4.

Table 8.4 The Benefits and Respective Examples Resulting from the IFC-based Web-enabled Integrated Building Design System

	Benefits	Example
Quality	Improved accuracy and quality	Minimized data re-entry
	Avoiding mistakes	All information is always up-to-date and instantly available. There is no longer any risk that team members are acting on information that is out of date, or incomplete.
Time	Increased speed of communication	Faster generation of project solutions
	Avoiding delays	Do not have to wait for the arrival of updated drawings
	Shorter lead-time on tasks	Save time in the query and approval process
Cost	Reduced errors and rework costs	All paper reports are sent on electronic form via the web.
	Minimized paper reports	The cost of hardcopy production, distribution and storage is reduced.
Risk	Higher reliability during the information exchange and sharing	IFC provides a standard interoperability approach

This kind of system synthesizes the advantage of IFC model to improve the information quality and the advantage of Internet to speed information communication and support distributed operations. The information transformation is also incorporated into the system which increases the accuracy of information transfer and reduces the errors caused by human translation. Table 8.4 has shown that the system is potentially able to save the cost and time, improve the design quality and decrease the risk by the application of an IFC-based web-enabled integrated system. They are able to achieve this saving or improving through the following means:

1. The use of IFC models eliminates the inefficiencies and inconsistencies associated with conventional practices of data-reentry. It minimizes data re-entry and improves accuracy and quality. The integrated communication process promotes more accurate information transfer as illustrated by the description in section 8.2.4. Through the speedy and accurate transfer of information, the efficiency is improved. Efficiency and accuracy allows the project team to explore more alternatives early in the project and conduct life-cycle analyses to help choose the best alternative.

2. The errors during information transfer are decreased because the structural information is directly deduced from architectural design. In addition, mistakes are avoided because the relevant information is always up-to-date and instantly available. There is no longer the risk that team members would be acting on information that is out of date, or incomplete.

3. The time in the structural idealization process is saved by generating the idealized structural model on server. And the drawing time is also saved by providing the application compliant input to the engineer.

4. Even compared with the email attachment, the speed and quality of communication is also improved. The integrated system is open for all participants which have the rights to download required information from the same database. From one database, the information always keeps up-to-date and the consistency of information can be made sure when different participants require the same part of information. It can be guaranteed that the same information is transferred to different participants. The

errors caused by the misoperation or omission during sending more than one email with attachments are eliminated. And the amount of sending email is decreased. Possibly before the engineer needs to send the same document to different parties by different emails, but now what he needs to do is only to upload the file to the server once.

5. The using of network technologies substantially increases the speed of communicating which results in shorter lead-time on tasks. And expedited design coordination results in faster generation of building solutions.

6. Because of the time saved on some no value-adding works (e.g. drawing etc.) and the improved design accuracy, some of the engineer's efforts can be shifted from producing traditional outputs (e.g. construction drawings) to more value-adding work (e.g., buildability or value engineering studies).

7. As any other electronic data interchange system, the direct cost on communication is saved through the Internet as compared to phone calls or courier services as well as the decrease on hardcopy production and the reduction of distribution and storage for paper work. In addition, the much greater savings are potentially achieved through reduction in mistakes and reworks and by the increased accuracy of communications.

Although communication problems have been basically addressed through the above evaluation, the current prototype implementation for integrated building design system over the web has its weaknesses. For example, currently the communication is by the way of document-based exchanges. Initially, the exchange of IFC-based files was satisfactory. As the extension of system, an integrated database management system would be needed to provide a better environment for exchanging data.

8.5 Summary

In this chapter two case studies are carried out to illustrate the process of the collaboration and data exchange between architects and engineers. They demonstrate the feasibility and capabilities of generating and exchanging design information with

IFC extensions, as well as providing online services to maximize the interoperability and re-usability of design objects.

In addition, the process of information transform and transfer is also illustrated through the investigation of generated data in different running phases, i.e. in IFC file, in running program of background, in XML file, and in S2K file. Thereby, the consistency and accuracy during information transfer is proven.

The prototype implements the developed process and data models in the context of distributed, model-based, integrated system architecture. Via the services provided by IFC-based web-enabled integrated building design (IWIBD) system, the performance of architectural and structural design activities is improved in terms of the time-saving during communication, the accuracy associated with conventional practices of data-reentry, standardised paper-based models.

Chapter 9 Conclusion and Recommendations

Building design is a process which involves diverse parties having different professional skills and interests. Yet the process requires that these parties co-operate and exchange information in order to complete the building project. This research aims to improve the communication and inter-operation among different participants during building design process, mainly between architect and structural engineer. The research attempts to change the traditional "human-interpreted" communication, decrease the amount of misunderstanding or loss of the information during transfer and minimise the rework in design. This concluding chapter provides a brief summary and discusses some key features of the research. Furthermore, certain limitations of the research and directions for future works are discussed.

9.1 Conclusion

In this research, an IFC-compliant information model for building design processes and an integrated building design system are developed. IFC standards and models act as the common language of the integrated system for information exchange and sharing. It assessed the capability of IFC to support the integration of structural analysis and architectural design and necessary extensions are developed as the supplement for models. Whereafter, the framework for an IFC-based web-enabled integrated building design system is proposed that would allow engineers and users to easily access a model server and exchange design information. A prototype system is also developed and implemented to carry out the inter-operation and integration between these two domains.

This research shows that it is feasible and effective to integrate architectural design and structural analysis. The development opens up the possibility of exchanging and sharing interoperable information throughout the building lifecycle. The whole processes of research, including the information modeling, assessment of IFC standard models and development of the integrated system, also applies to and can be expanded to other domains till the full integration and inter-operation during the building lifecycle is achieved. The primary contributions lie on the following three aspects as described below.

a. Introduction of the Process-oriented Information Modeling (PoIM) Methodology

The first contribution of this research is the introduction of the process-oriented information modeling (PoIM) methodology. It is proposed as a new approach to analyze information requirements and develop IFC extension models in order to improve the effectiveness and efficiency of information requirement analysis. The initiative of PoIM is to find an effective and easy-to-use methodology to carry out information requirement analysis and get a general information flow and models for structural analysis and design processes for the benefit of the information sharing in building design process. This methodology is an integration of process models and information models. Through this methodology, the information requirements can be easily identified and analyzed through the corresponding process models. All the information is process-related. The model is generic, not tied to any specific design process model and is intended to characterize the flow of design information. In addition, a set of standard transformation procedures and mapping tables is also designed to help the modeller quickly and easily identify elements, corresponding information, and relationships. The mapping tables aim to provide a clear picture of information.

In addition, the new process for development of IFC extensions based on the methodology is also proposed in this research. The information requirements are extracted through this methodology and used to develop IFC extensions, which are then used for the integrated system development.

In this research, this methodology is later used to capture and identify the information requirements for the comparison and mapping with IFC models. The comprehensiveness of the IDEF0 and IDEF1 enhancements as well as the use of proposed transformation procedures and mapping tables is shown in this application. The simplicity and consistency of the methodology are also demonstrated.

The value and benefit of this methodology is that it can contribute towards the development of the industry and enhance knowledge for further academic research. From an industry users' viewpoint, this methodology provides an effective and easy-to-use approach to develop reusable models for information analysis and planning in the sub-domain of building design process. From an academic viewpoint, the research develops a methodology to integrate process model with information model.

b. Assessment of IFC Models for Structural Analysis Domain and Contribution to the Effort in Establishing Industry Standard

The structural analysis domain knowledge was just incorporated into the Release IFC2x Edition 2 in May, 2003. At the time of that, this research was carried out. There has not been any well-documented assessment and validation of how well the IFC models can support structural analysis. No structural analysis and design software provides the support for IFC models to date. This gap is intended to be filled in by this research.

The assessment of IFC models for structural analysis is conducted from two levels and perspectives. The information requirements from these two different perspectives are analyzed and modelled by the proposed PoIM methodology. First, a generic and conceptual model, i.e. not limiting to any specific analytical method, or structural type, is developed with the knowledge gathered from professionals. It concentrates on the information that flows among individual design activities regardless of the activities' sequence and requirements. Secondly, at a much detailed level, the requirements of structural analysis software are modelled. In this research SAP2000 is used for such purposes. Subsequently the capability of current IFC models to support structural analysis is evaluated through the comparison between requirements and IFC extensions.

Basically the current IFC models are enough to support the requirements of an engineer to do structural analysis at the conceptual level. Most of information needed by SAP2000 to do structural analysis can also be explicitly supported by the current IFC models. However, IFC models still do not capture explicitly and provide a representation for some information, such as prestress load and types of load combination etc. In order to confirm whether it is necessary to change current IFC schema, a generality study is carried out by investigating ten different popular structural engineering softwares in this research. It shows that some gaps are not limited to SAP2000 and are considered as "commonly missing" for structural analysis. The appropriate extension approach is then selected and some suggestions on development of IFC extensions for these information gaps are proposed in the research to complement the standards.

As a whole, the key issues addressed in this research attempt to solve the main obstacles for the development of an IFC-based integrated building design system. First, the capability of IFC models to support structural analysis at multiple levels of detail is thoroughly assessed. Secondly, the assessment from the requirements of the softwares currently available in market are helpful in solving the difficulty in data communication from one program to another which is resulted from the absence of standardization and the lack of coordination among software developers.

c. Development of IFC-based Web-enabled Integrated Building Design (IWIBD) System

An IFC-based web-enabled integrated building design (IWIBD) system is designed and its prototype system is implemented. A model server is developed to support both IFC-based data integration and transaction-based interoperability between architectural design and structural analysis processes by taking advantage of the Internet, distributed computing and other advanced computing technologies. An overview of the requirements, architecture and modular design for this integrated system is provided. The prototype implements the developed processes and models in the context of distributed, model-based, integrated system architecture.

Two case studies are carried out to demonstrate the capabilities of generating and exchanging information with IFC extensions, as well as providing online services to maximize the interoperability and re-usability of design objects. The first case is used to illustrate the interoperability with architectural design, the user interface browsing and editing capabilities. The useful information in architectural design is extracted and automatically translated to structural information for structural analysis. The second case shows the data transfer to, and interoperability with structural analysis and design software. The data exchange and sharing between two different disciplines and different applications based on IFC models is successfully executed.

In addition, the process of information transformation and transfer is also illustrated through the investigation of generated data in different running phases, i.e. in IFC file, in running program of background, in XML file, and in S2K file. Thereby, the consistency and accuracy during information transformation is achieved. The efficiency of design process can be improved by using the network technology. And Java technology has been proven to be suitable to offer the desirable functionalities required by the collaboration design process. It not only provides a platform for the information exchanging between different users like other systems, but it also incorporates the information transformation into exchange, making it the most advanced feature of this system. It shows that the structural idealization model can be derived directly from the architectural model.

The platform provides a means of integrated services in a modular and systematic way. The application is not just limited to the building design processes and similar scenarios can be generated for various processes in the whole lifecycle. By introducing a standard data representation and a modular infrastructure, every component of the system can be added or updated without substantial amount of modification to the existing system. The utilization of standard data representation (XML) and the deployment of the Internet for delivering data is another factor that makes the system flexible and extendible.

With regard to the level of integration, it implements the combination of data interoperability and integrated systems. As mentioned in last chapter, the lowest level of integration, data exchange, has already been implemented. The current system provides the foundation for the implementation of data integration, especially for structural analysis domain and structural analysis applications. Basically, all related structural information has already been processed and saved on current system. It also is a starting point to move to higher level of integration. By developing an interface between the structural design tools and the system, the data integration with structural design will be achieved.

9.2 Limitations of the Research

As described in previous section, this research has basically fulfilled its goals for a feasible development of an IFC-based collaboration framework to integrate architectural design and structural analysis. However, there are still a number of issues that must be addressed.

9.2.1 The Scope

The focus of the research is on the information exchange between CAD design and structural analysis. It is only the start of the research on integration of structural analysis and architectural design. More research on more complicated structures and structural analysis results need be studied. The structural model tested only include the column and beam. The integration with other structural elements and building design processes has not been considered.

9.2.2 The Evolving of IFC Standard and Models

The major hindrances to utilizing IFC models for the implementation of a prototype system are the immaturity of the model and the lack, or limited availability of software tools that can facilitate rapid application prototyping. The IFC model is fast evolving and has good prospects for industry acceptance. With more and more IFC versions released, there may be incompatibility in exchanging data among different applications developed on different IFC versions.

9.2.3 Limitations of the System

Due to limited time and other resources, a prototype system is implemented to demonstrate the validity and concept of information exchange and sharing between architectural design and structural engineering domains based on IFC extensions in this research.

Although the prototype system demonstrates a very convenient and flexible way of information exchange and sharing, performance of the integrated framework remains to be a key challenge for the wide adoption of the integrated system for engineering practice. In conclusion, the limitations of proposed prototype system are:

- **Support to Latest IFC Release:** Currently, only the file in format of IFC 2.0 is accepted by prototype system due to the usage of IFCsvr R200. The development of IFCsvr Active X component has not caught up with the evolving of IFC models.

- **Data Storage in the Integrated System (File Transfer):** Presently, the data storage for structural analysis models primarily relies on file systems and the information is based on document-based exchanges. However, there are many intrinsic drawbacks associated with the direct usage of file system for storing large volume of data, because it does not support efficient random data-access, a query language to access the data in files or data integrity in the case of concurrent access.

- **Application–specific Input/Output:** Currently only the support for SAP2000 is provided by the prototypic system. Each application has its own specific disciplinary requirements and specific application view that requires an irreversible application-specific transformation. Undoubtedly as the developing of IFC standard models continues, structural analysis software will in future provide the functions for IFC models like some of the present CAD design software. When that time comes, the direct application-application communication can be considered.

- **Lack of Security Etc.:** The proposed prototype system only provides a simple mechanism to identify users and projects, and to enforce access control. That is why only one user can access the server at a certain time. Since an integrated system should generally support multiple software services and a number of users, the authentication of these parties and the security of the communication are important to guarantee the integrity of the system.

9.3 Future Directions of the Research

There are many possible research and development works based on this research. First, the scope of the information modeling and IFC model assessment can be expanded to include other building design processes through the whole building lifecycle. The methodology can be further optimized upon the expansion. Next, the new extensions and some complex information gaps need further review. Finally, new research and developments are needed to further enhance the robustness and functionalities of the system framework. The following enlists a selected few of the research tasks that could be considered for future investigation.

9.3.1 Further Prospect of Methodology

Currently, the methodology uses enhanced IDEF1 as information modeling approach. As IFC extensions are finally expressed by EXPRESS-G and EXPRESS, the integration with EXPRESS-G and EXPRESS may be further studied in future based on existing process-oriented information modeling. It will make the methodology be more acceptable by IFC developers and more compatible to IFC extensions development.

Furthermore, tthe methodology is designed only for IFC model development. It can be extended to accommodate wider applications. Whether and how to connect this methodology with the standard product model development in an effective way could be topics of future research. Additionally, as the development of knowledge-based system, the modeling procedure could even be completed by a computerized integrated knowledge-based system, to provide the knowledge for identifying the modeling elements and their properties. It will overcome the major problems of manual generation of the information models and makes it easier, faster and more convenient for users to build the information models.

9.3.2 IFC Extension Development

After the assessment of several softwares, some new IFC extensions have been developed for the missing information for structural analysis domain. For those complex problems which are out of the current scope of information modeling and unsolved, continuing research work on the modeling and assessment based on the approach proposed in this research is needed.

9.3.3 Future Development of the Proposed Integrated System

The system is conceptually mature, but only tentatively implemented. The server is extensible and applies itself to an open collaboration environment for the whole building process. This is a very extensive and time consuming work which needs to be done in future. To fully achieve the integration of building design process, the following tasks could be carried out in the future.

1. Building up an IFC compliant database: Instead of directly using the file systems to store the data, an object-oriented database management system would allow certain structure for the saved data, allow the users to query and modify the data, and help manage very large amounts of data and many concurrent operations on the data.

2. Developing the interface to structural analysis program: The interface would allow structural analysis program to be incorporated into the central server as a compute engine. More than one structural analysis programs can connect to the server and perform different computation according to the requirements and preference of the engineer. Consequently, the data integration and process integration can be finally carried out. The research can go on and focus on the study for higher level integration until the full integration is achieved.

In addition, future study is recommended for extending the application to support the collaboration between other disciplines in AEC/FM. The principle of application is not limited to architectural design and structural design processes only. Similar scenarios can be generated for demonstrating data exchange for diverse processes in the whole life cycle. Further consideration of the security issues needs to be addressed in the network level. Ultimately the system can in future be developed into a generic purpose data management system for the whole lifecycle of building project instead of remaining as a data translation model server.

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- Chen, P.H., Wan, C. Y., Tiong, R.L.K., Ting, S.K., and Yang, Q. (2004), "Augmented IDEF1-Based Process-Oriented Information Modeling", Automation in Construction, Vol. 13, No. 6, November 2004, pp. 735-750.
- Chen, P.H., Cui, L., Wan, C. Y., Yang, Q., Ting, S.K., and Tiong, R.L.K. (2005), "Implementation of IFC-Based Web Server for Collaborative Building Design between Architects and Structural Engineers", Automation in Construction, Vol. 14, No. 1, January 2005, pp. 115-128. (SCI)

Conference Papers:

- Wan, C. Y., Tiong, R.L.K., Chen, P.H., Ting, S.K., and Yang, Q. (2003), "IFC-compliant Integration of Architectural Design and Structural Design", PDT Europe Conference, Manchester Conference Centre, UMIST, Manchester, 25-27 November, 2003.
- Wan, C. Y., Tiong, R.L.K., Chen, P.H., Ting, S.K., and Yang, Q. (2003), "A Framework for the Integration of Architectural Design and Structural Design", Conference: the Ninth East Asia-Pacific Conference on Structural Engineering and Construction, Bali, Indonesia, 16-18 December 2003.

Appendices

Appendix A: Database Structure of SAP2000

Table A.1 Constraints

CONSTRAINT	JOINT

Table A.2 Frames

FRAME	JOINT _I	JOINT _J	SEC-TION	LOCAL_ ANG	RELEASE _P	RELEASE _V2	RELEASE _V3	RELEASE _T	RELEASE _M2	RELEASE _M3	SEGM ENTS	IOFF-SET	JOFF SET	RIGID_ FACTOR	LENGTH

Table A.3 Joints

(for concrete)

JOINT	GLOBAL _X	GLOBA L_Y	GLOBAL _Z	RESTRAINT _U1	RESTRAINT _U2	RESTRAINT _U3	RESTRAINT _R1	RESTRAINT _R2	RESTRAINT _R3

(for steel)

JOINT	GLOBAL _Z	RESTRAINT _U1	RESTRAINT _U2	RESTRAINT _U3	RESTRAINT _R1	RESTRAINT _R2	RESTRAINT _R3	LOCAL _ANG_A	LOCAL _ANG_B	LOCAL _ANG_C

Table A.4 Shells

SHELL	JOINT_1	JOINT_2	JOINT_3	JOINT_4	SECTION	LOCAL_ANG	AREA

Table A.5 FrameProps

SEC-TION	MATE-RIAL	SHAPE	T3	T2	TF	TW	T2_BOT	TF_BOT	AREA	J	I33	I22	A2	A3	S33	S22	Z33	Z22	R33	R22

Table A.6 ShellProps

SECTION	MATERIAL	TYPE	THICK_MEMB	THICK_BEND	ANGLE

Table A.7 FramePointloads

LOAD	FRAME	TYPE	CSYS	DIRECTION	DISTANCE	VALUE

Table A.8 FrameDistLoads

LOAD	FRAME	TYPE	CSYS	DIRECTION	DISTANCE_A	VALUE_A	DISTANCE_B	VALUE_B

Table A.9 FrameGravityLoads

(for concrete)

LOAD	FRAME	CSYS	UX	UY	UZ

(for steel)

LOAD	FRAME	TYPE	CSYS	DIRECTION	DISTANCE	VALUE

Table A.10 FrameThermalLoads

LOAD	FRAME	TYPE	VALUE	PATTERN	MULTIPLIER

Table A.11 JointForceLoads

LOAD	JOINT	FX	FY	FZ	MX	MY	MZ

Table A.12 ShellGravityLoads

LOAD	SHELL	CSYS	UX	UY	UZ

Table A.13 ShellUniformLoads

LOAD	SHELL	CSYS	DIRECTION	VALUE

Table A.14 ShellThermalLoads

LOAD	SHELL	TYPE	VALUE	PATTERN	MULTIPLIER

Table A.15 ShellPressLoads

LOAD	SHELL	VALUE	PATTERN	MULTIPLIER

Table A.16 Materials

MATERIAL	E	U	A	WEIGHT	MASS	DESIGN	STEEL_FY	FC	REBAR_FY	FCS	FYS

Table A.17 Reactions

JOINT	LOAD	F1	F2	F3	M1	M2	M3

Table A.18 Displacements

JOINT	LOAD	U1	U2	U3	R1	R2	R3

Table A.19 FrameForces

FRAME	LOAD	STATION	P	V2	V3	T	M2	M3

Table A.20 ShellForces

SHELL	LOAD	JOINT	F11/22/12	FMAX	FMIN	FVM	M11/22/12	MMAX	MMIN	V13/23	VMAX

Table A.21 ShellStresses

SHELL	LOAD	JOINT	S11_BOT	S22_BOT	S12_BOT	SMAX_BOT	SMIN_BOT	SVM_BOT	S11_TOP	S22_TOP	S12_TOP	SMAX_TOP	SMIN_TOP	SVM_TOP	S13_AVG	S23_AVG	SVMAX_AVG

Appendix B: Information Modeling for Structural Analysis

B.1 Mapping Tables for the Structural Analysis by SAP2000

Table B.1 A32 Define Member Section Properties

IDEF0 Activity	IDEF0 Output	Corresponding IDEF1 Element	Relative Inputs & Control	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A321 Define frame sections	Frame section	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
			Material definition	Entity	Composition	Has-a (M:1)
A322 Define shell sections	Shell section	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
			Material definition	Entity	Composition	Has-a (M:1)

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Table B.2 A43 Assign Frame Static Loads

IDEF0 Activity	IDEF0 Output	Corresponding IDEF1 Element	Relative Inputs & Control	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A431 Assign gravity loads	Gravity load	Entity	Structural scheme design	Entity	Dependency	Based on
			Static load case	Entity	Dependency	M:1
A432 Assign point & uniform loads	Point load	Entity	Structural scheme design	Entity	Dependency	Based on
			Static load case	Entity	Dependency	M:1
	Uniform load	Entity	Structural scheme design	Entity	Dependency	Based on
			Static load case		Dependency	M:1
A433 Assign trapezoidal loads	Trapezoidal load	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
			Static load case	Entity	Dependency	M:1
A434 Assign temperature loads	Temperature load	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
			Static load case	Entity	Dependency	M:1
			Joint pattern	Entity	Dependency	Based on
A435 Assign prestress loads	Prestress load	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
			Static load case	Entity	Dependency	M:1
			Frame prestressing pattern	Entity	Dependency	M:1

Table B.3 A45 Assign Shell Static Loads

IDEF0 Activity	IDEF0 Output	Corresponding IDEF1 Element	Relative Inputs & Control	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A451 Assign gravity loads	Gravity load	Entity	Structural scheme design	Entity	Dependency	Based on
			Static load case	Entity	Dependency	M:1
A452 Assign uniform loads	Shell uniform load	Entity	Structural scheme design	Entity	Dependency	Based on
			Static load case	Entity	Dependency	M:1
A453 Assign pressure loads	Pressure load	Entity	Structural scheme design	Entity	Dependency	Based on
			Static load case	Entity	Dependency	M:1
			Joint pattern	Entity	Dependency	M:1
A454 Assign temperature loads	Temperature load	Entity	Structural scheme design	Entity	Dependency	Based on
			Static load case	Entity	Dependency	M:1
			Joint pattern	Entity	Dependency	M:1

Table B.4 A2 Set Up Structural Model

IDEF0 Activity	IDEF0 Output	Corresponding IDEF1 Element	Relative Inputs & Control	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A21 Define geometry of frame elements & assign related information	Frame element data	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
A22 Define location & orientation of shell elements	Shell element data	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
A23 Define location of joints and restraints	Joint data	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
			Frame element data	Entity	Non-specific	M:N
			Shell element data	Entity	Non-specific	M:N
A24 Assign other information to joints	Joint springs	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
	Joint masses	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
	Joint constraint	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on

Table B.5 A3 Define Properties

IDEF0 Activity	IDEF0 Output	Corresponding IDEF1 Element	Relative Inputs & Control	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A31 Define material properties	Material definition	Entity	Structural scheme design	Entity	Dependency	Based on
A32 Define member section properties	Member section	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
			Material definition	Entity	Dependency	M:1
A33 Define static load cases	Static load case	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
A34 Define joint patterns	Joint patterns' name	Attribute	NA	NA	NA	NA
A35 Define load combination	Load combination	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
			Static load case	Entity	Dependency	M:1

Table B.6 A4 Assign Properties

IDEF0 Activity	IDEF0 Output	Corresponding IDEF1 Element	Relative Inputs & Control	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A41 Assign member sections	Section assignment	Domain	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
			Member section	Entity	Dependency	Based on
A42 Assign prestressing pattern & joint patterns	Joint pattern	Entity	Joint pattern's name	Attribute	NA	NA
			Structural scheme design	Entity	Dependency	Based on
	Prestressing pattern	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code		Dependency	Based on
A43 Assign frame static loads	Frame static load	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
			Static load case	Entity	Dependency	Based on
			Joint pattern	Entity	Dependency	Based on
			Prestressing pattern	Entity	Dependency	Based on
A43 Assign joint static loads	Joint force	Entity	Structural scheme design	Entity	Dependency	Based on
			Static load case	Entity	Dependency	Based on
	Joint displacement	Entity	Structural scheme design	Entity	Dependency	Based on
			Static load case	Entity	Dependency	M:1
A44 Assign shell static loads	Shell static load	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
			Static load case	Entity	Dependency	M:1
			Joint pattern	Entity	Dependency	Based on

Table B.7 A5 Define Analysis Options

IDEF0 Activity	IDEF0 Output	Corresponding IDEF1 Element	Relative Inputs & Control	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A51 Define available DOFs	Degree of freedoms	Entity	Structural scheme design	Entity	Dependency	Based on
A52 Whether dynamic analysis	Dynamic parameters	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
A53 Set P-delta parameters	P-delta parameters	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
A54 Set output options	Output options	Entity	Structural scheme design	Entity	Dependency	Based on
A55 Compile Analysis Options	Analysis options	Entity	Degree of freedom	Attribute	NA	NA
			Dynamic parameters	Entity	Composition	Has-a
			P-delta parameters	Entity	Composition	Has-a
			Output options	Entity	Composition	Has-a

Table B.8 A7 Run Analysis

IDEF0 Activity	IDEF0 Output	Corresponding IDEF1 Element	Relative Inputs & Control	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A71 Review joint related responses	Joint reactions	Entity	Structural analysis model	Entity	Dependency	Based on
	Joint displacements	Entity	Structural analysis model	Entity	Dependency	Based on
	Joint spring forces	Entity	Structural analysis model	Entity	Dependency	Based on
A72 Review frame related responses	Frame element forces	Entity	Structural analysis model	Entity	Dependency	Based on
A73 Review shell related responses	Shell element forces	Entity	Structural analysis model	Entity	Dependency	Based on
	Shell element stresses	Entity	Structural analysis model	Entity	Dependency	Based on
A74 Compile Structural Response Model	Structural responses	Entity	Structural analysis model	Entity	Dependency	Based on
			Building design codes	Entity	Dependency	Based on
			Joint reactions	Entity	Composition	Has-a
			Joint displacements	Entity	Composition	Has-a
			Joint spring forces	Entity	Composition	Has-a
			Frame element forces	Entity	Composition	Has-a
			Shell element forces	Entity	Composition	Has-a
			Shell element stresses	Entity	Composition	Has-a

Table B.9 A0 Do Structural Analysis by SAP2000

IDEF0 Activity	IDEF0 Output	Corresponding IDEF1 Element	Relative Inputs & Control	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A1 Define default values	Dimensions & Design codes	Entity	Structural scheme design	Entity	Dependency	Based on
A2 Set up structural model	Structural idealization model	Entity	Structural scheme design	Entity	Dependency	Based on
			Dimensions & design codes	Entity	Dependency	Based on
A3 Define properties	Member section & joint pattern	Entity	Structural scheme design	Entity	Dependency	Based on
			Dimensions & design codes	Entity	Dependency	Based on
	Material definition	Entity	Structural scheme design	Entity	Dependency	Based on
			Dimensions & design codes	Entity	Dependency	Based on
	Static load case	Entity	Structural scheme design	Entity	Dependency	Based on
			Dimensions & design codes	Entity	Dependency	Based on
	Load combination	Entity	Structural scheme design	Entity	Dependency	Based on
			Dimensions & design codes	Entity	Dependency	Based on

Table B.9 <Continued>

IDEF0 Activity	IDEF0 Output	Corresponding IDEF1 Element	Relative Inputs & Control	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A4 Assign properties	Section assignments	Entity	Structural scheme design	Entity	Dependency	Based on
			Dimensions & design codes	Entity	Dependency	Based on
			Member section	Entity	Non-specific	M:1
	Static load		Structural scheme design	Entity	Dependency	Based on
			Dimensions & design codes	Entity	Dependency	Based on
A5 Define analysis options	Analysis options	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
A6 Compile whole model	Structural analysis model	Entity	Analysis options	Entity	Composition	Has-a
			Structural idealization model	Entity	Composition	Has-a
			Material definition	Entity	Composition	Has-a
			Section assignments	Entity	Composition	Has-a
			Load combination	Entity	Composition	Has-a
			Static load	Entity	Composition	Has-a
A7 Run analysis	Structural responses	Entity	Structural analysis model	Entity	Dependency	Based on
			Dimensions & design codes	Entity	Dependency	Based on

Table B.10 A-0 Do Structural Analysis by SAP2000 (Top Model)

IDEF0 Activity	IDEF0 Output	Corresponding IDEF1 Element	Relative Inputs & Control	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A0 Do structural analysis by SAP2000	Structural analysis model	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
	Structural responses	Entity	Structural scheme design	Entity	Dependency	Based on
			Building design code	Entity	Dependency	Based on
			Structural analysis model	Entity	Dependency	Based on

Table B.11 Mapping Table for the Conversion between Levels

Parent Activity	Parent Element	Corresponding IDEF1 Element	Child Element	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A32 Define member section properties	Member section	Entity	Frame section	Entity	Generalization	Is-one-of
			Shell section	Entity	Generalization	Is-one-of
A43 Assign frame static loads	Frame static load	Entity	Gravity load	Entity	Generalization	Is-one-of
			Point load	Entity	Generalization	Is-one-of
			Uniform load	Entity	Generalization	Is-one-of
			Trapezoidal load	Entity	Generalization	Is-one-of
			Temperature load	Entity	Generalization	Is-one-of
			Prestress load	Entity	Generalization	Is-one-of
A45 Assign shell static loads	Shell static load	Entity	Gravity load	Entity	Generalization	Is-one-of
			Shell Uniform load	Entity	Generalization	Is-one-of
			Pressure load	Entity	Generalization	Is-one-of
			Temperature load	Entity	Generalization	Is-one-of
A2 Set up structural model	Structural idealization model	Entity	Frame element data	Entity	Composition	Has-a
			Shell element data	Entity	Composition	Has-a
			Joints data	Attribute	Composition	Has-a
			Joint constraint	Entity	Composition	Has-a
			Joint masses	Entity	Composition	Has-a
			Joint springs	Entity	Composition	Has-a

Table B.11 <Continued>

Parent Activity	Parent Element	Corresponding IDEF1 Element	Child Element	Corresponding IDEF1 Element	Relationship Type	Relationship Name & Multiplicity
A4 Assign properties	Section assignment	Entity	Section assignment	Entity	Same (NA)	NA
	Static load	Entity	Frame static load	Entity	Generalization	Is-one-of
			Joint force	Entity	Generalization	Is-one-of
			Joint displacement	Entity	Generalization	Is-one-of
			Shell static load	Entity	Generalization	Is-one-of
A0 Do Structural analysis by SAP2000	Structural Analysis model	Entity	Structural idealization model	Entity	Composition	Has-a
			Member section properties	Entity	Composition	Has-a
			Material properties	Entity	Composition	Has-a
			Basic load cases	Entity	Composition	Has-a
			Section assignments	Entity	Composition	Has-a
			Load assignments	Entity	Composition	Has-a
			Analysis options	Entity	Composition	Has-a
	Structural responses	Entity	Structural responses	Entity	Same (NA)	NA

B.2 Information Diagrams for Each Level of Process Models

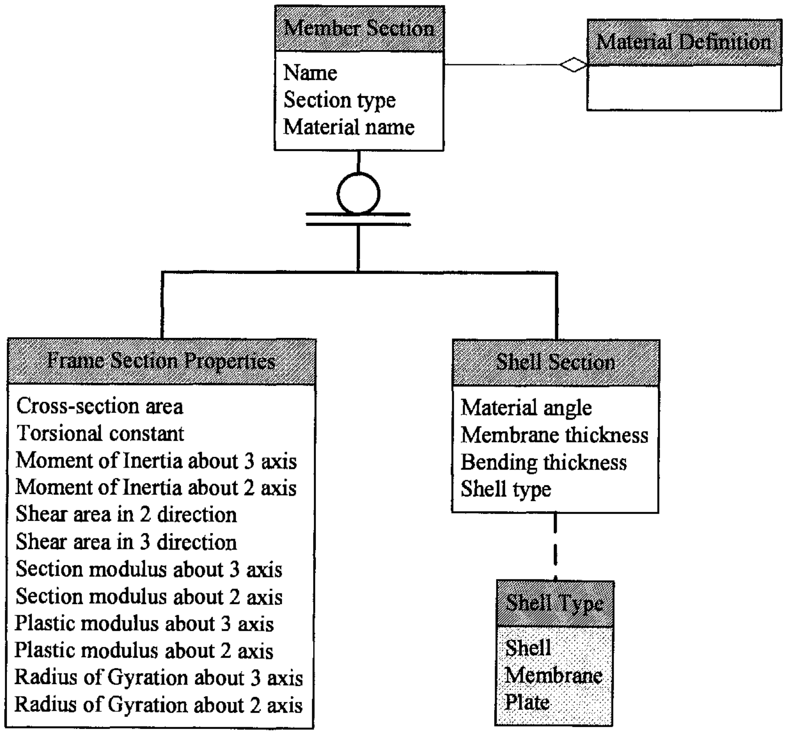

Figure B.1 Information Diagram for A32 "Define Member Sections Properties"

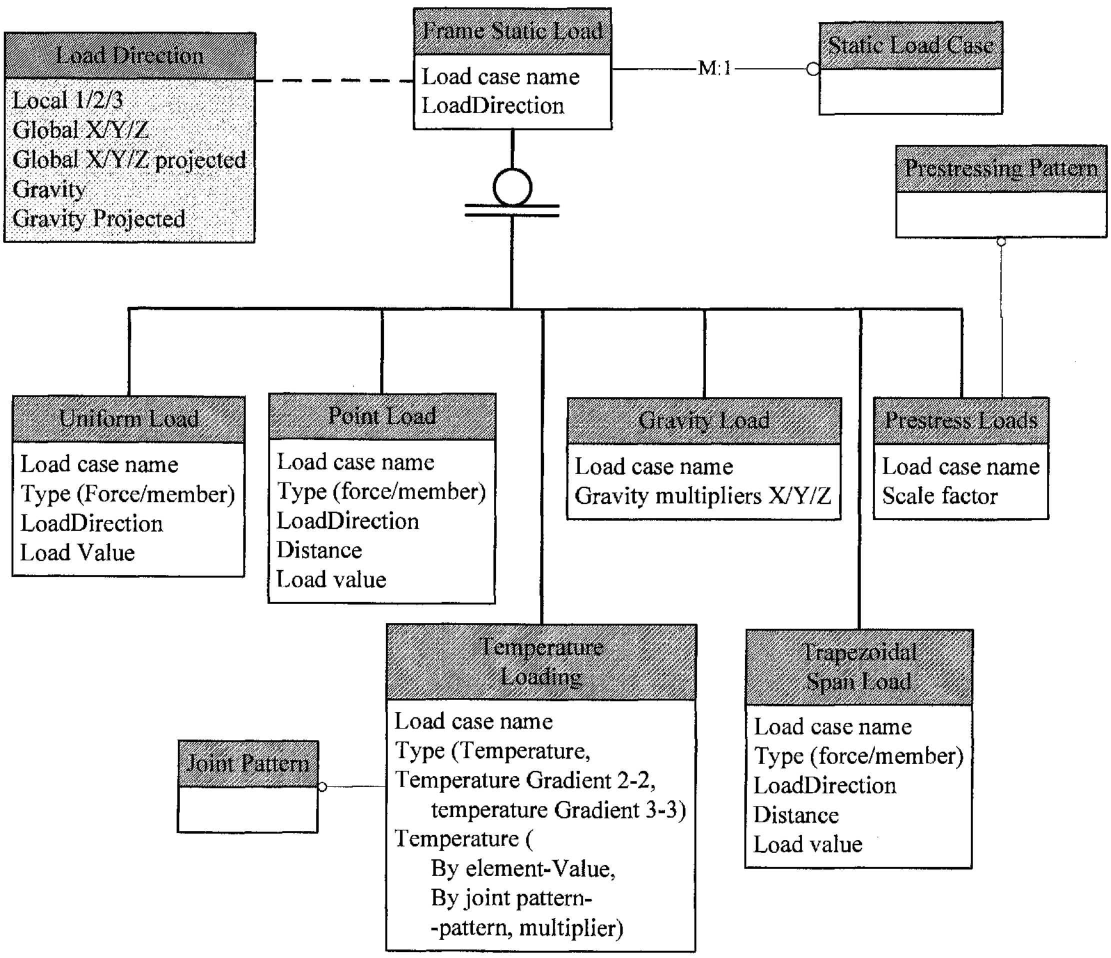

Figure B.2 Information Diagram for A43 "Assign Frame Static Loads"

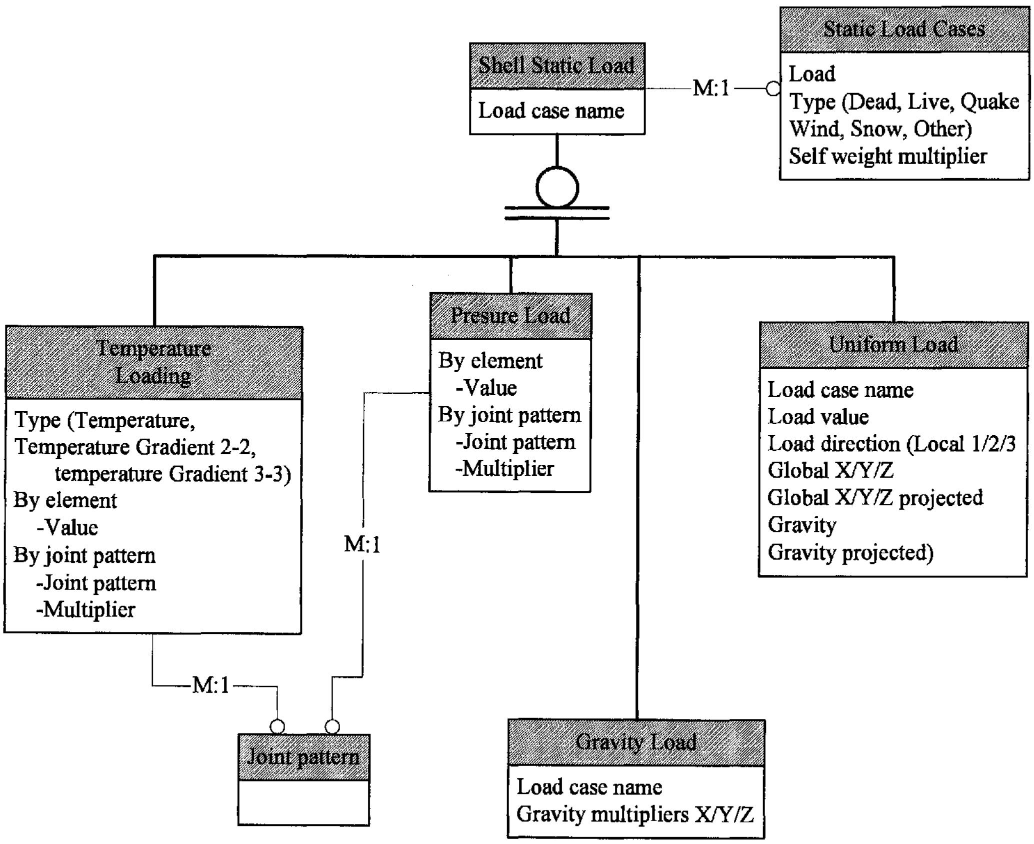

Figure B.3 Information Diagram for A45 "Assign Shell Static Loads"

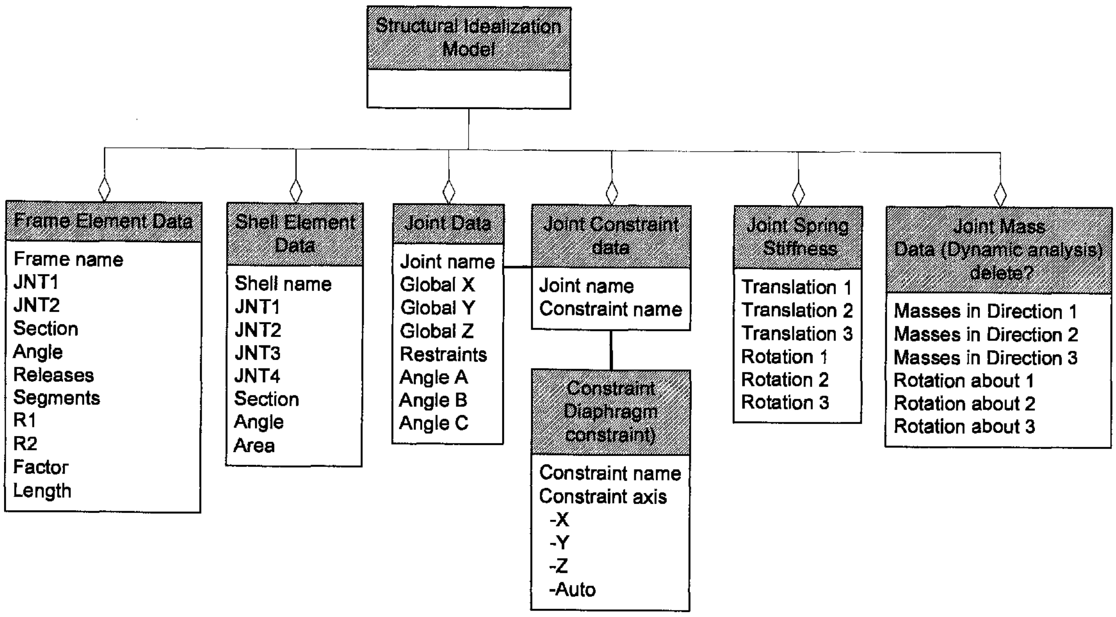

Figure B.4 Information Diagram for A2 "Set up Structural Model"

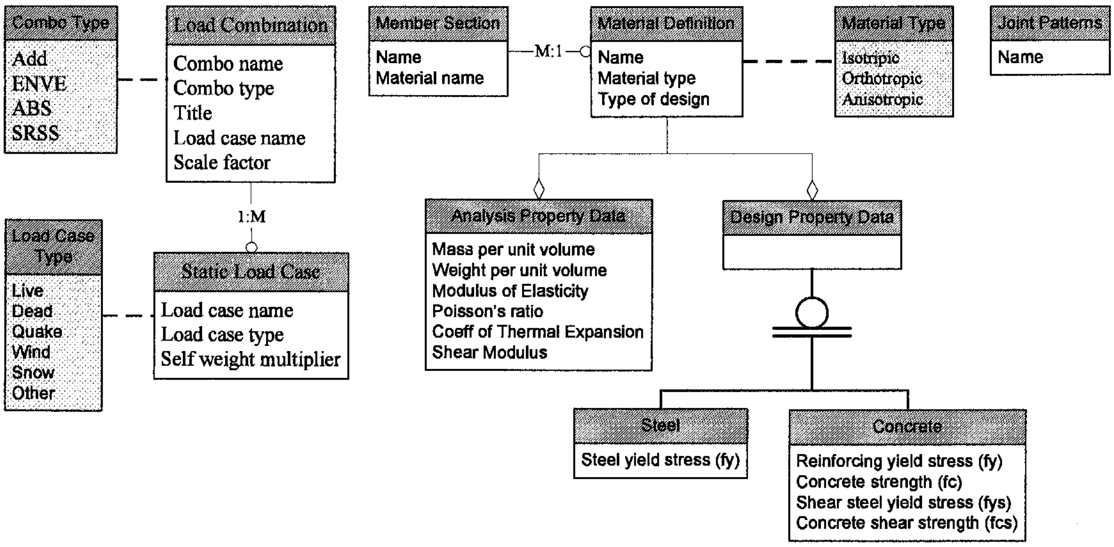

Figure B.5 Information Diagram for A3 "Define Properties"

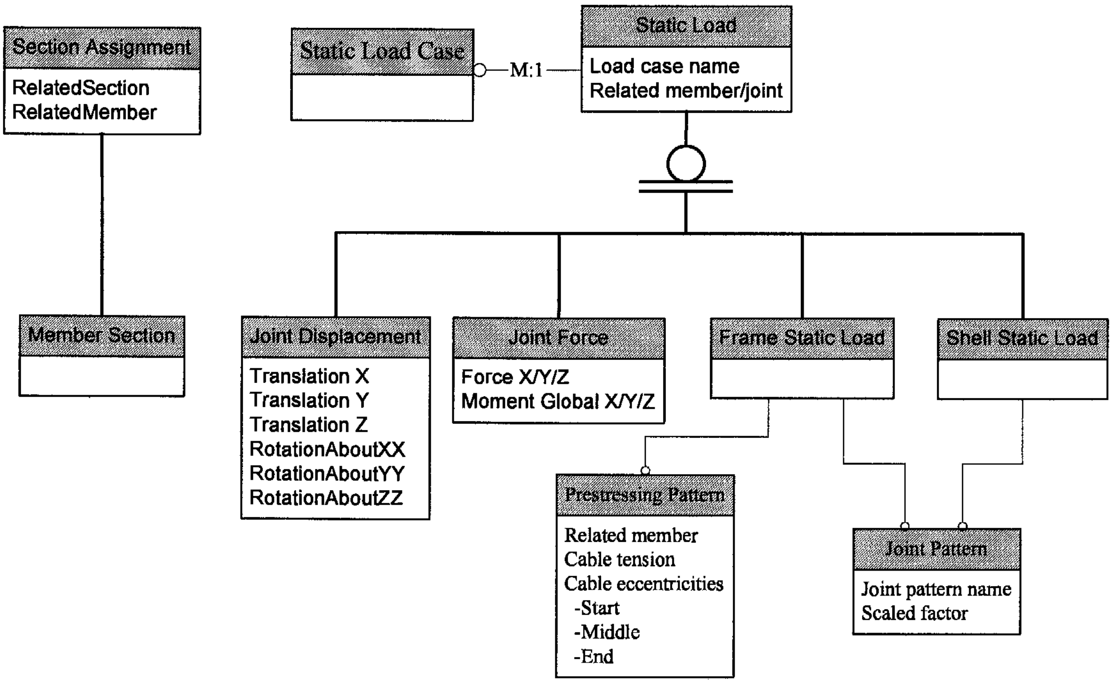

Figure B.6 Information Diagram for A4 "Assign Properties"

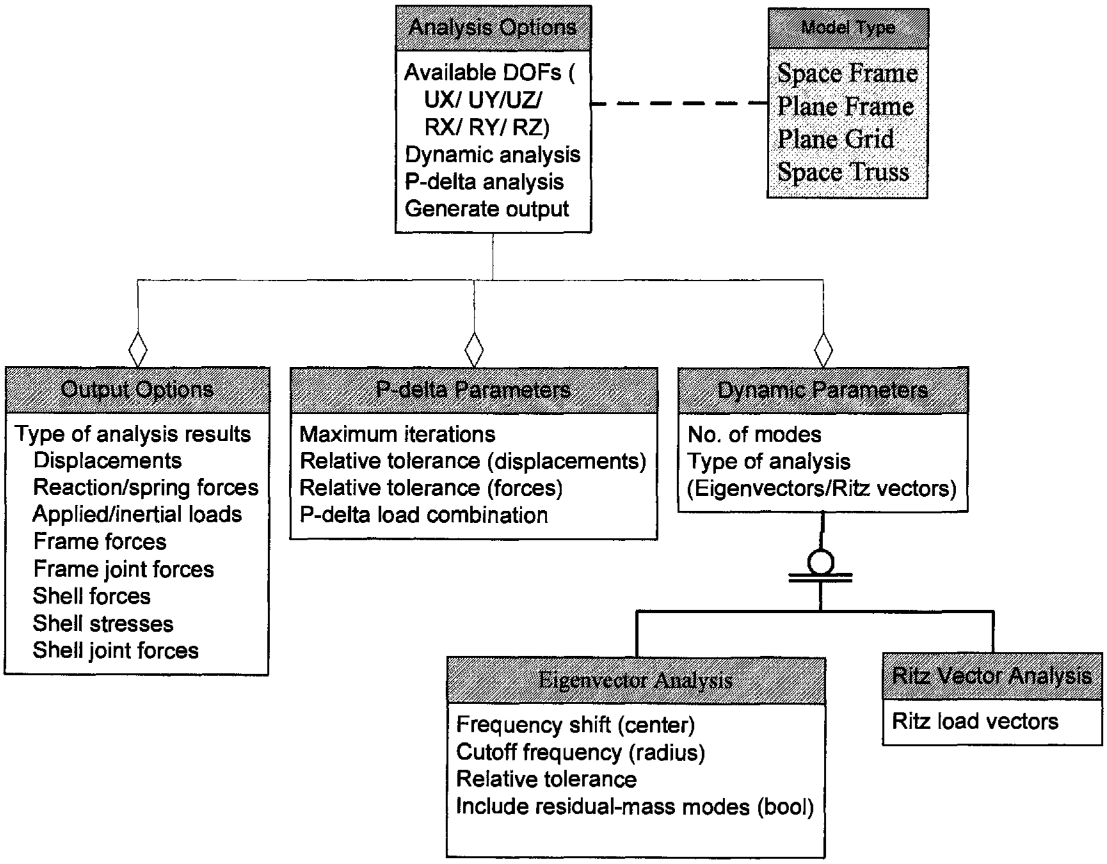

Figure B.7 Information Diagram for A5 "Define Analysis Options"

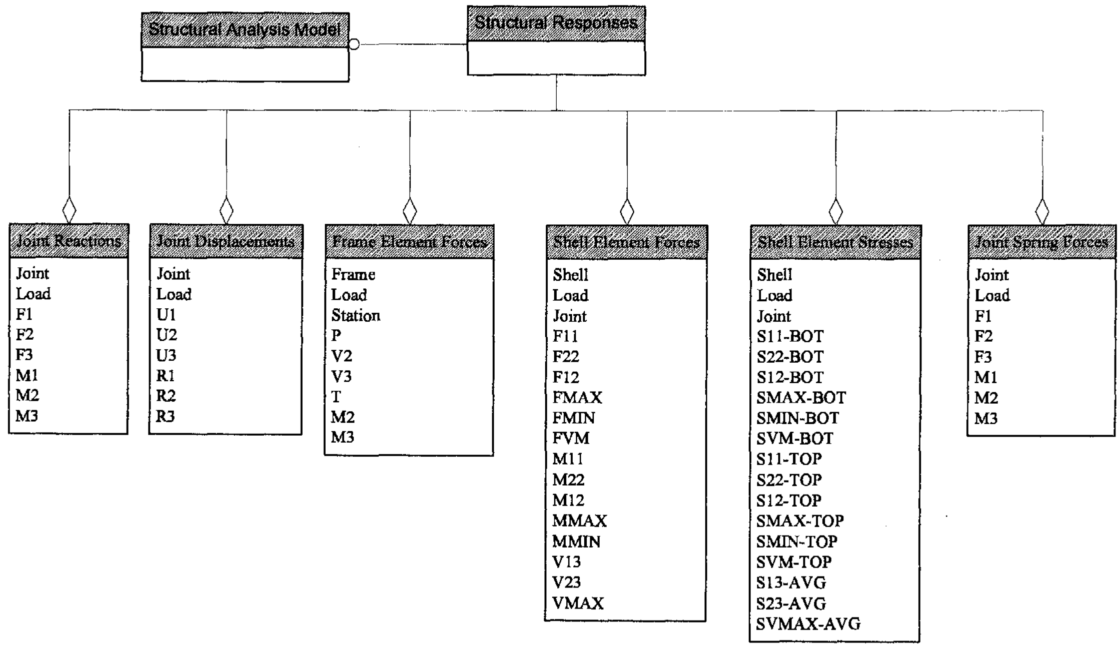

Figure B.8 Information Diagram for A7 "Run Analysis"

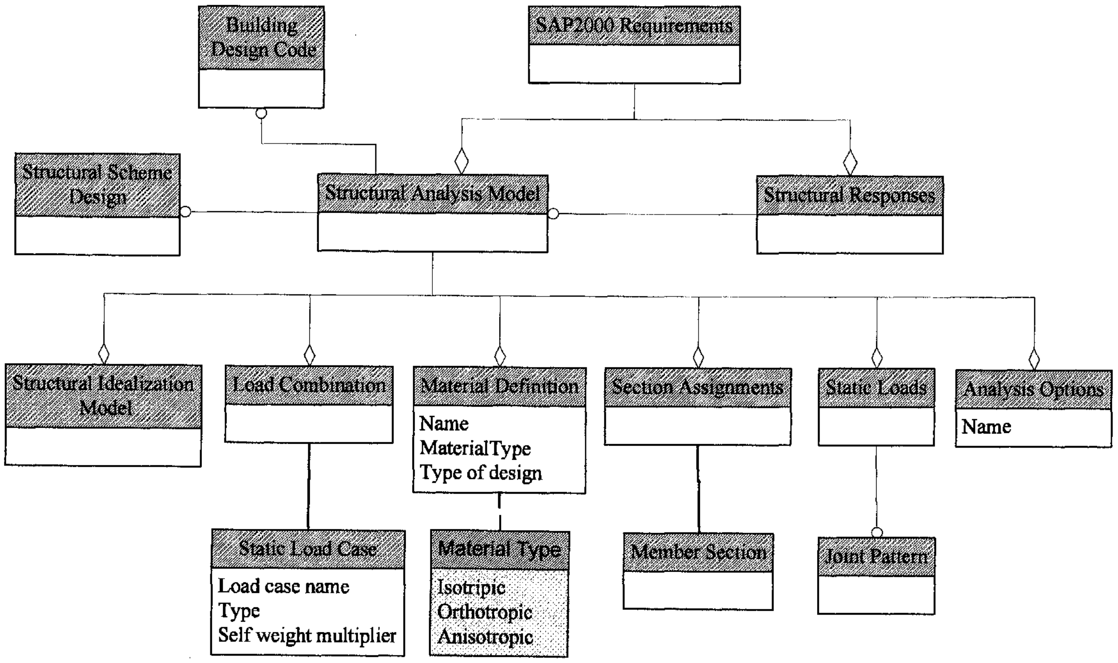

Figure B.9 Information Diagram for A0

Appendix C: Comparison of Information Requirements with Current IFC Models

Table C.1 Geometry Information

Software Requirements			IFC Extensions	
Geometry	**Elements**	**Data type**	**Entities**	**Attributes**
Joint Data				
Basic	Joint name	Text	IfcStructuralConnection	GlobalId (IfcGloballyUniqueId)
Location	Global_X	No.	IfcStructuralConnection	Representation (IfcProductRepresentation)
	Global_Y	No.	IfcProductRepresentation	Representations (IfcRepresentation)
	Global_Z	No.	IfcRepresentation	Items (IfcPoint)
			IfcPoint	Coordinates [1] /[2] /[3]
Restraints	Restraints_U1	Text (Y/N)	IfcStructuralConection	AppliedCondition (OPTIONAL IfcBoundaryCondition)
	Restraints_U2	ditto	IfcStructuralConection	AppliedCondition (OPTIONAL IfcBoundaryCondition)
	Restraints_U3	ditto	IfcStructuralConection	AppliedCondition (OPTIONAL IfcBoundaryCondition)
	Restraints_R1	ditto	IfcStructuralConection	AppliedCondition (OPTIONAL IfcBoundaryCondition)
	Restraints_R2	ditto	IfcStructuralConection	AppliedCondition (OPTIONAL IfcBoundaryCondition)
	Restraints_R3	ditto	IfcStructuralConection	AppliedCondition (OPTIONAL IfcBoundaryCondition)
Local Axes	Local Ang_A / B /C	No.	**Inferred** from ObjectPlacement (IfcLocalPlacement)	
			IfcLocalPlacement	RelativePlacement
			IfcAxis2Placement	RefDirection
Frame Element data				
Basic	Frame	Text	IfcStructuralCurveMember	GlobalId (IfcGloballyUniqueId)
	JNT-1	Text	IfcRelConnectsStructuralMember	RelatedStructuralConnection (IfcStructuralConnection)
	JNT-2	Text	IfcRelConnectsStructuralMember	RelatedStructuralConnection (IfcStructuralConnection)
Sections	Section	Text	IfcRelAssociatesProfileProperties	RelatingProfileProperties (IfcProfileProperties)
			IfcStructuralProfileProperties	ProfileName (IfcLabel)
Local Axes	Local Angle	No.	**Inferred** from ObjectPlacement (IfcLocalPlacement)	

Table C.1 <Continued>

Release	Release-P	Text (Start& End)	**(SET OF)** IfcRelConnectsStructuralMember	AppliedCondition (OPTIONAL IfcBoundaryCondition)
	Release-V2	ditto	IfcRelConnectsStructuralMember	AppliedCondition (OPTIONAL IfcBoundaryCondition)
	Release-V3	ditto	IfcRelConnectsStructuralMember	AppliedCondition (OPTIONAL IfcBoundaryCondition)
	Release-T	ditto	IfcRelConnectsStructuralMember	AppliedCondition (OPTIONAL IfcBoundaryCondition)
	Release-M2	ditto	IfcRelConnectsStructuralMember	AppliedCondition (OPTIONAL IfcBoundaryCondition)
	Release-M3	ditto	IfcRelConnectsStructuralMember	AppliedCondition (OPTIONAL IfcBoundaryCondition)
Seg-ments	Segments	No.	**Absent**	
Frame End Offsets	Ioffset	No.	**Absent**	
	Joffset	No.	**Absent**	
	Rigid factor	No.	**Absent**	
	Length	No.	Pset_ColumnCommon_Height / Pset_BeamCommon_Span	
Joint Constraints Data				
	Joint name	Text	IfcStructuralConnection	GlobalId (IfcGloballyUniqueId)
	Constraint Type	Text	**Absent**	
Shell Element Data				
Shell	Shell name	Text	IfcStructuralSurfaceMember	GlobalId (IfcGloballyUniqueId)
	Joint 1/2/3/4	Text	IfcRelConnectsStructuralMember	RelatedStructuralConnection (IfcStructuralConnection)
	Section	Text	IfcRelAssociatesProfileProperties	RelatingProfileProperties (IfcProfileProperties)
			IfcStructuralProfileProperties	ProfileName (IfcLabel)
	Angle (Local axis)	No.	**Inferred** from ObjectPlacement (IfcLocalPlacement)	
	Area	No.	IfcRelAssociatesProfileProperties	RelatingProfileProperties (IfcProfileProperties)
			IfcStructuralProfileProperties	CrossSectionArea (IfcAreaMeasure)

Table C.2 Material information

Software Requirements			IFC Extensions	
Material	**Elements**	**Data Type**	**Entities**	**Attributes**
Material Definition	name	Text	IfcMaterialProperties	Material
			IfcMaterial	Name
	Type of Materials	Text	In SAP2000, three types of material are selected: Isotropic, Orthotropic, Anisotropic. In current IFC only isotropic material are allowed for.	
Analysis Properties data	Mass per unit volume	No.	IfcGeneralMaterialProperties	MassDensity
	Weight per unit volume	No.	**Absent**	
	Modulus of Elasticity	No.	IfcMechanicalMaterialProperties	YoungModulus
	Poisson's Ratio	No.	IfcMechanicalMaterialProperties	Poisson's Ratio
	Coeff of Thermal Expansion	No.	IfcMechanicalMaterialProperties	ThermalExpansionCoefficient
	Shear Moduli	No.	IfcMechanicalMaterialProperties	ShearModulus
Design Properties Data				
Concrete	Reinforcing yield stress (fy)	No.	IfcMechianicalSteelMaterial-Propeties	YieldStress (IfcPressureMeasure)
	Concrete strength (Cylinder) (fc)	No.	IfcMechanicalConcreteMaterial Properties	CompressiveStrength (IfcPressureMeasure)
	Shear steel yield stress (fys)	No.	IfcMechianicalSteelMaterial-Propeties	YieldStress (IfcPressureMeasure)
	Concrete shear strength (fcs)	No.	**Absent** 5N/mm2 or $0.8\sqrt{f_{cu}}$	
Steel	Steel yield stress (fy)	No.	IfcMechianicalSteelMaterial-Propeties	YieldStress (IfcPressureMeasure)

Table C.3 Load Information

Software Requirements				IFC extensions	
Load		**Elements**	**Data Type**	**Entities**	**Attributes**
Static Load Cases		Load case name	Text	IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
		Load case type	Text	IfcStructuralLoadGroup	ActionSource
		(Dead, Live, Quake, Snow, Other)	Domain	IfcActionSourceTypeEnum (Note: in this case, the "PredefinedType" of IfcStructuralLoadGroup specifies a LOAD_CASE.)	
		Self weight multiplier	No.	IfcStructuralLoadGroup	Coefficient
Load Combination		Combo name	Text	IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
		Combo type	Text	**Absent (because of static analysis)** Four types in SAP2000: ADD, ENVE, ABS, SRSS	
		Title	Text	IfcStructuralLoadGroup	Purpose
		Load case name	Text	IfcStructuralLoadGroup	IsGroupedBy (IfcRelAssignsToGroup)
				IfcRelAssignsToGroup	RelatingGroup (IfcStructuralLoadGroup)
		Scale factor	No.	IfcStructuralLoadGroup	Coefficient
Static Load	Joint Static Load	Joint Force		IfcStructuralPointAction	AppliedLoad (IfcStructuralLoad)
		1. Load case name	Text	IfcRelAssignsToGroup	RelatingGroup (IfcStructuralLoadGroup)
				IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
		2. Joint name	Text	IfcRelConnectsStructural-Activity	RelatingElement
		3. Force X/Y/Z	No.	IfcStructuralLoadSingleForce	Force X/Y/Z
		4. Moment Global XX/YY/ZZ	No.	IfcStructuralLoadSingleForce	Moment X/Y/Z
		Joint Displacement		IfcStructuralPointAction	AppliedLoad (IfcStructuralLoad)
		1. Load case name	Text	IfcRelAssignsToGroup	RelatingGroup (IfcStructuralLoadGroup)
				IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
		2. Joint name	Text	IfcRelConnectsStructural-Activity	RelatingElement
		3. Translation X/Y/Z	No.	IfcStructuralLoadSingle-Displacement	Displacement X/Y/Z
		4. Rotation about XX/YY/ZZ	No.	IfcStructuralLoadSingle-Displacement	RotationDisplacement RX/RY/RZ

Table C.3 <Continued>

Static Load	Frame Member Static Load	Gravity load		IfcStructuralPointAction	
		1. Load case name	Text	IfcRelAssignsToGroup	RelatingGroup (IfcStructuralLoadGroup)
				IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Gravity multipliers	×	IfcStructuralLoadGroup	Coefficient
		Point load		IfcStructuralPointAction	
		1. Load case name	Text	IfcRelAssignsToGroup	RelatingGroup (IfcStructuralLoadGroup)
				IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Type	×	**Inferred** (= Force /Moment)	
		4. Direction	Text	IfcStructuralActivity	GlobalOrLocal
				IfcStructuralAction	ProjectedOrTrue
		5. Distance	No.	IfcStructuralPointAction	Representation
				IfcProductRepresentation	Representations
				IfcTopologyRepresentation	Items (IfcVertexPoint)
		6. Load value	No.	IfcStructuralPointAction	AppliedLoad
				IfcStructuralLoadSingleForce	Force/Moment
		Uniform load		IfcStructuralLinearAction	
		1. Load case name	Text	IfcRelAssignsToGroup	RelatingGroup (IfcStructuralLoadGroup)
				IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Type	Text	**Inferred** (= Force /Moment)	
		4. Direction	Text	IfcStructuralAction	GlobalOrLocal, ProjectedOrTrue
		5. Load value	No.	IfcStructuralLinearAction	AppliedLoad
				IfcStructuralLoadLinearForce	LinearForce /LinearMoment
		Prestress load			
		1. Load case name	Text	IfcRelAssignsToGroup	RelatingGroup (IfcStructuralLoadGroup)
				IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Scale factor	Text	IfcStructuralLoadGroup	Coefficient

Table C.3 <Continued>

Static Load	**Frame Member Static Load**	Temperature load		IfcStructuralLinearAction	
		1. Load case name	Text	IfcRelAssignsToGroup	RelatingGroup (IfcStructuralLoadGroup)
				IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Type	Text	Three types: Temperature, by gradient 2-2 / 3-3 = *Temperature* **(Inferred);**	
		4. Temperature (by element)	No.	IfcStructuralLoadTemperature	DeltaT_Constant
		5. Pattern (Temp/Pres)	Text	**Absent**	
		6. Multiplier	No.	**Absent**	
		Trapezoidal span load		IfcStructuralLinearActionVaring	
		1. Load case name	Text	IfcRelAssignsToGroup	RelatingGroup (IfcStructuralLoadGroup)
				IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Type	Text	**Inferred** (=Force /Moment)	
		4. Direction	Text	IfcStructuralActivity	GlobalOrLocal
				IfcStructuralAction	ProjectedOrTrue
		5. Distance	No.	IfcStructuralLinearActionVaring	VaryingAppliedLoadLocation
				IfcPointOnCurve	PointParameter
		6. Load value	No.	IfcStructuralLinearActionVaring	SubsequentAppliedLoads
	Shell Member Static Load	Gravity load			
		1. Load case name	Text	IfcRelAssignsToGroup	RelatingGroup (IfcStructuralLoadGroup)
				IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Gravity multipliers X/Y/Z	No.	IfcStructuralLoadGroup	Coefficient
		Pressure load		IfcStructuraPlanarActionVarying	
		1. Load case name	Text	IfcRelAssignsToGroup	RelatingGroup (IfcStructuralLoadGroup)
				IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Pressure (by element)	No.	IfcStructuralLoadPlanarForce	PlanarForce X/Y/Z
		4. Pressure (by Pattern)	Text	**Absent (IfcStructuralPlanarActionVarying)**	
		5. Multiplier	No.	**Absent**	

Table C.3 <Continued>

Static Load	Shell Member Static Load	Uniform load		IfcStructuraPlanarAction	
		1. Load case name	Text	IfcRelAssignsToGroup	RelatingGroup (IfcStructuralLoadGroup)
				IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Load value	No.	IfcStructuraPlanarAction	AppliedLoads
				IfcStructuralLoadPlanarForce	PlanarForce X/Y/Z
		4. Direction	Text	IfcStructuralActivity	GlobalOrLocal
				IfcStructuralAction	ProjectedOrTrue
		Temperature load		IfcStructuralPlanarAction	
		1. Load case name	Text	IfcRelAssignsToGroup	RelatingGroup (IfcStructuralLoadGroup)
				IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
		2. Frame name	Text	IfcRelConnectsStructuralActivity	RelatingElement
		3. Type	Text	**Absent** (Two Types: Temperature, Gradient)	
		4. Temperature (by element)	No.	IfcStructuralLoadTemperature	DeltaT_Constant
		5. Pattern	Text	**Absent**	
		6. Multiplier	No.	**Absent**	

Table C.4 Member Section Information

General Information about Frame Section

Software Requirements			IFC Extensions	
Section	**Elements**	**Data type**	**Entities**	**Attributes**
General Frame Section Information (Frame Properties)				
Section Assign	Relating section	Text	IfcRelAssociatesProfile-Properties	RelatingProfileProperties (IfcProfileProperties)
	Relating member	Text	IfcRelAssociatesProfile-Properties	RelatedObjects (IfcStructuralItem)
Member Section	Name	Text	IfcProfileProperties	ProfileName
	Material	Text	**Absent** (derived from IfcRelAssociatesMaterial)	
	Type (Shape)	Text	**Absent** (derived)	
Frame Section Properties	Cross-section (axial) area (Area)	No.	IfcProfileProperties (IfcStructuralProfileProperties)	CrossSectionArea
	Torsional constant (J)	No.	IfcProfileProperties (IfcStructuralProfileProperties)	TorsionalConstantX
	Moment of Inertia about 3 axis (I33)	No.	IfcProfileProperties (IfcStructuralProfileProperties)	MomentOfInertiaY
	Moment of Inertia about 2 axis (I22)	No.	IfcProfileProperties (IfcStructuralProfileProperties)	MomentOfInertiaZ
	Shear area in 2 direction (A22)	No.	IfcProfileProperties (IfcStructuralProfileProperties)	ShearDeformationAreaZ (ShearAreaZ)
	Shear area in 3 direction (A33)	No.	IfcProfileProperties (IfcStructuralProfileProperties)	ShearDeformationAreaY (ShearAreaY)
	Section modulus about 3 axis (S33)	No.	IfcProfileProperties (IfcStructuralProfileProperties)	MaximumSectionModulusY MinimumSectionModulusY
	Section modulus about 2 axis (S22)	No.	IfcProfileProperties (IfcStructuralProfileProperties)	MinimumSectionModulusZ MaximumSectionModulusZ
	Plastic modulus about 3 axis (Z33)	No.	**Absent** (derived)	
	Plastic modulus about 2 axis (Z22)	No.	**Absent** (derived)	
	Radius of Gyration about 3 axis (R33)	No.	**Absent** (derived)	
	Radius of Gyration about 2 axis (R22)	No.	**Absent** (derived)	

Special Member Section

	t3	t2	tf	tw	t2b	tfb	dis
I/wide flange	Outside height	Top flange width	Top flange thickness	Web thickness	Bottom flange width	Bottom flange thickness	
IfcIShapeprofileDef — OverallDepth, OverallWidth, FlangeThickness, WebThickness, FlangeThickness							
Channel	Outside depth	Outside flange width	Flange thickness	Web thickness			
IfcUShapeProfileDef — Depth, FlangeWidth, FlangeThickness, WebThickness							
Tee	Outside stem	Outside flange	Flange thickness	Stem thickness			
IfcTShapeProfileDef — Depth, FlangeWidth, FlangeThickness, WebThickness							
Angle	Outside vertical leg	Outside horizontal leg	Horizontal leg thickness	Vertical leg thickness			
IfcLShapeProfileDef — Depth, Width, Thickness(Note: In IFC, Horizontal leg thickness=Vertical leg thickness)							
Double Angle	Outside depth	Outside width	Horizontal leg thickness	Vertical leg thickness			Back to back distance
IfcCompositeProfileDef — IfcLShapeProfileDef; IfcLShapeProfileDef — Depth, Width, Thickness(Note: In IFC, Horizontal leg thickness = Vertical leg thickness)							**Absent**
Box/ Tube	Outside depth	Outside width	Flange thickness	Web thickness			
IfcRectangleHollowProfileDef — Xdim, YDim, WallThickness(Note: In IFC, Flange thickness = Web thickness);							
Pipe	Outside diameter			Wall thickness			
IfcCircleHollowProfileDef — Radius, WallThickness							
Rectan-gular	Depth	Width					
IfcRectangleProfileDef — XDim, YDim							
Circle	Diameter						
IfcCircleProfileDef — Radius;							
General	Depth	Width					
IfcEllipseProfileDef — SemiAxis1, SemiAxis2							
Double Channel	Outside depth	Outside width	Flange thickness	Web thickness			back to back distance
IfcCompositeProfileDef — IfcProfileDef; IfcUShapeProfileDef — Depth, FlangeWidth, FlangeThickness, WebThickness							**Absent**

Shell Sections

Software Requirements			IFC Extensions	
Geometry	**Elements**	**Data type**	**Entities**	**Attributes**
Shell Section Information				
Basic	Section Name	Text	IfcProfileProperties	ProfileName
Material	Material Name	Text	**Absent (derived from IfcRelAssociatesMaterial)**	
	Material Angle	No.	**Absent (NA)**	
Thickness	Membrane	No.	IfcStructuralSurfaceMember	Thickness
	Bending	No.	IfcStructuralSurfaceMember	Thickness
Shell Type	Shell / Membrane / Plate / Thick Plate	Text	IfcStructuralSurfaceMember	PredefinedType (IfcStructuralFaceTypeEnum)
			IfcStructuralSurfaceType-Enum	Bending_Element, Membrane_Element, Shell, UserDefined, NotDefined

Table C.5 Structural Responses

Software Requirements			IFC Extensions	
Others	**Elements**	**Data type**	**Entities**	**Attributes**
Structural Responses			IfcStructuralAnalysisModel	HasResults (IfcStructuralResultGroup)
			IfcRelAssignsToGroup	RelatingGroup (IfcStructuralResultGroup)
			IfcRelAssignsToGroup	RelatedObjects (IfcStructuralReaction)
Joint Responses	**Joint Reactions**		IfcStructuralReaction	AppliedLoad (IfcStructuralLoad)
	Joint name	Text	IfcStructuralConnection	GlobalId (IfcGloballyUniqueId)
	Load case name	Text	IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
	F1/ F2/ F3	No.	IfcStructuralLoadSingleForce	Force X/Y/Z
	M1/ M2 /M3	No.	IfcStructuralLoadSingleForce	Moment X/Y/Z
	Joint Displacement		IfcStructuralReaction	AppliedLoad (IfcStructuralLoad)
	Joint	Text	IfcStructuralConnection	GlobalId (IfcGloballyUniqueId)
	Load case name	Text	IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
	U1/ U2/ U3	No.	IfcStructuralLoadDisplacement	Displacement X/Y/Z (IfcLengthMeasure)
	R1/ R2/ R3	No.	IfcStructuralLoadDisplacement	RotationalDisplacemnt RX/RY/RZ (IfcPlaneAngleMeasure)
Frame Responses	**Frame Element Forces**		IfcStructuralReaction	AppliedLoad (IfcStructuralLoad)
	Frame	Text	IfcStructuralMember	GlobalId (IfcGloballyUniqueId)
	Load case name	Text	IfcStructuralResultGroup	ResultForLoadGroup (IfcStructuralLoadGroup)
			IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
	Station	No.	IfcStructuralLinearActionVarying	VaryingAppliedLoadLocation (IfcShapeAspect)
	P /V2/ V3	No.	IfcStructuralLinearActionVarying	SubsequentAppliedLoads (IfcStructuralLoad)
			IfcStructuralLoadSingleForce	Force X/Y/Z
	T /M2/ M3	No.	IfcStructuralLinearActionVarying	AppliedSubsequentLoads (IfcStructuralLoad)
			IfcStrcuturalLoadSingleForce	MomentX/Y/Z

Table C.5 <Continued>

Shell Responses	**Shell Element Forces**		IfcStructuralReaction	AppliedLoad (IfcStructuralLoad)
	Shell name	Text	IfcStructuralMember	GlobalId (IfcGloballyUniqueId)
	Load case name	Text	IfcStructuralResultGroup	ResultForLoadGroup (IfcStructuralLoadGroup)
			IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
	Joint	No.	IfcRelConnectsStructuralMember	RelatedStructuralConnection (IfcStructuralConnection)
	F11/F22/F12	No. No.	IfcStructuralReaction	AppliedLoad (IfcStructuralLoad)
			IfcStructualLoadSingleForce	Force X/Y/Z
	M11 /M22/ M12	No.	IfcStructuralReaction	AppliedLoad (IfcStructuralLoad)
			IfcStructualLoadLinearForce	LinearMoment X/Y/Z
	FMAX / FMIN / FVM	No.	IfcStructuralLoadLinearForce	LinearForce X/Y/Z
	MMAX / MMIN	No.	IfcStructuralLoadLinearForce	LinearMoment X/Y/Z
	V13 / V23	No.	IfcStructuralLoadLinearForce	LinearForce X/Y/Z
	VMAX	No.	IfcStructuralLoadLinearForce	LinearForce X/Y/Z
	Shell Element Stresses		IfcStructuralReaction	AppliedLoad (IfcStructuralLoad)
	Shell name	Text	IfcStructuralMember	GlobalId (IfcGloballyUniqueId)
	Load case name	Text	IfcStructuralResultGroup	ResultForLoadGroup (IfcStructuralLoadGroup)
			IfcStructuralLoadGroup	GlobalId (IfcGloballyUniqueId)
	Joint	Text	IfcStructuralConnection	GlobalId (IfcGloballyUniqueId)
	S11-BOT S22-BOT S12-BOT SMAX-BOT SMIN-BOT SVM-BOT S11-TOP S22-TOP S12-TOP SMAX-TOP SMIN-TOP SVM-TOP S13-AVG S23-AVG SVMAX-AVG	No.	**Absent (Out of Scope)**	

Appendix D: Expressions of IFC Extensions Development by EXPRESS

D.1 Expression of End Offsets and Releases of Frame Elements Structural Member through Use of Property Sets

PropertySet Definition:

PropertySet Name	Pset_StructuralCurveMemberCommon
Applicability	IfcStructuralCurveMember entity
Applicable Classes	IfcStructuralCurveMember
Applicable Type Value	
Definition	Definition: Properties common used in all applications of all occurrences of IfcStructuralCurveMember.

Property Definitions:

Name	Property Type	Data Type	Definition
Ioffset	IfcPropertySingleValue	IfcPositiveLengthMeasure / LENGTHUNIT	The offset at start point of frame element
Joffset	IfcPropertySingleValue	IfcPositiveLengthMeasure / LENGTHUNIT	The offset at end point of frame element
Length	IfcPropertySingleValue	IfcPositiveLengthMeasure / LENGTHUNIT	The clear length of frame element
Release_P	IfcPropertySingleValue	IfcBoolean	The release of translation on X axes
Release_V2	IfcPropertySingleValue	IfcBoolean	The release of translation on Y axes
Release_V3	IfcPropertySingleValue	IfcBoolean	The release of translation on Z axes
Release_T	IfcPropertySingleValue	IfcBoolean	The release of rotation about X axes
Release_M2	IfcPropertySingleValue	IfcBoolean	The release of rotation about Y axes
Release_M3	IfcPropertySingleValue	IfcBoolean	The release of rotation along Z axes

D.2 Expression of Restraints of Joint through Use of Property Sets

PropertySet Definition:

PropertySet Name	Pset_StructuralConnectionCommon
Applicability	IfcStructuralConnection entity
Applicable Classes	IfcStructuralConnection
Applicable Type Value	
Definition	Definition: Properties common needed to the definition of all occurrences of IfcStructuralConnection.

Property Definitions:

Name	Property Type	Data Type	Definition
RestraintsU1	IfcPropertySingleValue	IfcBoolean	The restraints along X axes
RestraintsU2	IfcPropertySingleValue	IfcBoolean	The restraints along Y axes
RestraintsU3	IfcPropertySingleValue	IfcBoolean	The restraints along Z axes
RestraintsR1	IfcPropertySingleValue	IfcBoolean	The restraints of rotation about X axes
RestraintsR2	IfcPropertySingleValue	IfcBoolean	The restraints of rotation about Y axes
RestraintsR3	IfcPropertySingleValue	IfcBoolean	The restraints of rotation about Z axes

D.3 Derive Attribute for Angle of Local Axis

```
ENTITY              IfcDirection;
SUBTYPE OF          (IfcGeometricRepresentationItem)
 DirectionRatios    :  LIST [2:3] OF REAL;
DERIVE
                Dim    :  IfcDimensionCount := HIINDEX(DirectionRatios);
             Angles   :   LIST [2:3] OF REAL:= IfcLocaAngles
                          (DirectionRatios)
END_ENTITY          ;
```

Attribute definitions:

Angles: The angles of the direction vector in the direction of X axis (Angles [1]), of Y axis (Angles [2]), and of Z axis (Angles [3]).

```
FUNCTION IfcLocalAngles
 (DirectionRatios:LIST [2:3] OF REAL) :LIST [2:3] OF REAL;

 LOCAL
   Angles : LIST [2:3] OF REAL;
   Distance: REAL;
 END_LOCAL;

 IF HIINDEX (DirectionRatios)=2 THEN
   Distance: = SQRT (DirectionRatios[1]**2+ DirectionRatios[2]**2);
 ELSE
   Distance: = SQRT (DirectionRatios[1]**2+ DirectionRatios[2]**2+
 DirectionRatios[3]**2);
  END_IF;

  REPEAT i:=1 TO HIINDEX(DirectionRatios);
   Angles[i] :=ACOS (DirectionRatios[i]/Distance);
  END_REPEAT;

  RETURN (Angles);

 END_FUNCTION;
```

D.4 Expression of Combo Types by Adding New Attribute to IfcStructuralLoadGroup and New Type

```
ENTITY              IfcStructuralLoadGroup;
SUBTYPE OF          (IfcGroup)
      PredefinedType   :   IfcLoadGroupTypeEnum;
          ActionType   :   IfcActionTypeEnum;
        ActionSource   :   IfcActionSourceTypeEnum;
         Coefficient   :   OPTIONAL IfcPositiveRatioMeasure;
             Purpose   :   OPTIONAL IfcLabel;
           ComboType   :   OPTIONAL IfcComboTypeEnum;
INVERSE
 SourceOfResultGroup   :   SET [0:1] OF IfcStructuralResultGroup
                           FOR ResultForLoadGroup;
        LoadGroupFor   :   SET OF IfcStructuralAnalysisModel FOR
                           LoadedBy;
END_ENTITY;
```

Attribute definitions:

ComboType: Optional definition of the combination type which is normally needed if '*PredefinedType*' specifies a LOAD_COMBINATION (see also IfcComboTYpeEnum).

```
TYPE IfcComboTypeEnum = ENUMERATION OF (ADD, ENVE, ABS, SRSS);
END_TYPE;
```

D.5 Expression of Types of Material by Adding New Attributes to IfcMaterial

```
ENTITY          IfcMaterial;
          Name     :    IfcLabel;
  MaterialType     :    IfcMaterialTypeEnum;
INVERSE
  ClassifiedAs     :    SET [0:1] OF
                        IfcMaterialClassificationRelationship FOR
                        ClassifiedMaterial;
END_ENTITY      ;
```

Attribute definitions:

MaterialType: Select a predefined type for the material (see IfcMaterialTypeEnum).

```
TYPE IfcMaterialTypeEnum = ENUMERATION OF (Isotropic, Orthotropic,
                                 AnisotropicMaterial);
END_TYPE;
```

D.6 Expression of Properties of Composite Sections by Adding New Attributes or new Class to IfcCompositeProfileDef

```
ENTITY          IfcCompositeProfileDef;
SUBTYPE OF      (IfcProfileDef)
     Profiles  :      SET [2:?] OF IfcProfileDef;
        Label  :      OPTIONAL IfcLabel;
      Spacing  :      OPTIONAL IfcPositiveLengthMeasure;
        WHERE
          WR1  :      SIZEOF(QUERY(temp <* Profiles |
                      temp.ProfileType <>
                      Profiles[1].ProfileType)) = 0;
          WR2  :      SIZEOF(QUERY(temp <* Profiles |
                      'IFCPROFILERESOURCE.IFCCOMPOSITEPROFILEDEF'
                      IN TYPEOF(temp))) = 0;
   END_ENTITY  ;
```

Attribute definitions:

Spacing: Optional definition of the distance between the component profiles.

D.7 New class for Prestress Load

```
ENTITY IfcStructuralLoadStatic
ABSTRACT SUPERTYPE OF (ONEOF (IfcStructuralLoadSingleForce,
                              IfcStructuralLoadLinearForce,
                              IfcStructuralLoadPlanarForce,
                              IfcStructuralLoadDisplacement,
                              IfcStructuralLoadTemperature,
                              IfcStructuralLoadPrestressing));
 END_ENTITY;
```

```
ENTITY          IfcStructuralLoadPrestressing;
 SUBTYPE OF     (IfcStructuralLoadStatic)
   PrestressForce  :   IfcForceMeasure;
   Eccentricities  :   List [3:3] of IfcReal;
END_ENTITY         ;
```

Attribute definitions:

PrestressForce: definition of the tension of prestressing cable which is assumed to be constant along the length and does not change with element deformation.

Eccentricities: definition of the drape configuration of prestressing cable, which is assumed to be parabolic. It is specified by giving three drapes at the two ends and at the center.