A study of cost-effective reinforced concrete structural systems

Li, Shengping

2005

Li, S. (2005). A study of cost-effective reinforced concrete structural systems. Master's thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/11899>

<https://doi.org/10.32657/10356/11899>

Nanyang Technological University

Downloaded on 26 Apr 2023 18:46:04 SGT

A Study of Cost-Effective Reinforced Concrete Structural Systems

LI SHENGPING

SCHOOL OF CIVIL AND ENVIRONMENTAL
ENGINEERING
NANYANG TECHNOLOGICAL UNIVERSITY

2005

A Study of Cost-Effective Reinforced Concrete Structural Systems

**SUPERVISED
BY**

Assoc. Prof. Robert L. K. Tiong

**SUBMITTED
BY**

Li Shengping

**SCHOOL OF CIVIL AND ENVIRONMENTAL
ENGINEERING**

**A Thesis presented to the Nanyang Technological
University in fulfillment of the requirements for the
Degree of Master of Engineering**

Jan 2005

Acknowledgment

The author wishes to express his sincere appreciation and gratitude to Assoc. Prof. Tiong Lee Kong, who has helped in the successful completion of the author's Master of Engineering study and has shared his vast knowledge with the author. His tireless patience and reassuring advice are appreciated very much. His commitment and brilliance have been inspiring and the author feels the most pleasure and enjoyment working with him.

The sincere appreciation also goes to Mr. Andrew Seet, Managing Director and Ms Florence Lim, Quantity Surveyor of Santarli Construction Pte Ltd, for supplying the information and providing guidance on the carrying out of the project. Dr. Susanto Teng from NTU, Ms. Annie Yee from Jurong Consultant (Sin), Mr. Eddy Tan from Consoft Pte Ltd, Mr. Gary Soon from Utracoss and Mr. Suresh from VSL have been providing generous help and encouragement to make this study successful.

Table of contents

ACKNOWLEDGMENT	I
TABLE OF CONTENTS.....	II
SUMMARY	IV
LIST OF TABLES	V
LIST OF FIGURES	VI
LIST OF SYMBOLS AND ABBREVIATIONS	VII
CHAPTER 1.....	1
INTRODUCTION	1
1.1. BACKGROUND.....	1
1.2. OBJECTIVES.....	3
1.3. RESEARCH METHODOLOGY.....	4
1.4. OUTLINE OF THE THESIS.....	4
CHAPTER 2.....	6
LITERATURE REVIEWS	6
2.1. COMMON REINFORCED CONCRETE SYSTEMS	6
2.1.1. Conventional RC System.....	6
2.1.2. Flat Slab System.....	9
2.1.3. Precast Concrete System.....	12
2.1.4. Post-Tensioned System.....	15
2.2. PREVIOUS COST STUDIES.....	19
2.2.1. Deductive and Inductive Cost modeling of building.....	19
2.2.2. Trial-design cost comparison for various structural systems.....	22
2.2.3. Project-based cost comparisons for various structural systems.....	27
2.3. OTHER COST THEORIES	29
2.3.1. Cost significance in construction project.....	29
CHAPTER 3.....	31
DEVELOPMENT OF RESEACH FRAMEWORK	31
3.1. RESEARCH FRAMEWORK.....	31
3.2. THE TRIAL-BUILDINGS	34
3.3. DESIGN ASSUMPTIONS	37
3.4. FINITE ELEMENT ANALYSIS SOFTWARE	39
3.5. ACCURACY OF THE CALCULATION	39
3.6. CONSTRUCTION COST AND COST DATA COLLECTION	42

3.6.1. Study scope of the construction cost	42
3.6.2. Cost data collection and the Unit rates	43
CHAPTER 4.....	48
DESIGN QUANTITIES AND CALCULATIONS	48
4.1. CONCRETE, FORMWORK AND PRESTRESS TENDON.....	49
4.2. REINFORCING STEEL QUANTITIES.....	52
4.2.1. Reinforcing steel quantities in columns	53
4.2.2. Reinforcing steel quantities in beams	54
4.2.3. Reinforcing steel quantities in slabs	56
4.2.4. Total reinforcing steel quantities	56
CHAPTER 5.....	58
RESULTS AND DISCUSSIONS.....	58
5.1. MODIFIED UNIT RATES AND OTHER CONSIDERATIONS	58
5.1.1. Flat slab unit rates	58
5.1.2. Precast costing.....	59
5.1.3. Other modified unit rates	61
5.1.4. Precast member mass.....	61
5.2. STRUCTURAL COST (SC)	62
5.2.1. Total structural cost.....	62
5.2.2. Structural cost breakdown	65
5.2.3. Other cost implications	69
CHAPTER 6.....	70
CONCLUSION AND RECOMMENDATIONS.....	70
6.1. CONCLUSION	70
6.2. LIMITATIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH.....	72
REFERENCES.....	74
APPENDICES	78

Summary

Reinforced Concrete (RC) is the most commonly used building material in Singapore. Various RC structural systems have been developed to fully utilize the properties of RC. Some examples of RC structural systems are conventional cast in-situ beam-slab system, post-tensioned flat slab system, and precast system.

With the various RC structural systems available in the market, finding a cost-effective structural system becomes a pressing issue in the construction industry. Attempts on construction cost comparison for various structural systems have been made to identify the cost-effective system. However, due to the complexity of building construction, no comprehensive study on this topic has been done.

This study provides a comprehensive cost comparison of the common RC structural systems. The structural cost calculation framework was developed. Trial-buildings were designed using finite element software and material quantities were found out. The structural costs were calculated utilizing the input of current unit rates from local construction industry. It was hoped that this cost calculation framework could be helpful in the field of construction cost study.

With the available cost information, the cost-effective ranges for various RC structural systems in grid size and live load were identified in terms of the structural cost. The results might serve as a useful guideline in the early construction cost estimate and the selection of the cost-effective RC structural system.

List of Tables

TABLE 2.1. COST COMPARISON: PRESTRESSED VS. REINFORCED FLAT SLAB	23
TABLE 2.2. COST COMPARISON: PRECAST VS. CONVENTIONAL.....	24
TABLE 2.3. COST COMPARISON: RC VS. STEEL.....	25
TABLE 2.4. COST COMPARISON: PRECAST VS. SEMI-PRECAST	26
TABLE 2.5. COST COMPARISON: FLAT PLATE VS. OTHERS	27
TABLE 2.6. COST COMPARISON: FLAT PLATE, FLAT SLAB AND BEAM-SLAB	28
TABLE 2.7. COST COMPARISON: FLAT SLAB IN MIXED DEVELOPMENT	29
TABLE 3.1. TRIAL BUILDINGS CONFIGURATIONS	36
TABLE 3.2. CPG UNIT RATES 2003 Q3	46
TABLE 4.1 (1). MEMBER SIZES FOR CONVENTIONAL SYSTEM.....	49
TABLE 4.1 (2). MEMBER SIZES FOR PRECAST SYSTEM.....	49
TABLE 4.1 (3). MEMBER SIZES FOR PT FLAT SLAB SYSTEM	49
TABLE 4.2. OVERALL CONCRETE AND FORMWORK QUANTITIES FOR VARIOUS CONFIGURATIONS	51
TABLE 4.3. SAMPLE STEEL QUANTITIES FOR COLUMNS	53
TABLE 4.4. SAMPLE STEEL QUANTITIES CALCULATION FOR BEAMS.....	55
TABLE 4.5. TOTAL STEEL QUANTITY FOR THE TRIAL-BUILDING	57
TABLE 5.1. PROPORTIONS OF DELIVERY AND INSTALLATION COST IN TOTAL PC MEMBER COST.....	60
TABLE 5.2. MODIFIED CPG UNIT RATES 2003 Q3	60
TABLE 5.3. PRECAST MEMBER MASS.....	61
TABLE 5.4. SC (S\$/m ²) AND COST DIFFERENCES.....	62
TABLE 5.5 (1). COST BREAKDOWN FOR BUILDING MATERIALS IN CONVENTIONAL CONSTRUCTION	65
TABLE 5.5 (2). COST BREAKDOWN FOR BUILDING MATERIALS IN PT FLAT SLAB CONSTRUCTION	65
TABLE 5.6. COST BREAKDOWN ACCORDING TO STRUCTURAL MEMBERS.....	67

List of figures

FIGURE 3.1. RESEARCH FRAMEWORK FOR STRUCTURAL COST CALCULATION	33
FIGURE 3.2. DIFFERENT RC STRUCTURAL SYSTEMS.....	34
FIGURE 3.3. SAP2000 6M×6M GRID MODELING.....	35
FIGURE 3.4. SECONDARY BEAM LAYOUT	36
FIGURE 3.5. MOMENT DISTRIBUTION FOR FLOOR 4 TO FLOOR 1	40
FIGURE 3.6. REINFORCED STEEL REQUIREMENT (mm^2) IN VARIOUS BEAM SECTIONS FOR DIFFERENT FLOORS	41
FIGURE 3.7. MOMENT DISTRIBUTION IN SLAB FROM SAFE 6.20 AND SAP2000.....	42
FIGURE 4.1. SAMPLE TENDON LAYOUT	52
FIGURE 4.2. SAMPLE REINFORCING STEEL ARRANGEMENT IN BEAMS.....	54
FIGURE 5.1. STRUCTURAL COST ($\text{S\$/m}^2$) VS. GRID SIZES (M) FOR VARIOUS LIVE LOADS.....	63
FIGURE 5.2. COST BREAKDOWN TO BUILDING MATERIALS	66
FIGURE 5.3. COST BREAKDOWN TO STRUCTURAL MEMBERS	68

List of symbols and abbreviations

A	Area
b	Width of the structural member
BCA	Building and Construction Authority, Singapore
BS	British Standard
CIDB	Construction Industry Development Board, Singapore
Conv.	Conventional
CPG	CPG Corporation
d	Depth of the structural member
fcu	Value of the cube strength of concrete
fy	Value of the yield strength of reinforcement
GFA	Gross floor area
LL	Live load
RC	Reinforced concrete
P	Force
PC	Precast
PT	Post-tensioned
Sec.	Secondary

CHAPTER 1

INTRODUCTION

1.1. Background

Reinforced Concrete (RC) is the most commonly used building material in Singapore construction industry. Reinforced concrete has the advantages of relatively low construction cost, low maintenance cost, flexibility in construction and it is more familiar to the builders in the business. Various RC structural systems have been developed to fully utilize the properties of RC. Some examples of RC structural systems are conventional cast in-situ beam-slab system, flat slab system, prestressed system and precast system.

With the many RC structural systems in choice, finding a suitable structural system becomes a pressing issue in the construction industry for builders to secure the work and increase the profit margin. In fact, this study was a direct result of a local contractor's proposal for research into the cost advantages of the commonly used RC structural systems in the market.

Different RC structural systems have various pros and cons but the emphasis of this study was on the cost-effectiveness of various RC structural systems in terms of structural cost. The costs of the different systems vary from each project. The design schemes, architectural layouts, construction methodologies and the industry infrastructure of the region all affect the structural cost.

Previous cost modeling of buildings was classified into deductive and inductive methods (Wilson 1982). The deductive method is to relate the building cost to some design variables through past cost data. The relation is normally figured out from previous cost data by statistical means. The inductive method focuses on studying the design and construction process to relate the cost to the process element.

For the specific studies into cost of various RC structural systems, a deductive kind of approach was considered not feasible due to the inability to find a reasonably large pool of historical cost data for each of the structural systems studied. On the other hand, inductive attempts on construction cost comparison for various structural systems have been made to identify the cost-effective system. However, due to the complexity of building construction, no comprehensive study has been done. Previous studies include comparisons on a few trial-designed buildings and comparisons on real projects. Trial-design approach is normally to conceptually design structures in different RC structural systems to calculate the different material quantities. Some of the trial-design attempts include the ones conducted by Dorwick & Narasimhan (1978) on prestressed vs. reinforced flat slab and Neo (1997) on precast vs. semi-precast concrete structures. Project-based comparisons are carried out on real projects and some of the examples include Mo (1998) on flat slab and Mayer (1998) on flat slab.

The trial-design approach is a general approach but time consuming. The real project based comparison (case study) is carried out on a certain project with normally one extra design besides the original design to compare the cost effectiveness. The main limitations of project-based comparison are that the study is much subjected to the characteristics of that project and is usually limited to 2 systems. Another disadvantage of such comparison

is that it is largely based on the experience of the design engineer. Different engineers have different safety factors in design. Some may attempt to use very big safety factors, which will result in the inaccuracy of the comparison.

Some clarification on the cost and price on a building project is necessary. In the short term, the bidding price is market-oriented rather than merely contractor's cost plus markup in a competitive bidding environment. In the long term, the price has to be based on the cost incurred (Rafety 1991, Runeson 2000). In the context of the author's work, price and cost are used interchangeably referring to the cost to the developer (price to the contractor).

1.2. Objectives

The purpose of the study was to construct a research framework to compare the structural costs of some commonly used RC structural systems utilizing finite element (FEM) design software. The relative cost information was to be collected and studied. A study of the structural costs using the proposed framework was to be carried out in Singapore construction industry. The advantages and disadvantages of various systems were also to be summarized.

Based on a trial building of fixed size, the important design variables were identified as RC structural systems, grid sizes and live loads. The cost-effective range in terms of grid sizes and live loads for the various RC structural systems would be identified with the available cost information.

The study was intended to propose a way of cost comparison for various structural systems. The result could help the decision-makers in the schematic design for choosing the most economical structural system for a project.

1.3. Research methodology

A RC trial building of 4-storey high with a GFA of 2304m² was adopted as the base for the design. Details on the conceptual building were explained in Section 3. After the construction of the research framework, a structural cost comparison for the trial building was done for the common RC structural systems, namely conventional column-beam-slab, prestressed flat slab and precast column-beam-slab systems. The trial buildings were designed in different RC structural systems; grid sizes and live loads using FEM design software. The material quantities were tabulated; and the structural cost of the trial-buildings was calculated based on local cost information. Cost for different systems would be compared in terms of the other two design variables including live loads and grid sizes and the relative cost-effective RC structural system would be identified.

This study by the author was considered to be an inductive approach because the cost was related to the design process and the relatively detailed material quantities were worked out based on the designs. The cost information (unit rates) was extracted from local market prices, which was done by local authority and company through statistical means.

The software SAP2000, SAFE and ADAPT Floor were chosen as the design software. SAP2000 generates the design quantities for beam and column while SAFE generates the conventional slab reinforcing output. ADAPT Floor was used to design post-tensioned flat slab structures. Cost data was acquired through references and interviews. Microsoft Excel spreadsheets were used to help calculate the quantities and costs. More details on the research methodology could be found in Section 3.

1.4. Outline of the thesis

After the introduction from Chapter 1, Chapter 2 gives the literature review. Different RC structural systems were summarized and their advantages and disadvantages were given. Previous researches on construction cost were reviewed and the deductive and inductive

approaches were mentioned. The inductive approach on the topic of cost-effective structural systems were grouped into trial-design approach and project-based approach. Some relevant theories on construction cost were also mentioned in this chapter.

Chapter 3 is the development of the research framework. The framework was presented and the illustration and clarifications of the framework were given. The cost data collection was also discussed in this chapter.

Chapter 4 shows the analysis of the design software and the calculation of the building material quantities. How the quantities were sorted out was explained in detail in this chapter.

Chapter 5 is the results and discussions. The structural costs were calculated and some relevant issues were discussed. The costs were also broken down to building materials and structural members to give better illustrations on structural cost.

Finally, Chapter 6 concludes the author's study. The findings were summarized and some limitations of the research and recommendations for future research were presented in this chapter.

CHAPTER 2

LITERATURE REVIEWS

2.1. Common Reinforced Concrete Systems

Various RC structural systems have been studied for the pros and cons of each. There are many considerations to take besides the cost evaluation (some might try to quantified every aspect using cost, but it is still difficult at this moment). The advantages and disadvantages of the main RC structural systems studied were summarized. The summary was done with reference to Huntington and Mickadeit (1981), FIP (1994), Teng and Sui (2003) and Goodchild (1997).

2.1.1. Conventional RC System

The conventional reinforced concrete system is the traditional cast in-situ RC system, which adopts column/wall, beam and slab system. It is the earliest type of reinforced concrete system employed in Singapore and is still the most popular RC system in Singapore till now. However, with the advancement of technology and higher demand on quality and duration shortening, this system is slowly replaced by other systems in the construction industry.

The following was summarized from the work done by Teng and Sui (2003) and Holland (1997).

Advantages

1. **Structural Continuity.** As the beam and slab are cast monolithically, there will be more structural interaction between the elements and complicated connection designs can hence be avoided.
2. **Relatively Simple and Standard Construction Techniques.** Engineers are more confident in the construction site planning and management as they have been practicing this method for the past decades. No requirement of specialized skills or equipments; all operations are the basic construction processes, which can be carried out by workers under the supervision of site supervisors or any authorized personnel. This is important, as most of the construction labors are unskilled foreign workers who have little or no knowledge in this field.
3. **Design Flexibility.** There will be more flexibility for any changes in the design or architectural layout during the construction stages. Whereas in the precast system, changes might not be feasible as the precast components have been prefabricated in the factories.

Disadvantages

1. **Longer Construction Duration.** Apart from the amount of time needed to erect the falsework and formwork, this system needs considerable time for mixing, casting and curing of the concrete, all of which affect the final strength of concrete if any of

the stated activities is not carried out according to the requirements. The time schedule of the in-situ works can also be readily affected by inclement weather.

2. **High Usage of Formwork and Falsework.** More formworks and falseworks are required for the holding of the cast members in place until they gain sufficient strength to support themselves. This reduces their useful recycle time and in today's construction industry, formwork usage tends to be very expensive and the cost can amount to one to two-thirds (in cases of low formwork recycling rates) of the total cost of conventional system.

3. **Construction Defects.** Shrinkage cracks and honeycombs due to poor concrete placing will affect the concrete strength. Although these defects will also occur in the other systems, the chances of them occurring in conventional system are the highest due to the difficulty in quality control on site and the higher number of members designed and cast on site.

4. **Section Limitation.** The low strength per unit weight of concrete leads to heavy members. This becomes an increasingly important matter for long spanning structures where concrete's large dead weight has a great effect on bending moments. Similarly, the low strength per unit volume of concrete means member will be relatively large and this is an important consideration for tall buildings and long spanning structures.

5. **Labor Intensive and Massive Material Flow.** The adoption of this system requires a higher manpower usage (for assembling & disassembling of formworks and falseworks, concreting works and curing) and since all the works occur on-site, materials such as steel reinforcement bars, formworks, falseworks, vibrators and others need to be properly stored, thereby requiring better housekeeping and extra storage area.

2.1.2. Flat Slab System

Flat slab is defined in ACI code as a concrete slab reinforced in two or more directions, generally without beams or girders to transfer the loads to its supports. The supports are usually columns. To assist in transferring the loads to its supports, the column heads are sometimes enlarged to form a column capital. Flat slab is suitable for bays, which are approximately square. The reinforcement is usually arranged in two directions parallel to the sides of the panel. The minimum permissible thickness of the slab with drop panels is one-fourth of the longest span but in no cases is to be less than 100mm. The side of the drop panel must be at least one-third the parallel span. The maximum effective central angle of the column capital is 90deg. The advantages and disadvantages of flat slab construction as stated below were summarized from Teng and Sui (2003) and Huntington and Mickadeit (1981).

Advantages

1. **Shorter Construction Time.** This system facilitates builders to adopt big table form to increase site productivity. From observation, moving of system formwork from one end to the other and from floor to floor can be carried out within a day with minimum manpower. Welded steel mesh as bottom reinforcement and prefabricated steel reinforcement are placed over columns and walls the following day. Concreting to the floor can then be carried out on the third day of the floor cycle. Since the setting up of columns and walls is done in parallel with the curing of concrete slab, a floor cycle time of 6 to 7 days for a floor area of 2,000 m² is possible at construction sites nowadays.
2. **Height Reduction and Unobstructed Ceiling Space.** Flat slab construction places no restrictions on the positioning of horizontal services and partitions and can minimize floor-to-floor heights when there is no requirement for a deep false ceiling.

A reduction in floor-to-floor height may results in an additional floor without increasing the height of the building and alternatively a lower building height for the same number of floors. This can have knock-on benefits such as reduced external cladding costs and prefabricated services. Cost of vertical services runs can also be lowered due to the reduced floor-to-floor height.

3. Flexibility in Room Layout. This system of construction offers considerable flexibility in terms of architectural layout to the occupier who can easily alter internal layouts to accommodate changes in the use of the structure. Columns and beams need not be aligned and brick wall position could be placed anywhere on the slab structure without affecting the structural behavior (subjected to the wall load constraint). This flexibility results from the use of a square or near-square grid and the absence of beams, downstands or drops that complicate the routing of services and location of partitions.

4. Standardization of Members. By nature of the design, flat slab requires a minimum section of floor thickness and size of the columns to be provided to satisfy punching shear criteria. This indirectly deters changes to be freely made to the dimensions of these members and enables them to be standardized for ease and speed of construction. The effort given to the standardization of members and keeping the types of structural elements to a bare minimum will encourage builders to adopt lighter formwork system for the vertical structural members.

5. Ease of Installation of M&E Services. For Flat Slab design, the underside of floor system is kept free of beams within the dwelling units. As a result, all M&E services can be mounted directly on the underside of the slab instead of bending them to avoid the position of beams as normally experienced in the beam and slab case. It helps to avoid the occurrence of incidents such as having the problem to hack through beams for subsequent installation of services that are required by the owner after the handling over of the units. This certainly will help smooth over some of the teething maintenance issues during the defects liability period.

6. **BCA Buildability Score.** BCA buildability score in Singapore is a measure of productivity of construction. A minimum score is required for a building project to be approved. By virtue of its simplicity in structural layout and adaptability to precast technology, it will allow standardized structural members and prefabricated sections be integrated into the design for ease of construction. This process will make the structure more buildable and reduce the number of site workers and increase the productivity at construction site. Hence it is more buildable and has a natural tendency to achieve a higher BCA buildability score.

Disadvantages

1. **Problem of Punching Shear.** Flat slab construction is not ideal from the structural point of view, due to stress concentration at points of support, such as columns. In reinforced concrete design, the problem is a matter of preventing brittle punching shear failure.

2. **Dealing with Deflections.** For thin flat slabs, serviceability criteria are likely to govern the design. Deflections will generally be greatest at the centre of each panel. However, as partitions may be placed along column lines, it is usual to check deflection here also. The possible effect of deflections on cladding should also be considered carefully. In most cases, a simplified approach using span/depth ratios will be perfectly adequate.

3. **Dealing with Construction Loads.** A high ratio of dead to live load is an inherent feature of flat slabs. With the trend towards faster construction and lower design imposed loads, the 'spare capacity' of a slab over its self-weight is being reduced. There is evidence that early striking and early loading through rapid floor construction has some impact on long-term deflections. This has implication for the

extent of cracking, which can marginally increase deflection when more permanent loads are applied.

4. **Dealing with Holes.** Holes in flat slab near columns need special attention as they reduce local resistance to both bending and punching shear. Very small isolated holes can be ignored. Holes away from columns are less critical.

5. **Other limitations.** Flat slab systems are best for light and medium loadings as in flats and offices. In cases of buildings with heavier building load, thicker floor slabs will be needed, thereby increasing the overall cost of construction in terms of concrete and steel reinforcements.

2.1.3. Precast Concrete System

In precast concrete construction, the structure is divided for manufacturing purposes into separate and distinct structural elements that are later assembled into the final structure. Precast members cast at the building site or at a casting yard remote from the structure are transported to the site of structure and positioned by crane. Precast structural concrete elements can be either conventionally reinforced or prestressed.

Precast slabs are built together via reinforcement bars placed in the castellated horizontal joints. Such connections are able to transmit shear forces vertically as well as horizontally. In some case, a thin structural screed is cast on top. Beside slab, structural precast components also include beams, columns and walls.

A precast structure has less continuity than a cast on-site structure. Normally, all precast components are simply supported and therefore the designer has to put in emphasis on the structural joints. Structural joints are normally divided in relation to their loading or their behavior. The benefits of the system summarized below were drawn from the work by

Huntington and Mickadeit (1981) and FIP Planning and design handbook on precast building structures (1994).

Advantages

1. **Shorter Construction Duration.** Construction will be more rapid and the owner can take possession of the building in a shorter space of time after the site is made available. Casting in the precast plant is normally unimpeded by adverse weather conditions and is carried out in parallel with the site activities.
2. **Less Usage in Formwork and Falsework.** Reduction in site costs as scaffolding, shuttering and other temporary supports will not be needed in such quantities as for in-situ concrete work. Precast units can be made by mass production methods and there should be a rapid re-use of moulds, which can be made to a precision not possible on-site and more intricate work can be carried out, resulting in less material wastage. Precast elements can be designed as beams supporting the weight of wet concrete and construction loads above. Thus, support scaffolding can be reduced or even eliminated altogether.
3. **Reduction in Labour and On-Site Material Demand.** There will be considerably less in-situ concrete work, thus reducing the amount of wet work on site, which in turn reduces the demand for local site labour and the import of local raw material.
4. **Better Finishes.** Units can be made to a good, even excellent standard due to the use of a trained and specialized labor working force under factory conditions. Precast units may also be cast in the most favorable orientation to improve finishes on the most important faces. Finished products can be inspected before it is erected and there is an opportunity to reject any substandard work before incorporation in the structure.

5. **Flexibility in Design.** Non-structural elements (timber inserts, electrical conduits and other services) can be incorporated into the units. Shapes and finishes may be achieved which would be difficult or impossible with in-situ concrete techniques.

6. **Better Quality.** Precast concrete can be made denser, more resistant to erosion and corrosion, less permeable, stronger, and of more uniform quality than concrete cast-in-place in the field. Improved quality of the concrete will result in lower maintenance and repair costs and longer service life for the structures.

Disadvantages

1. **Detailed Joint Connection Design Required.** The joints between precast units have to be made under site conditions. Skill is required to design and detail a joint that can be easily formed onsite whilst at the same time providing the necessary strength. Clumsy details can impair the ultimate appearance of the structure and details, which may appear satisfactory on paper, might require an excess amount of time or labour to assemble. Temporary supports may be necessary to ensure stability while the work of assembling is being carried out. To provide continuity and comply with ultimate stability requirements, some in-situ reinforced concrete acting in conjunction with the precast concrete section is often necessary.

2. **Less Flexible to Changes.** If the advantage of speed of construction is to be achieved, precast units must be made well in advance of the time when they are required onsite. Last minute changes cannot be accommodated once the precast members are cast. The functional aim in precast system is to complete all the specialized tasks (requiring trained and skilled operators) in the workmanship before the units are dispatched to site.

3. **Considerations on Handling, Transporting and Erection.** Some additional reinforcement and fittings may be required for handling, transporting and erection. It

has to be appreciated that the precast concrete member has to be designed not only to function as part of a total structure but also for the stress conditions obtained during handling, transporting and erecting. If a large amount of units are required or if they are large in size, problems can arise concerning storage areas, transportation and erection costs.

4. Member Standardization Required. Precast tends to be less suitable for buildings with irregular features. It has already been said that to obtain the greatest economy from precision moulds, there should be high degree of repetition.

5. Crane. There must be a restriction on the size and weight of precast concrete units, as they all have to be lifted and placed in the position by some means. The lifting capacity and range of cranes available can govern the size and weight of the units. Indeed, the type of crane to be considered not only with regard to the precast concrete members it has to lift but also thought has to be given to other uses of the crane throughout the building project. Cranes are expensive and full use must be made of them while they are onsite. It is no use designing precast concrete members weighing say 10 tons each if for the rest of the contract loads no greater than 5 tons are required to be lifted. This would mean the crane provided specially for the precast concrete units would be uneconomic for the rest of the job. It could, of course be removed and replaced but this again would be a very expensive operation.

2.1.4. Post-Tensioned System

In today's construction industry, architects place greater emphasis on the necessity of providing larger uninterrupted floor space and the flexibility of internal layout. Prestressing facilitated the construction of concrete floor slabs, giving larger clear spans, fewer columns and supports and reduced floor thickness. This method of construction has, over the past 20 years been widely used in many countries and has proven to be more economical than many of the traditional methods.

Prestressing technology includes post-tensioning and pre-tensioning. In post-tensioning, prestressing force is applied by jacking steel tendons against the hardened concrete member. The tendons are either inserted in the holes formed by removable cores cast in the concrete or pre-positioned before the concrete is poured. Once the tendons have been tensioned to their full force, the jacking force is transferred to the concrete through special built-in anchorage. The concentrated force applied through the anchorage set up a complex state of stress within the surrounding concrete & reinforcement is required around the anchorage to prevent the concrete from splitting. Cement grout is injected to fill the space between the tendon and the duct. This is to protect the tendon and to improve the ultimate strength capacity of the member.

The principal structural advantages of post tensioning over the use of pre-tensioning units are:

1. Structural continuity
2. Monolithic concrete joints at walls and columns
3. Greater freedom in the layout of the tendons

However, there is limitation to the length of the slab that can be post-tensioned at any one time and in areas where construction and slab-column joints are required; there is a need for careful detailing.

The advantages and disadvantages as stated below on post-tensioned construction were summarized from Teng and Sui (2003), Goodchild (1997) and Huntington and Mickadeit (1981).

Advantages

1. **Minimum Deflection and cracking.** Concrete is very strong in compression but weak in tension, i.e. it will crack when forces act to pull it apart. Post-tensioned

structures can be designed to have minimal deflection and cracking, even under full load. Hence, the quality is improved and the durability of the structure enhanced

2. Building Height and Weight Reduction. The reduced slab thickness permits a maximum exploitation of the floor and building height, meaning a lower overall building height for the same floor-to-floor height and hence less concrete requirement. Post tensioning can thus allow a significant reduction in building weight versus a conventional concrete building with the same number of floors. This reduces the foundation load and can be a major advantage. A lower building height can also translate to considerable savings in mechanical systems and facade costs.

3. Larger Span Obtainable. Larger spans are possible which permits a more flexible arrangement of partition walls. Beams and slabs can be continuous, i.e. a single beam can run continuously from one end of the building to the other. Structurally, this is much more efficient than having a beam that just goes from one column to the next.

4. Structurally Improved. By arranging the tendons in the support strip, crossing the idealized punching shear cylinder over the columns, the punching shear conditions are considerably improved. Also, as the slab is virtually crack-free and the deflection due to live loads is very small, the quality and the durability of the structure improved.

5. Shorter Construction Duration. The formwork can be removed at an earlier concrete age because deflection due to creep and shrinkage are significantly less important. The normal reinforcement steel quantity is considerably reduced and the arrangement simplified. Therefore, construction time can also be shortened.

6. Reduction/Elimination of Joints. Expansion/Construction joints can practically be eliminated resulting in cost savings and prevention of slab deterioration from forklift traffic.

7. **Improved Durability.** Post-tensioned floors are more durable and their resistance to wear and abrasion is significantly better.

Disadvantages

1. **Specialized Skill Requirement.** After stressing the tendons, the remaining space in the ducts may be left empty, or more usually be filled with grout under high pressure ('bonded construction'). Although this grout assists in transmitting forces between the steel and concrete under live loads and improves the ultimate strength of the member, the principal use is to protect the highly stressed strands from corrosion. That is why quality of the workmanship of grouting is so important to avoid air pockets being formed, which may permit corrosion. Cost will therefore be higher as skilled and experience personnel will be tasked to do the above job.
2. **Corrosion and Sensitivity to High Temperature.** In safety, if cracks should occur, corrosion can be more serious in prestressed concrete. In regards of fire resistance, the high tensile steel used in prestressed members is more sensitive to high temperatures.
3. **Required specialized equipment and material.** The adoption of the Post-tensioned System will bring about a higher unit cost; more auxiliary materials such as end anchorages, conduits and grouts are required for prestressing.
4. **Complicated Construction and Design.** More labor is required to place a unit weight of steel in prestressed concrete, especially when the amount of work involved is small. More attention and supervision to design is involved and necessary; the amount of additional work will depend on the experience of engineer and the construction crew.

2.2. Previous cost studies

2.2.1. Deductive and Inductive Cost modeling of building

The approach of building cost modeling could be classified into two different, although not mutually exclusive types, namely *deductive* modeling and *inductive* modeling (Wilson 1982). According to Skitmore and Marston (1999), the two approaches were termed *product element* modeling and *production process element* modeling.

The deductive modeling is to study a set of design variables and relate them to the cost through past cost data. It is a process to discover what the buildings should cost based on what the buildings used to cost. A formal mathematical expression relating the cost and the set of design variables was derived usually. Some of the typical design variables include GFA, volume, etc. This modeling method utilizes the statistical techniques and is largely limited by the suitability of the design variables chosen and the accuracy of the cost data.

An example of deductive cost modeling is the study of “Predesign cost estimating function for buildings” by V Kouskoulas and E. Koehn (1974). This study was for the purpose of preliminary cost estimation and the method utilized past cost information to study some relevant variables, which represented the characters of projects. The 6 independent measurable variables chosen were building locality, price index, building type, building height, building quality and building technology. A multi-linear cost-estimation function was derived in the end.

Rather than studying the given cost data, the inductive modeling, on the other hand, focuses on explaining the cost to the process of the project. It involves the synthesis of cost of individual discrete design solution from the constituent components of the design. Inductive methods require the summation of cost over some suitably defined set of

subsystems appropriate to the design. The subsystems could be operations, activities and cost centers and the most detailed subsystem would be the individual resources themselves.

Two relevant inductive studies with similar methodologies to the author's were summarized as follows:

2.2.1.2. The Study by Wilderness Group (1964)

The study by the Wilderness Group was titled "An investigation into building cost relationships of the following design variables: storey height, floor loading, column spacing, number of storeys". It was the product of the group's "several years' research". A trial design and cost calculation was carried out for steel framed building with RC slab. This study demonstrates the idea to "go right back to the first principle upon which the cost of a building arises: in fact that it should embark upon an investigation into the economics of design".

The variables used were indicated in the title. The cost was limited to structure, foundation and basic finishes, and was based on the rate from Spon's "Architects' and Builders' Price Book" 1956-1957 (82nd Edition). The findings were the relative but not absolute costs of the "core" for varying storey height, floor loading, column spacing and number of storeys. The limitations of the study included the following: the size and shape of the building were not taken into account; the application of steel-framed structure on low-rise building was not common and the extra cost in hoisting in multi-story building was not considered.

This study was considered as an inductive approach because individual design was carried out to sort out the various material quantities and price them accordingly. Although the costs were represented as varying with the sets of design variables like a deductive approach, the cost differences were in fact rooted from the different quantities

calculated due to the changes in the design variables. And material quantities are process elements.

2.2.1.2. “The Economics of Factory Buildings” by Stone (1962)

This study is part of the research in the Factory Building Studies by Her Majesty’s Stationary Office in the 1960’s. It introduced the concept of “cost in use”, which included the initial and the running cost of the factory. The “model” factory was a single-storey steel-framed building with an area of 20,000 sq. ft. The cost elements of the factory included Foundation, Floor, Structure, Walls, Roof, Stairs and Lifts. The running cost including Maintenance, Heating and Lighting was added to reach the “cost in use” of the factory.

The design variables studied included area of the factory, plan ratio, number of storeys, wall types, roof types, etc. (the “model” factory changes with some of the design variables). Design was prepared for each solution and the works were quantified and priced. The “pricing” used unit rates to measured bill. The data was collected from surveys and published price data.

Because a more detailed discussion on the quantities calculation and pricing was not presented in the study, it was impossible to judge whether sufficient considerations were given to issues like accuracy of the quantities, extra hoisting cost for multi-storey building construction, suitability of the pricing data, etc.

For the specific studies into cost of various RC structural systems, judging between the deductive and inductive cost approaches, the requirement of the deductive approach to find a reasonable large pool of historical cost data to cover various RC structural systems was extremely difficult, especially when adequate fairness in the cost comparison need to be ensued. An inductive cost approach, which goes back to the first principle of

economics in design, was then thought to be feasible and reasonable. Some cost comparisons had been done, but due to the complexity of building construction, it is difficult to get accurate results to be used as a general reference. While focusing on the inductive type of study in this field, the inductive studies could be further classified into trial-design approach and project-based comparison approach of different RC structural systems. Some previous trial-design and project-based cost comparisons were summarized at the following sections.

2.2.2. Trial-design cost comparison for various structural systems

Trial-design method is to do conceptual designs using the RC structural systems studied. Normally one whole structure is designed using two or more kinds of structural system to compare the cost on an equal basis. Effort should be made to ensure the designs in the different methods are carried out to the same standard, so that to ensure the subsequent costing are based on quantities not in favor of any single structural system.

2.2.2.1. Prestressed vs. Reinforced flat slab by D. Dowrick and N. Narasimhan (1978)

In 1978, David Dowrick and N. Narasimhan from Ove Arup and Partners did a cost comparison between prestressed and reinforced concrete flat slabs in UK. A trial-design of 5-storey building was made using reinforced coffer slab, prestressed coffer slab and prestressed solid slabs. The details of the study are presented in Table 2.1. It was found that, using coffered slab construction; the prestressed cost was about ten percent less than the reinforced concrete alternative.

Table 2.1 gives the summary of the trial-building's design information. The three slab systems studied include RC coffer slab, prestressed RC coffer slab and prestressed RC solid slab. The costs of the buildings were estimated based on standard estimating rates quoted by Quantity Surveyors of Ove Arup and partners in March, 1978 and prestressing

rates by the Prestressing Equipment Manufacturers Association in May, 1978. Allowance was also made for non-structural items, like excavation and cladding to arrive at the final cost. The cost was calculated in terms of sterling pound.

Table 2.1. Cost comparison: Prestressed vs. Reinforced flat slab

Topic	Prestressed vs. Reinforced flat slab		
Time & place of research	1978, UK		
Researcher(s)	D. Dorwick & N. Narasimhan		
Building info	48X28m plan, 5-storey with 3m clear height each floor		
Grid	10 and 12m in long direction, 8m in short direction		
Floor live load	4kN/ m ²		
Structural system	RC structure; RC coffer slab vs. PSC coffer slab vs. PSC solid slab		
Cost info (£):	RC coffer	PSC coffer	PSC solid
Structure	336,783	300,483	359,639
Excavation and earthwork	19,760	11,474	14,102
Cladding (exc. glazing)	53,899	51,511	49,466
Common items	1,942,200	1,888,532	1,888,532
Total cost	2,299,000	2,252,000	2,312,000
Overall unit cost (£/m ²)	342	335	344

For the structural cost alone, the cost using prestressed coffer slab is 12 per cent less than the one using RC coffer slab. For overall unit cost comparison, the difference is fairly small. The study by David Dowrick and N. Narasimhan did not include economic implication of timesaving from fast construction. The study was only focused on construction cost of the building. Meanwhile, only one kind of layout and loading condition was included, which cannot be used as a general guideline.

2.2.2.2. Precast vs. Conventional by A. Warszawski and D. Carmel (1984)

In 1984, A. Warszawski and Carmel conducted a trial-design cost comparison between conventional RC construction and precast construction in Israel. The precast elements

chosen were floor slabs and exterior walls. The ground floor and roofing were not included in the comparison. The design model was selected from the standard housing plans of Israeli Ministry of Building. The evaluation of cost included: the site labor requirement, the construction cost, the construction time and various considerations of more subjective nature. The details of the study are presented in Table 2.2. In the study, the fast construction of precast method was reimbursed with time-saving values, which was added to the final cost comparison.

Table 2.2. Cost comparison: Precast vs. conventional

Topic	Utilization of precast concrete element					
Time & place of research	1984, Israel					
Researcher(s)	A. Warszawski and D. Carmel					
Building info	4-storey residential building, 4 units of 94m ² -apartment each floor					
Grid	9.6m and 6.6m examined respectively					
Floor live load	N. A.					
Structural system	Conventional RC vs. precast floor slab and (or) exterior walls					
Cost information	Direct cost in US\$ per dwelling					
	Conventional	Precast floor		Non-bearing precast walls	Precast floor on PC bearing walls	
		9.6m span	6.6m span		9.6m span	6.6m span
Horizontal	2,684	3,304	2,548	2,684	2,711	1,955
Vertical	2,269	2,075	2,164	2,906	2,527	2,616
Total	4,952	5,379	4,712	5,590	5,238	4,571
Time saving:						
Time saving in month	-	1	1	1	4	3
Cost adjusted *	4,592	5,099	4,432	5,310	4,118	3,731

The cost of precast elements included their direct fabrication cost and the plant overhead. The time-saving value was examined from both the developer and contractor viewpoint. It was further assumed that values of saving of both parties were combined to an amount of about 1% of the total investment per month of construction time saved according to the study by Warszawski and Carmel (1984).

2.2.2.3. RC vs. Steel by M. M. Ali and T. C. Ang (1984)**Table 2.3. Cost comparison: RC vs. Steel**

Topic	Structural steel vs. concrete in tall buildings					
Time & place of research	1984, Singapore					
Researcher(s)	M. Ali and T. C. Ang					
Building info	ST1	RC1	ST2	RC2	ST3	RC3
	25-sty, 102m high, 21,600m ³ total FA		40-sty, 161m high, 56,560m ³ total FA		60-sty, 238m high, 153,780m ³ total FA	
Materials	Structural steel: Grade 43					
	Reinforcing steel: Grade 410					
	Concrete: G30 (G40 for lower 20 storeys in the 60-storey bldg)					
Floor live load	2.5kN/m ²					
	ST1	RC1	ST2	RC2	ST3	RC3
Structural system	Steel rigid frame	In-situ RC rigid frame	Frame with wind bracing	In-situ RC frame & shear walls	Steel framed tube	In-situ RC framed tube
Direct cost	Total in Singapore dollars					
Superstructure	4,190,455	2,701,020	13,531,535	9,103,640	46,784,139	35,781,560
Substructure	503,216	568,416	1,030,702	1,180,752	2,350,804	3,052,404
Preliminary, M&E, etc	9,000,000	9,000,000	20,000,000	20,000,000	75,000,000	75,000,000
Timesaving \$	-26,653	-	-1,071,540	-	-10,514,100	-
Net bldg cost	13,693,671	12,269,436	33,490,697	30,284,392	113,620,843	113,833,964
Unit cost (\$/m ²)	634.0	568.0	592.1	535.4	738.9	740.1

In 1984, M. M. Ali and T. C. Ang conducted a comprehensive cost comparison study for tall buildings constructed in both structural steel and reinforced concrete. Although the study was not about various RC structural systems, it did serve as a guide for cost comparison of different structural systems.

Three tall buildings were designed in both structural steel and reinforced concrete. The three configurations as shown in Table 2.3 were 25-storey, 40-storey and 60-storey high.

The factors affecting cost effectiveness of high-rise buildings were summarized by the authors as construction techniques and degree of mechanization, local infrastructure, speed of construction, performance of steel and concrete and price structure of material and labor.

The value of time-saving was calculated from early rental of floor space, saving on borrowed loan minus the income and property tax. After involving in the timesaving value, the cost of building against number of storeys was plotted. It was found the “break-even level” was 59 storeys, which means for buildings shorter than 59 storeys, concrete was more cost-effective; otherwise structural steel would be more economical.

2.2.2.4. Precast vs. semi-precast by Neo R. (1997)

From 1997 to 1998, Neo, R. did a cost comparison among precast, cast in-situ and semi-precast construction. The study was only focused on the column and beam cost, which included material, labor, equipment and transportation costs. Table 2.4 summarized the findings from Dr. Neo’s research.

Table 2.4. Cost comparison: Precast vs. Semi-precast

Time & place of research	1997-98, Singapore		
Researcher(s)	Presented by Dr. Roland Neo, Neo Co.		
Building info	N.A.		
Grid sizes	N.A.		
Floor live load	N.A.		
Structural system	PC, Semi-PC and cast in-situ beam-column		
Cost info (S\$/m ³ concrete)	PC beam and column	In-situ concrete	Shell column & hollow beam (60% in-situ joint concrete)
Unit cost (S\$/m ³)	750	600	484

Table 2.4 summarized the study on the construction using precast beam-column, in-situ beam-column and shell column & hollow beam with in-situ filled concrete. The shell column and hollow beam were pre-fabricated and the internal hollow space to be filled

with in-situ concrete occupied 60% of the total member volume. The final finding was that the shell column and hollow beam with in-filled in-situ concrete was the cheapest within the three methods studied. The cost was S\$484/m³.

2.2.3. Project-based cost comparisons for various structural systems

Many investigations of comparative structural system cost were done at project level in Singapore. These investigations were normally carried out for existing projects and one additional system were designed besides the actual design in use to compare the cost difference. The method is quite accurate but also very much project dependent. Tables 2.5 to Table 2.7 are examples of researches done on different RC structural systems in recent years in Singapore.

Table 2.5. Cost comparison: Flat plate vs. Others

Time & place of research	1998, Singapore					
Researcher(s)	Presented by Mr. John Mo, BBR construction systems Pte Ltd					
Building info:	N. A.					
Grid sizes	7.5X3.5m; 8X8m; 8X12m					
Floor live load	1.5-2kN/m ² ; 3kN/m ²					
Structural system	Flat plate		RC conventional		Flat slab with drop panel	One way post-tensioning banded beam
	7.5×3.5m, LL=1.5-2kN/m ²	8×8m, LL=3kN/m ²	7.5×3.5m, LL=1.5-2kN/m ²	8X8m, LL=3kN/m ²	8X8m, LL=3kN/m ²	8X12m, LL=3kN/m ²
Overall unit cost (S\$/m ²)	76	90.4	95.7	119.9	85.7	110.1

The comparison done by John Mo (1998) as shown in Table 2.5 was between flat plate, flat slab, conventional and banded beam constructions. The live loading ranged from 1.5-3kN/m². The cost elements included concrete, formwork, reinforcing bars and post tension cost. For different grid sizes, the most economical structural system varied. For a grid size of 7.5×3.5m, flat plate construction gives the least cost of S\$76/m², and for a grid size of 8×8m, S\$85.7/m² is provided by flat slab construction with drop panels.

The cost comparison done by Max Mayer (1997) as shown in Table 2.6 was between flat plate, flat slab, and conventional beam-slab constructions. The live loading ranged from $1.5\text{-}3\text{kN/m}^2$ and the grid sizes studied included $7.5\times 3.5\text{m}$ and $8\times 8\text{m}$. The cost elements included concrete, formwork, reinforcing bars and post tension cost. The results show that for residential building with 7.5×3.5 grid size and live loading of $1.5\text{-}2\text{kN/m}^2$, post-tensioned flat plate construction gives the cheapest unit cost of $\text{S\$}66/\text{m}^2$, and for office building with $8\times 8\text{m}$ grid size and live loading of 3kN/m^2 , flat slab with drop panels is the most economical one with a rate of $\text{S\$}74.7/\text{m}^2$.

Table 2.6. Cost comparison: Flat plate, Flat slab and Beam-slab

Time & place of research	1997-98, Singapore				
Researcher(s)	Presented by Mr. Max Meyer, VSL (S) Pte Ltd				
Building info	N. A.				
Grid sizes	$7.5\times 3.5\text{m}$; $8\times 8\text{m}$				
Floor live load	$1.5\text{-}2\text{kN/m}^2$; 3kN/m^2				
Structural system	Residential bldg ($7.5\times 3.5\text{m}$, $1.5\text{-}2\text{kN/m}^2$)		Office bldg ($8\times 8\text{m}$, 3kN/m^2)		
	Beam-slab	Post-tensioned flat plate	Beam-slab	Post-tensioned flat plate	Flat slab with drop panel
Unit direct cost ($\text{S\$}/\text{m}^2$)	83.2	66.0	102.9	79.1	74.7

The cost comparison done by Tong C. and Tan E. P. (2000) as shown in Table 2.7 was between flat slab and conventional beam-slab constructions. For different usage of the building, different forms of flat slab consecution were studied due to the different grid size and live loading requirements. The different forms of flat slab construction included flat plate, flat slab with drop panels and banded flat slab. Each flat slab construction form was compared with conventional beam-slab construction. The cost elements included concrete, formwork, reinforcing bars and post tension cost. Both the price of year 1997 and 2000 were used to compare the cost differences. The results show that for various construction requirements, the different forms of flat slab construction can give the cost saving over conventional beam slab construction.

Table 2.7. Cost comparison: Flat slab in mixed development

Time & place of research		1999-2000, Singapore					
Researcher(s)		Tong C. from ADDP Architects and Tan E. P. from Tan Ee Ping & Partners					
Building info		SunShine plaza, 3 residential blocks, 1 office block and 1 carpark block GFA=26389 m ²					
Grid		N. A.					
Floor live load		N. A.					
Structural system		Residential blocks		Carpark blk		Office blk	
		Flat plate	Convention al	Flat slab + drop panel	Conv.	Banded flat plate	Conv.
Overall unit cost (S\$/m ²)	1997 price	77.41	95.70	79.26	-	99.30	119.85
	2000 price	60.26	73.10	60.85	-	76.45	90.80

2.3. Other cost theories

2.3.1. Cost significance in construction project

The principle of cost significance in construction project is that a relatively small number of cost items contribute to a large portion of the total project cost. Many researches had been done on this topic and it was found the hypothesis true in the United Kingdoms that “80 per cent of the value of a project relates to only 20 per cent of the bill items.” This so called 80/20 rule in fact exists in many fields of human life and it is a very interesting topic.

The principle of cost significance was also investigated in Singapore. Poh (1993, 1995) did an investigation on eight student hostels in Singapore to find out that the 80/20 distributions fitted into the bills of quantities. The cost items investigated were pertaining to Builders Works only, which did not include preliminary and external works. Several

cost-significant items were chosen and the study was carried out. The number of cost significant items to the number of total builders works items were found to have an average of 20.99%, and the total cost of the cost significant items to the total builders works cost had a mean of 83.33%.

The cost significant study could greatly reduce the work in cost estimating. The author would also include this topic in the comparison for the structural cost modeling.

CHAPTER 3

DEVELOPMENT OF RESEACH FRAMEWORK

In this chapter, the research framework was presented followed by the explanations to the framework model. Clarifications were made on the trial-buildings, the designs, the Finite Element design software, the accuracy of the calculations and the construction cost & cost data collections.

This is a study on construction cost. It did not intend to calculate the “actual” construction costs of the structures; instead, the “relative” building costs were calculated. This is due to the constraint of the cost data. Details of the trial building costing method are explained in Section 3.6.

3.1. Research framework

Two kinds of inductive cost comparison approach were summarized in the previous chapters. In this study, the trial design approach was adopted because this approach can give a general overall view on the issue of cost for various structural systems.

The study was limited to three RC structural systems in a fixed-sized trial building in local context. The other two design variables were grid sizes and live loads. A number of

trial-buildings (27 buildings) with different RC structural systems, grid sizes and live loads were designed conceptually using Finite Element (FEM) software.

The material quantities (including concrete, reinforcement steel, formwork, prestress tendon, hollow core slab panel, etc) associated with each design were extracted from the design software outputs. The structural costs were worked out by multiplying the summarized material quantities and the corresponding unit rates. Only the costs of basic super-structures were considered in the cost study. Figure 3.1 shows the 4-step research framework of the cost analysis.

The 1st step is to do the preliminary member sizing. With each combination of structural system, grid sizes and live load, the preliminary sizes of the structural members were adopted from the relevant references.

The 2nd step is the analysis and design. For the trial buildings of the same size, each trial building with a particular RC structural system, grid size and live load combination was designed with proper FEM software. Software SAP2000 gave the design of the column and beam, and SAFE gave the design of the conventional slab. ADAPT Floor was used when designing post-tensioned flat slab. The member sizes were fine tuned if necessary from the preliminary member sizes adopted in Step 1. The outputs of the reinforcing steel requirement in each design section were generated.

The 3rd step is the material take-off. With the intensive help of the Microsoft excel spreadsheet, the quantity outputs generated in the 2nd step were arranged and summarized. The overall concrete, steel reinforcement, formwork and other building materials' quantities for the whole building were worked out in this step.

The 4th step is to work out the structural cost of the building by applying the unit rates onto the material quantities calculated from the previous step. The study did not intend to calculate the actual costs of the simple structures; instead, the “relative” building costs were calculated. Details of the building cost were explained in Section 3.6. The unit rates

of the various building materials came from trustable sources and the unit rate costing method was commonly used in Singapore construction industry.

Figure 3.1. Research framework for structural cost calculation

This study of structural cost has the following advantages:

1. A sufficient number of trial-buildings (27 buildings) were designed to give a general idea of the relative cost-effectiveness of various structural systems in terms of structural cost.
2. The cost-effectiveness was assessed through systems, grid sizes and live loads. It is more comprehensive compare with previous studies on structural systems.
3. The buildings were all conceptually designed using FEM software to keep a similar standard of designs.
4. Better accuracy in the quantity calculation is achieved due to the use of FEM design software.
5. The ultimate building products were kept the same even though different structural systems were used. The functions of the buildings would almost be the same besides the possible differences in the member sizes of the buildings.
6. The material quantities were calculated, so it is always possible to apply the more updated or insightful cost information to find out the cost in different time period and circumstances.

3.2. The trial-buildings

Figure 3.2. Different RC structural systems

The trial-buildings shall be suitably constructed using any of the three kinds of RC structural systems studied (figure 3.2 shows the general internal layouts). The trial-buildings were 4-storey high, with dimension of 24m×24m in plan and a total gross area of 2304m². The floor-to-floor height was 4.5 meters. The grid sizes included 4.8m×4.8m, 6m×6m and 8m×8m while the live loads ranged from 3kN/m², 7.5kN/m² to 15kN/m². The trial-buildings were more like industrial buildings rather than residential buildings.

Figure 3.3 shows the whole building and floor layout for a sample 6m×6m grid sized conventional trial-building extracted from FEM software SAP2000.

Figure 3.3. SAP2000 6m×6m grid modeling

The reason to choose the 3 different grid sizes was that the 3 sizes fitted well into the overall 24m×24m floor plan, which corresponded to 5, 4 and 3 bays. Also the 3 grid sizes used were common layouts for an industrial building. With the 3 different grid sizes, the column and beam (if any) numbers differed, so were the sizes of the structural members.

The 3 different live load inputs, 3kN/m², 7.5kN/m² and 15kN/m², were selected because they were the common live loads in industrial buildings. And the live load range well

covered light to heavy loaded buildings. Industrial professionals had also been consulted on the selection of the live loads.

Table 3.1. Trial buildings configurations

System	Live load	4.8m×4.8m	6m×6m	8m×8m
Conventional in-situ system	3kN/m ²	✓	✓	✓
	7.5kN/m ²	✓	✓	✓
	15kN/m ²	✓	✓	✓
Post-tensioned flat slab	3kN/m ²	✓	✓	✓
	7.5kN/m ²	✓	✓	✓
	15kN/m ²	✓	✓	✓
Full Precast	3kN/m ²	✓	✓	
	7.5kN/m ²	✓		
	15kN/m ²			
Precast hollow core slab with in-situ columns & beams	3kN/m ²			✓
	7.5kN/m ²		✓	✓
	15kN/m ²	✓	✓	✓

With the 3 different RC structural systems studied in different grid sizes and live loads, there would be a total of 27 conceptual designs made. Table 3.1 summarized the 27 configurations analyzed. Precast designs were divided into full precast and partial precast (precast hollow core slab with in-situ columns and beams) due to the precast member weight constraint. Details on the weight constraint were discussed in Section 5.1.4.

Figure 3.4. Secondary beam layout

For 8m×8m grid precast and conventional beam–slab design, secondary beams were used. The use of secondary beams would significantly save cost. Secondary beams in 2

directions were added in the middle for conventional design while precast design added secondary beams in one direction in the middle. Figure 3.4 shows the layout for the secondary beams for the conventional and precast systems. Although PT flat slab is normally used for large span, for the sake of comparison in a complete grid size range, PT flat slab cost was still studied for the 4.8m and 6m grid sizes.

3.3. Design assumptions

Designs were carried out according to British Standard: Structural Use of Concrete (BS8110: 1985). Only vertical loads were considered in the designs. Fixed supports and connections were used in the analysis. 1-hour fire resistance and mild exposure of concrete were assumed. Main reinforcement had a strength $f_y = 460 \text{ N/mm}^2$. The roofs were designed with 1.5 kN/m^2 live load. The designs of beams and slab for every floor were assumed to be the same (including the 1st floor). The roof was designed separately due to the load and member size differences.

The columns were of square shape and beams were rectangular. No overlapping of steel was considered. Steel in the slab used wired mesh plus steel bars configuration. Wired mesh were laid throughout the slabs and additional bars were placed in the mid spans and end spans where required.

The design assumptions for the individual structural systems were summarized below.

Conventional beam-slab design

The slabs were designed as two-way slab. The concrete used had an $f_{cu} = 30 \text{ N/mm}^2$. The imposed dead load (besides the self weight of the member) on floors and roof, which included services and partitions (if any) were 1.5 kN/m^2 and 0.5 kN/m^2 respectively.

The preliminary member sizes of columns, beams and slabs were adopted from Goodchild (1997).

Precast design

The slab used one-way precast prestressed hollow core. Concrete topping was placed on the hollow core slabs. Beams and columns mould used industrial systems (Neo, 1997). The concrete used for beams and columns had an $f_{cu}=35\text{N/mm}^2$. The imposed dead load (besides self weight of the member) on floors and roof were 2.7kN/m^2 and 1.7kN/m^2 respectively, which included topping finishing, services and partitions (if any).

The preliminary member sizes of columns, beams and slabs were adopted from CIDB (1997).

Post-tensioned flat slab design

Drop panels were used where necessary and in this study, only $8\text{m}\times 8\text{m}$ grid with live load of 15kN/m^2 used drop panels. The concrete used for slabs and columns had f_{cu} of 40N/mm^2 and 30N/mm^2 respectively. The imposed dead load (besides the self weight of the member) on floors and roof, which included services and partitions (if any) were 1.5kN/m^2 and 0.5kN/m^2 respectively. The roofs were designed as conventional since the live load was quite small.

Class 3 members were adopted in the design. The post-tensioning force over area ratio P/A was limited to be less than 3.5N/mm^2 . Necessary cover was provided. The prestress tendons were bonded and had diameters of 12mm. Ducts were group of 4 tendons and they run through the spans in the form of simple parabolic.

The preliminary member sizes and post-tensioned tendon numbers were adopted from Goodchild (1997).

3.4. Finite element analysis software

Finite element (FEM) software is commonly used for analysis. More and more designs are also carried out in FEM software because of the accuracy and saving in material achieved. FEM software SAP2000 Nonlinear, SAFE and ADAPT Floor were used in the analysis. Since SAP2000 does not generate slab design information, it was used to design column and beam while SAFE ver. 6.0 was used for conventional slab design. ADAPT Floor 1.17b was used to design post-tensioned flat slab.

The designs from FEM software might not be as conservative as the traditional designs. Since the three types of RC structural systems were all designed using FEM software, the basis for comparison was still valid and fair.

The study involved intensive design works. 27 trial-buildings were designed conceptually, which was quite some effort. Only with the help of the FEM software was the author able to finish the designs within a reasonable timeframe.

3.5. Accuracy of the calculation

Unlike ADAPT Floor, which is a design software, the FEM software SAP2000 and SAFE ver. 6.20 were more used for analysis. The results from the program were relatively not as conservative as the designs in practice. But they are still popular design tools in many parts of the world.

Because in SAP2000, the whole conceptual building, instead of one floor, was modeled to do analysis, the accuracy of using the same floor design for the 4 storeys became doubtful. To solve the doubt, the SAP2000 slab moment distributions for each floor were compared. The comparison is shown in Figure 3.4. This comparison was based on a

6m×6m grids building with live load of 7.5kN/m². It was found that the moment distributions in every floor were very close.

Figure 3.4 shows that the moment distributions in each floor are quite similar. The graph on the top left corner is the moment distribution of top floor and the one on the right is for 3rd floor and similarly, the moment distributions for 2nd and 1st floor are shown on the bottom left and right corners respectively. The contour for moment value is in the range of -30→30kN/m² as shown in the scale at the bottom of each graph.

Figure 3.5. Moment distribution for floor 4 to floor 1

For the beam design of each floor, the beams' steel reinforcement amount of the same positions from each floor was compared. Four representative points (A, B, C and D) were chosen and the results are shown in Figure 3.5. The steel quantities from the 4 points in each floor were summed up to find the total steel quantities needed. It is shown that the coefficient of variance from the total steel quantities from the 4 points was very small (0.01), which meant the value of total steel amount in each floor was very close. Thus it was concluded that the steel quantities from one of the floors could be used to represent the total steel needed.

Figure 3.6. Reinforced steel requirement (mm^2) in various beam sections for different floors

Figure 3.6 is the moment distribution comparison of SAFE and SAP2000 results. Both programs use $6\text{m} \times 6\text{m}$ grid with live load of 7.5kN/m^2 . The graph on the left is the slab moment distribution generated from SAFE program while the one on the right is a floor from SAP2000. The moment pattern is very similar to each other, so SAFE 6.0 can be used together with SAP2000 for the design of the same trial building. SAFE was used to design slabs while SAP2000 to design columns and beams, since SAP2000 does not generate slab design information.

Figure 3.7. Moment distribution in slab from SAFE 6.20 and SAP2000

3.6. Construction cost and cost data collection

3.6.1. Study scope of the construction cost

The cost of construction could be classified in 2 ways. According to the elements of construction work, the cost could be divided into: structural cost, sub-structure cost, Mechanical and Electrical cost, architectural cost, preliminary cost, etc. The other way is to divide the cost into site cost and markup. The site cost includes site direct cost and site overhead and the site overhead cost is the cost associated with the setup and maintaining of site-office. The cost markup includes company overhead and profit.

In this study, only the cost for the basic superstructure of the 4-storey building was investigated. The costs of the columns, beams (if any) and slabs were found out. The cost of staircase was not included. Due to the cost data obtained, the basic superstructure construction cost included site cost and markup. The cost information was further explained in Section 3.6.2.

3.6.2. Cost data collection and the Unit rates

As summaries by Dagostino (1993), the cost estimating methods could be classified into two types as detailed and preliminary methods. The detailed method determines the quantities and cost of everything required to complete the work including material, labor, equipment, insurance, etc and it is used for competitive bidding. The preliminary method is to multiply the volume or area of the building with an assumed cost per unit and it is used for preliminary estimating.

The unit rate costing method as described in this report is to sum up the construction cost of each construction material. The construction cost of each construction material could be found by multiplying the construction material quantity by its corresponding unit rate. For the construction of basic superstructure, the works could be classified into concrete work, reinforcement steel work, formwork work and other works, e.g. prestress work. After acquiring the various material quantities and the unit rates for each, the construction cost of the basic superstructure could be found out using Equation 3.1.

$$\text{Construction cost} = \sum (\text{unit cost} \times \text{material quantities}) \quad (\text{Eqn. 3.1})$$

The unit rate for each building material, e.g. “\$/m³ concrete work, \$/ton steel work” consists the cost of material, labor and necessary equipments and markup. The unit rates for the same building material under different structural system could be different and this was explained in details in Section 5.1. As explained in CPG cost index (CPG 2003), the rates included:

- 1) Labor and all costs in connection therewith
- 2) Materials and goods including waste, laps, joints, and all costs in connection with
- 3) Supplying, transporting, delivering, unloading, storing and hoisting materials and return of packings

- 4) Straight, raked or circular cutting
- 5) Fabricating, assembling, fitting, fixing and bedding materials and goods in position
- 6) Preparing surfaces to receive work
- 7) Protecting materials and work
- 8) Machinery, equipment and all costs in connection therewith
- 9) Cleaning up on completion and making good all work disturbed
- 10) Establishment charges, overhead charges, preliminaries and profit.

For the unit rate of each construction material, the rate was further clarified and explained in the CPG cost index as follows:

In-situ concrete rate:

- 1) Temporary grounds, pipes and boxings to form grooves, chases, mortices, holes and openings
- 2) Laying on any types of sub-base and laying on falls and campers
- 3) Compacting concrete by tamping or vibrating
- 4) Working between and around reinforcement

Reinforcing steel rate:

- 1) Cleaning and wire-brushing bars to remove rust, dust, mill scale, dirt, oil and other deleterious matters
- 2) Bending, cutting and notching around obstructions
- 3) Hooks and tying wires at all joints and crossings
- 4) Non-designed spacers or chairs and distance blocks

The rate of each item of Bar Reinforcement shall be applicable only to bar not exceeding 12m in length and shall include allowances for rolling margin.

Timber formwork rate:

- 1) Boarding, battens and supports
- 2) Erecting, framing, bolting and wedging

- 3) Wetting and treating with mould oil
- 4) Notching, allowance for overlaps and passage at angles
- 5) Forming chamfered edges and splayed internal angles not exceeding 50mm wide
- 6) Casting, skirting and removal of formwork

Precast hollow core slab rate:

- 1) Provision of recesses, brackets, embedded fixtures, covered opening and other services
- 2) Sealing the voids with approved epoxy, concrete and other materials
- 3) Hoisting with a lifting beam and top-lift clamps and accessory safety chains or belts
- 4) Conforming to water tightness as required

The unit rate, expressed as “fixed schedule of rates” in CPG Cost Index Quarterly, is “intended to be used for the pricing of variations” (CPG 2003). The rates are not used to price the whole project, but it could well reflect the relative construction costs of different construction materials.

As the costs for material, labor, equipment, etc are always fluctuating; a unified cost system could well reduce the variation and give a clearer overall picture. The unit rates were worked out through statistical means and they were tracked by both government agencies and private consultants including BCA (Building and Construction Authority of Singapore) and CPG Corporation over the years for quantity surveying and cost estimates purpose. It would be reasonably reliable in Singapore circumstance.

The unit rates from CPG (2003) did not include prestress cost, so the prestress unit rate was obtained from Singapore prestress contractors. The unit rates as extracted from CPG cost index quarterly (CPG 2003) and one major prestress contractor in Singapore were shown in Table 3.2.

Special attention must be paid when the sources of the different building materials’ unit rates were not the same. In this case, the unit rate for post-tensioned tendon was not the

same as the other materials. The basis for comparison might not be very fair in such circumstance. Cost information was very sensitive and confidential in the construction market, and in this study, the author tried to use the available cost information to give a reasonably fair cost comparison. Readers are always encouraged to use their own cost information (if available) to study the cost together with the material quantities obtained in this study.

Table 3.2. CPG unit rates 2003 Q3

Material	Description	Unit	Price (S\$)
Lean concrete	Grade 20	m ³	83
Reinforced concrete	Grade 30	m ³	82
	Grade 35	m ³	84
	Grade 40	m ³	86
	10mm diameter Mild steel	ton	1000
Reinforcement	10mm diameter HT	ton	930
	13mm diameter HT	ton	990
	16mm diameter HT	ton	980
	20mm diameter HT	ton	970
	22mm diameter HT	ton	960
	25mm diameter HT	ton	960
Fabric reinforcement	A7	m ²	4.11
	A8	m ²	5.27
	A9	m ²	6.57
	A10	m ²	8.01
Timber Formwork	Plan surface	m ²	23
	Plan surface (for flat slab)	m ²	19.55
Precast hollow core slab	215mm thick	m ²	61
	265mm thick	m ²	69
	325mm thick	m ²	79
	360mm thick	m ²	87
Prestress tendon	12mm bonded, duct of 4 cables	m	9.5

Source: CPG cost index 2003 Q3 and information provided by a local prestress company in Singapore

The unit rate information was more suitable to be applied on conventional construction, which is still the most widely used construction method in Singapore. Thus, necessary adjustment was carried out for the unit rates in other RC structural systems. For example, the unit rate of formwork for flat slab construction would generally be less than that for

conventional construction. Also, the formwork unit rate in the CPG cost index is for on-site timber formwork, and modifications on the rates were made for the formwork cost for precast members. Details of the adjustment were discussed in Section 5.

CHAPTER 4

DESIGN QUANTITIES AND CALCULATIONS

Lots of designs were carried out to calculate material quantities for different RC structural systems. The designs were done with reference to the relevant design guidebooks, including CIDB (1997) and Goodchild (1997). For 8m×8m grid precast and conventional beam–slab design, secondary beams were used. The use of secondary beams would significantly save cost. Secondary beams in 2 directions were added in the middle for conventional design while precast design added secondary beams in one direction in the middle.

As mentioned previously, the structural cost can be grouped according to building materials, which include formwork cost, concrete cost, reinforcing steel cost and other material cost like prestress tendon cost. For each trial building, the quantities of concrete and formwork could be easily found after determining the sizes of the structural members. The tedious part was to find the quantities of steel reinforcement in the members.

4.1. Concrete, formwork and prestress Tendon

Table 4.1 (1). Member sizes for conventional system

		4.8mX4.8m	6mX6m	8mX8m	8mX8m with sec beams
Slab (mm) (d)	1.5kN/m ² (roof)	140	160	220	135
	3kN/m ²	152	180	240	140
	7.5kN/m ²	160	190	252	140
	15kN/m ²	200	250	300	160
Beam (mm) (bXd)	1.5kN/m ² (r)	250x300	250x450	300x600	250x400
	3kN/m ²	250x400	300x500	300x600	250x400
	7.5kN/m ²	250x400	300x500	350x650	300x450
	15kN/m ²	300x400	300x500	400x650	300x500
Column (mm) (d)	1.5kN/m ² (r)	400	450	500	500
	3kN/m ²	400	450	550	550
	7.5kN/m ²	400	550	650	650
	15kN/m ²	500	650	750	750

Table 4.1 (2). Member sizes for precast system

		4.8mX4.8m	6mX6m	8mX8m	8mX8m with sec beams
Slab (mm) (d)	1.5kN/m ² (roof)	215hc*	215hc	265hc	215hc
	3kN/m ²	215hc	215hc	265hc	215hc
	7.5kN/m ²	215hc	265hc	265hc	265hc
	15kN/m ²	265hc	325hc	360hc	265hc
Beam (mm) (bXd)	1.5kN/m ² (r)	250x450	250x550	600X800	300x700
	3kN/m ²	250x450	250x650	600X800	300x700
	7.5kN/m ²	300x500	600x750	800x800	450x700
	15kN/m ²	500x600	800x800	1000x900	500x800
Column (mm) (d)	3kN/m ²	400	400	550	550
	7.5kN/m ²	450	550	650	650
	15kN/m ²	550	650	800	800

Table 4.1 (3). Member sizes for PT flat slab system

		4.8mX4.8m	6mX6m	8mX8m
Slab (mm) (d)	1.5kN/m ² (roof)(conv.)	140	160	135
	3kN/m ²	180	200	200
	7.5kN/m ²	180	200	210
	15kN/m ²	200	220	210DP*
Column (mm) (d)	1.5kN/m ² (r)(conv.)	400	450	500
	3kN/m ²	400	450	550
	7.5kN/m ²	400	550	650
	15kN/m ²	500	650	750

(* DP: with drop panel)

Table 4.1 shows the member sizes for the various structural configurations. They were adopted and modified from the preliminary sizing in the studies mentioned at the beginning of this Chapter. The beams were rectangular and expressed as the width $\times$ depth in the table. The sizes of the columns, beams and slabs were expressed in millimeter. The precast slab used hollow core (hc) slab. The PT flat slab used flat plate except the configuration of 8m $\times$ 8m grid with 15kN/m², which used drop panels.

For conventional and precast construction with 8m $\times$ 8m grid size, designs were made both with and without secondary beams. Finally, 8m $\times$ 8m buildings with secondary beams were used in the comparison because this configuration was more reasonable. The roof in PT flat slab construction was the same as conventional in-situ beam-slab system and the roof beam and slab sizes would be the same as the sizes for conventional construction in Table 4.1 (1).

With the member sizes determined, the concrete and formwork quantities could be calculated directly, and they are shown in Table 4.2. In Table 4.2, the concrete quantities in m³ and formwork quantities in m² are shown. The quantities were arranged according to various structural systems, grid sizes and live loads. They were further classified into column, beam and slab quantities. The formwork was calculated as the material necessary to cover and do the molding. For precast construction, there were no concrete and formwork quantities for slabs since they were industrialized hollow core slab. But the concrete quantities for in-situ topping on precast slabs were summarized.

Table 4.2. Overall concrete and formwork quantities for various configurations

Conventional		Concrete (m³)			Formwork (m²)		
		Column	Beam	Slab	Column	Beam	Slab
4.8×4.8	3kN/m²	103.7	136.8	430.9	1036.8	1023.6	2880.0
	7.5kN/m²	103.7	136.8	449.3	1036.8	1005.1	2880.0
	15kN/m²	147.4	159.8	541.4	1231.2	970.6	2880.0
6×6	3kN/m²	91.1	171.0	506.9	810.0	1101.6	2880.0
	7.5kN/m²	124.9	171.0	529.9	945.0	1082.4	2880.0
	15kN/m²	165.4	171.0	668.2	1080.0	967.2	2880.0
8x8 (with sec. beams)	3kN/m²	83.3	244.8	400.3	619.2	1729.0	2880.0
	7.5kN/m²	109.3	301.4	400.3	705.6	1930.6	2880.0
	15kN/m²	139.5	335.0	446.4	792.0	1972.8	2880.0
Precast		Concrete (m³)		Concrete Topping (m³)	Formwork (m²)		
		Column	Beam	Slab	Column	Beam	
4.8×4.8	3kN/m²	103.7	162.0	144.0	972.0	1656.0	
	7.5kN/m²	131.2	183.6	144.0	972.0	1828.8	
	15kN/m²	196.0	270.0	144.0	1490.4	2289.6	
6×6	3kN/m²	72.0	177.0	144.0	759.4	1812.0	
	7.5kN/m²	136.1	315.0	144.0	1141.9	2340.0	
	15kN/m²	190.1	406.2	144.0	1321.9	2628.0	
8x8 (with sec. beams)	3kN/m²	87.1	277.2	144.0	777.6	2244.0	
	7.5kN/m²	121.7	388.1	144.0	892.8	2402.4	
	15kN/m²	184.32	477.84	144	1065.60	2666.4	
Post-tensioned flat slab		Concrete (m³)			Formwork (m²)		
		Column	Roof beam	Slab	Column	Roof beam	Slab
4.8×4.8	3kN/m²	103.7	21.6	495.4	1036.8	164.2	2880.0
	7.5kN/m²	103.7	21.6	495.4	1036.8	164.2	2880.0
	15kN/m²	147.4	21.6	541.4	1231.2	164.2	2880.0
6×6	3kN/m²	91.1	27.0	553.0	810.0	199.2	2880.0
	7.5kN/m²	124.9	27.0	553.0	945.0	199.2	2880.0
	15kN/m²	165.4	27.0	599.0	1080.0	199.2	2880.0
8×8	3kN/m²	83.3	48.9	538.6	619.2	291.4	2880.0
	7.5kN/m²	109.3	48.9	561.6	705.6	291.4	2880.0
	15kN/m²	139.5	48.9	578.6	792.0	291.4	2961.0

The prestress tendons used in post-tensioned flat slab construction were grouped in flat ducts, and every duct comprising 4 tendons run through the spans in the form of simple parabolic. Figure 4.1 shows a tendon layout for the 6m×6m grid with live load of 7.5kN/m², with each solid line represents one strip of duct consisting 4 tendons of 12mm diameter each. About 60% to 75% of the post-tensioned tendons were distributed along the column strips while the remaining in the mid strips.

The tendon quantities, in the unit of meter for the 4-tendon-duct, ranged from 4608m to 7296m. 7296m of duct was used for 8m×8m grid with live load of 15kN/m² and 5760m of duct was used for 8m×8m grid with live load of 3kN/m² and 7.5kN/m². The other configurations of PT flat slab all used 4608m of PT duct.

Figure 4.1. Sample tendon layout

4.2. Reinforcing Steel quantities

The reinforcing steel design included longitudinal steel and shear steel designs. The shear reinforcement used 10mm mild steel or high tensile steel. Wire mesh is the first choice for steel in the slab. The minimum steel reinforcement requirement and maximum reinforcement spacing were followed accordingly in the quantity collections. Detailed outputs from the finite element software and the calculation spreadsheets are attached in the appendices.

The illustration sample of the calculations and results sheets in this section was of 6m×6m grid with 7.5kN/m² in conventional beam-slab construction. The overall steel

quantities together with the concrete, formwork and tendon quantities were summarized in the tables in Appendix A.

4.2.1. Reinforcing steel quantities in columns

The steel quantities in columns included longitudinal and shear reinforcement. For simplicity, the longitudinal steel reinforcement in the column was assumed to be the same continuously throughout for the 4 storey low-rise trial building. The longitudinal reinforcement bars were welded in connection, so no overlapping of reinforcement bars was considered.

Table 4.3. Sample steel quantities for columns

Elem	Station	Longitudinal (mm ²)	Shear22 (mm ² /mm)	Shear33 (mm ² /mm)
1	0	1210	0.55	0.55
1	2160	1210	0.55	0.55
1	4320	1210	0.55	0.55
2	0	1210	0.55	0.55
2	2160	1210	0.55	0.55
2	4320	1210	0.55	0.55
3	0	1210	0.55	0.55
3	2160	1210	0.55	0.55
3	4320	1210	0.55	0.55
4	0	1210	0.55	0.55
4	2160	1210	0.55	0.55
4	4320	1210	0.55	0.55

Table 4.3 gives the simplified column steel quantities output sample from SAP2000. Bigger sample of the original SAP2000 output for column was attached in Appendix B. Because this column was of the size 550mm×550mm, 12 no of reinforcement steel bars were used in each column. The shear link spacing in the column should not exceed 12 times minimum longitudinal bar diameter. In this case, the minimum longitudinal bars

chosen were 12 numbers of T16 and the total cross-sectional area was 2411 mm^2 . Additional longitudinal steel bars were added where necessary. The shear requirement for Element 1 to 4 was $0.55 \text{ mm}^2/\text{mm}$ and by providing T10 at 250mm interval ($0.628 \text{ mm}^2/\text{mm}$) the requirement for shear reinforcing was met.

4.2.2. Reinforcing steel quantities in beams

The beam longitudinal reinforcing steel design adopted the arrangement as shown in Figure 4.2. In the sample illustration, 2 T13 bars on top and 2 T13 bars at bottom were put throughout the beam for tying of shear links. Additional reinforcement was placed at mid-span or edges where applicable. For simplicity, the mid-span additional bottom reinforcement length was 60% of the beam span length, and the end-span additional reinforcement bars length on the top of the beams was 25% of the span length extended to both side of the column.

Figure 4.2. Sample reinforcing steel arrangement in beams

Table 4.4. Sample steel quantities calculation for beams

Elem ID	Station ID	Top (mm²)	Bttm (mm²)	Shear (mm²/mm)	End (Top) (mm²)	Mid Bttm (mm²)	Other (mm²)
581	275	409.9	0	0.3	614859	0	2149173
581	581.25	264.2	0	0.3	0	1375851.6	0
581	887.5	121.7	0	0.3	0	0	0
581	1193.75	0	195	0.3	0	0	0
581	1500	0	195	0.3	0	0	0
					0	0	0
582	0	0	195	0.3	0	0	0
582	375	0	226.4	0.3	0	0	0
582	750	0	282.3	0.3	0	0	0
582	1125	0	334.2	0.3	0	0	0
582	1500	0	382.2	0.3	0	0	0
					0	0	0
583	0	0	381.3	0.3	0	0	0
583	375	0	321.9	0.3	0	0	0
583	750	0	258.5	0.3	0	0	0
583	1125	0	195	0.3	0	0	0
583	1500	0	195	0.3	0	0	0
					0	0	0
584	0	0	195	0.3	0	0	0
584	306.25	24.11	0	0.3	0	0	0
584	612.5	156.5	0	0.3	0	0	0
584	918.75	291.5	0	0.3	0	0	0
584	1225	430.9	0	0.3	646320	0	0

Table 4.4 gives the simplified output from SAP2000 and the some calculations of steel reinforcement for beams. More detailed information about the beam design output could be found in Appendix C. In the calculation, the sides possible to provide additional longitudinal bars were firstly determined and that was the top at the ends of the beam and at bottom of the beam mid-span. Minimum longitudinal steel, which was represented as

“Other” in the table was calculated from the minimum steel requirement due to the beam size. Additional amount of longitudinal reinforcement was calculated from the results generated from SAP2000. In this case, the additional steel at top and bottom for Element 581-584 were 614859 and 1375851.6mm³ respectively. The shear link uses T10 at 250mm intervals also and the shear reinforcement area provided was 0.628mm²/mm, which was greater than the minimum design requirement 0.3mm²/mm for shear reinforcing at this section.

4.2.3. Reinforcing steel quantities in slabs

The steel quantities in the slabs were calculated by Finite Element software SAFE (conventional slab) and ADAPT (PT flat slab). Floor slab and roof slab were designed separately. Sample of SAFE and ADAPT outputs were attached in Appendix D and E. The steel reinforcement in slabs used wired mesh plus steel bar configuration and the wired mesh in this sample trial building was of size A8 (for wired mesh code: refer to Appendix F) for both the floor and roof slabs. The reinforcement in the slab was arranged according to column-strips and mid-strips. No vertical reinforcement was provided in the slab.

The minimum steel reinforcement requirement and maximum reinforcement spacing were followed accordingly in the quantity collection for the slabs.

4.2.4. Total reinforcing steel quantities

After calculating the steel quantities in columns, beams and slabs, the total steel quantities for a trial-building of 6m×6m grid with 7.5kN/m² live load in conventional beam-slab construction was summarized in Table 4.5.

Table 4.5. Total steel quantity for the trial-building

Steel quantities		Column	Beams		Slab			
			Floor	Roof	Floor		Roof	
Main Steel	Vol (m ³)	1.26428	0.958	0.135	1.63	Mesh A8	0.71	Mesh A8
	Mass (ton)	9.8614	7.474	1.05	12.73		5.51	
Shear Steel (B10)	Vol	0.37445	0.588					
	Mass	2.92067	4.585					

The overall steel quantities data sheet for the trial buildings with different configurations can be found in Appendix A.

CHAPTER 5

RESULTS AND DISCUSSIONS

5.1. Modified unit rates and other considerations

To work out the cost of each trial-designed building, proper unit rates must be applied onto the designed quantities. The unit rates directly extracted from CPG cost index are more suitable for conventional in-situ construction. For flat slab construction and precast construction, the unit rates should be modified in the cost calculations.

5.1.1. Flat slab unit rates

For flat slab construction, because of the ease in the reinforcing steel and formwork work in the slab construction, lower unit rates should be provided compared with conventional reinforcing steel and formwork unit rates.

Lau and Ng (1996) reported a relationship of reinforcing steel and formwork unit rates for slab between flat slab and conventional beam-slab as 0.8 and 0.85, which meant flat slab unit rates were lower by 20% and 15% for reinforcing steel and formwork work respectively. It was assumed the proportion of 0.8 and 0.85 still hold for 2003 Singapore

rates, thus the modified flat slab reinforcing steel and formwork unit rates from CPG cost index were shown in Table 5.2.

5.1.2. Precast costing

Precast construction cost was not directly found out by multiplying the quantities with respective unit rates. The cost of a precast member can be divided into component, delivery and installation costs. Studies on precast costing include Neo (1997) and BCA (1999). The component cost could be further divided into concrete, steel and formwork costs as like conventional construction.

There was a significant cost saving in precast component formwork cost and it was due to the use of standardized mould (formwork), which facilitated high number of formwork reuse (Neo 1997). Due to the project size constraint, project-based mould was used. The mould cost for columns and beams would go down to about 10% of the conventional formwork if maximum efficiency of the project-based mould was achieved, which was about 100 times of use.

Efficiencies of 80% for beams and 70% for columns were assumed for mould reuse because the column number ranged from 64 to 144 and beam number ranged from 210 to 250 from 4.8×4.8m grid to 8m×8m grid. Formwork material cost makes up about 40% of the formwork unit rate for timber formwork. Assuming the other costs making up the mould unit rate are the same for in-situ and precast formwork, thus the mould unit rates for precast column and beam could be reduced to:

$$\begin{aligned}\text{Column mould:} & \quad 23 \times 60\% + 23 \times 40\% \times 10\% \div 70\% = \$15.1/\text{m}^2 \\ \text{Beam mould:} & \quad 23 \times 60\% + 23 \times 40\% \times 10\% \div 80\% = \$15.0/\text{m}^2\end{aligned}$$

The delivery and installation costs also make up significant portions in overall precast construction cost and the cost percentages were studied by Neo and BCA. Table 5.2 summaries the cost percentages of delivery and installation in the total precast member

cost. The cost percentages as studied were quite close. There was on average a 3.25% cost component on delivery and 18.75% for installation. In total, there was a 22% cost component for delivery and installation in total. As the CPG unit rate for precast hollow core slab included delivery and installation cost as discussed in Section 3.6.2, the additional 22% delivery and installation cost would be applied onto precast column and beam component costs assuming off-site precasting.

Table 5.1. Proportions of delivery and installation cost in total PC member cost

	Delivery	Installation	Total
Neo 1997:	4%	20%	24%
BCA 1999	2-3%	15-20%	20%
Average	3.25%	18.75%	22%

Table 5.2. Modified CPG unit rates 2003 Q3

Material	Description	Unit	Price (S\$)
Lean concrete	Grade 20	m ³	83
Reinforced concrete	Grade 30	m ³	82
	Grade 35	m ³	84
	Grade 40	m ³	86
	10mm diameter Mild steel	ton	1000
Reinforcement	High Tensile (slab)	ton	980
	HT (column/beam)	ton	980
	HT (flat slab)	ton	784
Fabric reinforcement	A7	m ²	4.11
	A8	m ²	5.27
	A9	m ²	6.57
	A10	m ²	8.01
Timber Formwork	Plan surface	m ²	23
	Plan surface (for flat slab)	m ²	19.55
Project-based mould (precast)	Column	m ²	15.1
	Beam	m ²	15.0
Precast hollow core slab	215mm thick	m ²	61
	265mm thick	m ²	69
	325mm thick	m ²	79
	360mm thick	m ²	87
Prestress tendon	12mm bonded, duct of 4 cables	m	9.5

5.1.3. Other modified unit rates

In slab reinforcing, the reinforcing steel was mainly T13; while in beams and columns, it was mainly T16. So, the reinforcing steel unit rates were averaged and grouped into slab and column/beam rates from the original different rates for different bar sizes in the CPG cost index. Take into consideration the different flat slab and precast unit rates; the overall modified unit rates were presented in Table 5.2.

5.1.4. Precast member mass

One important consideration in precast construction is the member weight and crane capacity. If the member weight exceeds normal crane capacity, bigger crane has to be brought in for lifting and the cost would have to be increased by a lot. Neo (1997) suggested member mass to be less than 3 ton for normal crane to function.

Table 5.3. Precast member mass

Precast		Column			Beam			
		d (mm)	Length (m)	Weight (ton)	b (mm)	d (mm)	Length (m)	Weight (ton)
4.8×4.8	3kN/m²	400	4.5	1.728	250	450	4.8	1.296
	7.5kN/m²	450	4.5	2.187	300	500	4.8	1.728
	15kN/m²	550	4.5	3.267	500	600	4.8	3.456
6×6	3kN/m²	400	4.5	1.728	250	650	6	2.34
	7.5kN/m²	550	4.5	3.267	600	750	6	6.48
	15kN/m²	650	4.5	4.563	800	800	6	9.216
8×8	3kN/m²	550	4.5	3.267	600	800	8	9.216
	7.5kN/m²	650	4.5	4.563	800	800	8	12.288
	15kN/m²	800	4.5	6.912	1000	900	8	17.28
8x8 (with sec. beam)	3kN/m²	550	4.5	3.267	300	700	8	4.032
	7.5kN/m²	650	4.5	4.563	450	700	8	6.048
	15kN/m²	800	4.5	6.912	500	800	8	7.68

Since the trial buildings in the author's study were not of big size, it was not practical to use big cranes. Neo's finding was followed and the precast members weighted over 3

tons were changed to be constructed on site. Table 5.3 shows the member mass for the various configurations. In this case, as shown in bold italic letters in Table 5.3, only 4.8m×4.8m grid with live load of 3 and 7.5kN/m² and 6m×6m grid with live load of 3kN/m² were fully precast. Buildings of other precast configurations were constructed with precast hollow core slab with in-situ beams and columns.

5.2. Structural cost (SC)

5.2.1. Total structural cost

After the designs were done and the quantity and cost information obtained, the structural costs (SC) of the trial-buildings were worked out using Equation 3.1. Special attention must be paid when the sources of the different building material unit rates were not the same. In this case, the unit rate for post-tensioned tendons was not the same as the other materials. The basis for comparison with the post-tensioned flat slab system might not be as consistent.

Table 5.4. SC (S\$/m²) and cost differences

Grid (m)	LL (kN/m ²)	Conv (S\$/m ²)	Precast		PT flat slab	
			(S\$/m ²)	dif over Conv	(S\$/m ²)	dif over Conv
4.8x4.8	3	98.81	131	32.58%	98	-0.72%
	7.5	107.19	136	26.87%	98	-8.33%
	15	125.44	161	28.01%	105	-15.98%
6x6	3	104.04	128	23.02%	99	-5.23%
	7.5	120.05	156	29.60%	103	-14.52%
	15	136.26	174	27.82%	109	-19.83%
8x8 (with sec. beams)	3	102.44	141	37.86%	99	-3.41%
	7.5	113.24	161	42.60%	102	-9.81%
	15	127.74	178	39.17%	113	-11.32%
				31.95%	Average	-9.91%

Cost information was very sensitive and confidential. In this study, the author tried to use the available cost information to give a reasonably fair indicative cost comparison. It is

always encouraged to use other cost data (if available) to study the cost in conjunction with the material quantities obtained from this study.

Figure 5.1. Structural Cost (\$/m²) vs. Grid Sizes (m) for various Live Loads

The detailed quantities and costs data sheets for the various trial-buildings were attached in Appendix A. The summary of the structural cost for various live loads, structural systems and grid sizes were shown in Table 5.4 and they were also plotted in Figure 5.1 for better illustration. As discussed in Section 5.1.4, the figures in italic fonts for the

precast construction means fully precast structures with slabs, beams and columns precast, while the other precast configurations used only precast hollow core slabs with in-situ beams and columns due to the member weight constraint.

Figure 5.1 was plotted using the average cost per square meter of building area against the grid sizes for each of the 3 live loads. Table 5.4 and Figure 5.1 show that the structural cost of precast is more than the other 2 alternatives for every configuration. For fully precast buildings, the increase in unit cost is not as significant as the partially precast buildings, which represent larger grid and live load.

On average, full precast buildings cost 27.5% more than conventional construction while buildings with precast hollow core slab and in-situ beam-column cost 34.2% more than their conventional counterparts. Precast beams and columns gave cost advantages due to the use of the special moulds, which gave high number of usage. The high cost of precast hollow core slab seemed to be the main reason to drive up the building cost, and details of the individual member costs were discussed in Section 5.2.2. The higher cost of precast construction could also be partially due to the relatively conservative member size guidance from the CIDB precast design guidebook.

Post-tensioned flat slab construction was more cost-effective for larger grid sizes and higher load. The saving ranged from 0.7% to 19.8% over conventional construction. The cost of PT flat slab construction varies with the design requirements. In this study, the buildings were designed with class 3 members. Due to the different source of post-tensioned tendon unit rate, the cost for PT flat slab buildings could be inconsistent with the other two structural systems to certain extent.

For the same live load value, looking at the grid sizes, it was found that at 6m×6m grid, the conventional construction gave a slightly higher cost than 4.8 and 8m grid sizes. The drop of building cost from 6m grid to 8m grid was due to the use of the secondary beams in the 8m grid sized buildings. The secondary beams effectively reduced the bay size to 4m and the slab thickness was reduced. 8m grid-sized buildings without secondary beams

were expected to give a much higher cost compared to 6m grid size buildings. A relatively flat cost curve for PT flat slab construction reveals that the system has greater cost advantage for larger spans.

5.2.2. Structural cost breakdown

Table 5.5 (1). Cost breakdown for building materials in conventional construction

Grid (m)	LL (kN/m ²)	Total Cost (\$)	Steel		Concrete		Formwork	
			Cost (\$)	%	Cost (\$)	%	Cost (\$)	%
4.8	3	227658	58981	25.9%	55049	24.2%	113628	49.9%
	7.5	246973	77209	31.3%	56560	22.9%	113204	45.8%
	15	289018	102544	35.5%	69593	24.1%	116880	40.4%
6	3	239720	66454	27.7%	63058	26.3%	110207	46.0%
	7.5	276607	96021	34.7%	67715	24.5%	112870	40.8%
	15	313948	118251	37.7%	82372	26.2%	113326	36.1%
8	3	236022	56040	23.7%	59734	25.3%	120248	50.9%
	7.5	260906	67531	25.9%	66504	25.5%	126872	48.6%
	15	294313	88965	30.2%	75517	25.7%	129830	44.1%
Ave				30.3%		25.0%		44.8%
Std Dev				0.046		0.011		0.046

Table 5.5 (2). Cost breakdown for building materials in PT flat slab construction

Grid (m)	LL (kN/m ²)	Total Cost (\$)	Steel		Concrete		Formwork		Tendon	
			Cost (\$)	%	Cost (\$)	%	Cost (\$)	%	Cost (\$)	%
4.8	3	226014	42746	18.9%	52874	23.4%	86618	38.3%	43776	19.4%
	7.5	226403	43135	19.1%	52874	23.4%	86618	38.3%	43776	19.3%
	15	242840	47551	19.6%	60423	24.9%	91089	37.5%	43776	18.0%
6	3	227190	43967	19.4%	57241	25.2%	82207	36.2%	43776	19.3%
	7.5	236435	47339	20.0%	60008	25.4%	85312	36.1%	43776	18.5%
	15	251700	52215	20.7%	67292	26.7%	88417	35.1%	43776	17.4%
8	3	227963	36144	15.9%	57160	25.1%	79939	35.1%	54720	24.0%
	7.5	235305	37393	15.9%	61267	26.0%	81926	34.8%	54720	23.3%
	15	261007	41693	16.0%	65209	25.0%	84793	32.5%	69312	26.6%
Ave				18.4%		25.0%		36.0%		20.6%
Std Dev				0.018		0.010		0.018		0.030

To further breakdown the cost into concrete, formwork, steel and PT tendon cost, more insights could be found. Table 5.5 shows the building structural cost breakdown for the building materials for different RC structural systems. Since the precast construction cost components involved delivering and installing cost, it was not shown in Table 5.5. As shown in Table 5.5, the standard deviations of the cost components of various configurations are not very significant. Thus, the average cost components according to the various materials were plotted in Figure 5.2 to give a clearer illustration.

Figure 5.2 reveals that the formwork cost makes up almost half of the total structural cost for conventional construction, while for PT flat slab system, the figure is 36%. After finding out that the overall PT flat slab structure cost is less than the conventional construction in this study, the saving in formwork cost of PT flat slab construction is quite significant from conventional construction's 45%. The saving was due to the use of flat slab, which is easier to put up the formwork and also eliminates the formwork cost for floor beams.

From the figure, the formwork cost was always the highest among the building materials and this suggested that formwork was the factor to give more attention to in value engineering in order to save cost. The post-tension tendon cost was quite significant at 21% of the total structural cost for PT flat slab construction.

Figure 5.2. Cost breakdown to building materials

Table 5.6. Cost breakdown according to structural members

	Grid (m)	LL (kN/m ²)	Total Cost (\$)	Column		Beam		Slab	
				Cost (\$)	%	Cost (\$)	%	Cost (\$)	%
Conv	4.8	3	227658	45379	19.9%	44510	19.6%	137769	60.5%
		7.5	246973	45697	18.5%	45074	18.3%	156202	63.2%
		15	289018	58131	20.1%	48726	16.9%	182160	63.0%
	6	3	239720	35427	14.8%	51003	21.3%	153290	63.9%
		7.5	276607	44560	16.1%	51855	18.7%	180192	65.1%
		15	313948	55842	17.8%	50064	15.9%	208042	66.3%
	8	3	236022	28201	11.9%	80679	34.2%	127142	53.9%
		7.5	260906	32904	12.6%	94843	36.4%	133159	51.0%
		15	294313	39371	13.4%	106785	36.3%	148156	50.3%
	Average				16.1%		24.2%		59.7%
	Std deviation				0.029		0.082		0.059
Full PC	Grid (m)	LL (kN/m ²)	Total Cost (\$)	Column		Beam		Slab	
				Cost (\$)	%	Cost (\$)	%	Cost (\$)	%
	4.8	3	300809	43348	14.4%	63928	21.3%	193533	64.3%
	4.8	7.5	312465	46721	15.0%	72211	23.1%	193533	61.9%
	6	3	294543	31736	10.8%	69273	23.5%	193533	65.7%
	Ave				13.4%		22.6%		64.0%
PC HC slab	Std Dev				0.0185		0.0099		0.0156
	4.8	15	369986	66181	17.9%	91220	24.7%	212585	57.5%
	6	7.5	358477	48418	13.5%	97475	27.2%	212585	59.3%
		15	401299	60344	15.0%	114082	28.4%	226873	56.5%
		3	325389	35050	10.8%	96806	29.8%	193533	59.5%
	8	7.5	372051	41120	11.1%	113583	30.5%	217347	58.4%
		15	409582	54003	13.2%	138231	33.7%	217347	53.1%
	Ave				13.6%		29.1%		57.4%
PT Flat Slab	Std Dev				0.0242		0.0283		0.0218
	Grid (m)	LL (kN/m ²)	Total Cost (\$)	Column		Beam		Slab	
				Cost (\$)	%	Cost (\$)	%	Cost (\$)	%
	4.8	3	226014	45379	20.1%	7090	3.1%	173545	76.8%
		7.5	226403	45697	20.2%	7092	3.1%	173614	76.7%
		15	242840	58131	23.9%	7092	2.9%	177616	73.1%
	6	3	227190	35427	15.6%	8645	3.8%	183118	80.6%
		7.5	236435	44560	18.8%	8645	3.7%	183231	77.5%
		15	251700	55842	22.2%	8645	3.4%	187213	74.4%
	8	3	227963	27863	12.2%	12875	5.6%	187224	82.1%
		7.5	235305	33104	14.1%	12875	5.5%	189326	80.5%
		15	261007	38319	14.7%	12875	4.9%	209813	80.4%
	Ave				18.0%		4.0%		78.0%
	Std Dev				0.0377		0.0099		0.029

The overall structural costs were also broken down into the member cost of column, beam and slab. The overall cost breakdown is shown in Table 5.6. The values were arranged according to structural systems, grid sizes and live loads. The precast member cost was broken down separately for fully precasted construction and precast hollow core slab with in-situ beam and column construction. The 8m grid sized conventional and precast buildings were constructed with secondary beams. The slab cost for precast includes topping cost for hollow core slabs. Since the standard deviations of the various construction systems are not significant. The average cost components of the different members were plotted in the pie charts as shown in Figure 5.3.

Figure 5.3. Cost breakdown to structural members

Figure 5.3 shows the slab cost was always the highest in the 3 different structural members. This suggested that slab should be given more attention in order to save structural cost. The cost percentages ranged from 55% for conventional construction to 78% for PT flat slab construction. The second largest cost component came from beams except PT flat slab construction, where the beam cost only came from the roof beam

using conventional beam-slab construction. The significant cost saving from the elimination of the beams was one of the reasons PT flat slab gave lower overall cost.

For precast construction, when the structures were fully precasted, the slabs made up of 64% of the overall structural cost. When only the slabs were precasted, the slab cost were only 57% on average. This is due to the fact that in-situ column and beam could not enjoy the cost saving from the use of standard formwork.

5.2.3. Other cost implications

Choice of RC structural systems would have other impacts on project cost, which include overhead and interest savings due to faster construction; more revenue as well as tax from early rental income; less substructure cost due to lighter structure; less M & E costs due to easier installation; less cost from safety allowance due to safer work, etc.

All the mentioned costs could be project related and would be difficult to quantify. This part of the cost was not the emphasis of the study but it could be something worth further studying into. Some previous research did give some cost implication due to early completion of structural steel construction and precast construction. These studies include Ali and Ang (1985) and BCA (1999).

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1. Conclusion

This report described a comprehensive trial-design cost study to search for the cost-effective RC structural systems. The research framework was presented and the focus was on the construction costs of the basic RC superstructure on the 4 storey trial-buildings with 24m×24m in plan in local context. The study was initiated to present a way to compare the structural cost for various RC structural systems.

Previous cost modeling of buildings was classified into deductive and inductive methods (Wilson 1982). The deductive method is to relate the cost to previous cost data through mathematical means. The inductive method focuses on studying the design and construction process to relate the cost to the process element. This research study was an inductive approach because the cost was calculated based on the different quantities and unit rates originated from the design differences. The cost information (unit rates) was extracted from local market prices, which was done by local authority and company through statistical means.

Two important studies were done with similar methodologies to the author's but at a larger scale. Both of the studies were in the 1960's. The study done by Wilderness Group

(1964) and Stone (1962) both focused on low-rise steel-framed structure with the latter specifically focused on single-storey factory building. Both of the studies did not touch on the design variables of structural systems because steel frames were used for both study and conventional in-situ RC system was still the main stream at the time. These two studies demonstrated the examples of trial design approach, which goes back to the first principle of building cost: the economics of design.

Comparing with other cost studies focusing on various RC structural systems, this study was more comprehensive and systematic. With the use of FEM analysis and design software, a great effort had been taken to design 27 trial-buildings in different RC structural systems, grid sizes and live loads. The quantities of material were analyzed and reasonable accuracy could be achieved. The unit rate costing approach was adopted to find out the construction cost of the superstructure. The modifications of the unit rates for different structural systems were also studied into.

The intention was not to find out the actual construction cost in the real life. In Singapore, unit rates are used to price the variation works; and they are not the actual cost incurred to build the structure.

With the available cost information, the post-tensioned flat slab was found to be cost-effective in terms of structural cost, especially when the grid sizes were large and the live loads were high. Precast construction was generally more expensive. The structural costs breakdown study was also carried out. In terms of building material cost breakdown, the formwork cost was found to be the most significant. When the costs were broken down according to structural members, the slab costs were found to be of the highest percentage, which ranged from 55% to 78% of the total structural cost.

The unit rates of various building materials are always changing, and the changes are determined by many issues, which include the industry infrastructure, the advancement of the technology, the raw material supply, etc. The main parts of this study are the research

framework and the trial-building designs and quantity collection. The final cost discussion was only confined to the available cost information.

6.2. Limitations and Recommendations for future research

The study was based on a simplified fixed-sized trial building and the common RC structural systems were limited to conventional cast in-situ beam-slab system, prestressed flat slab system and precast system. The other two design variables were chosen as grid size and live load. More design variables could be investigated to give a more comprehensive view in choosing the RC structural system, e.g. plan ratio.

This study only included the construction cost of the basic superstructure of the trial-buildings. Besides the structural cost consideration for the cost-effectiveness of the structural systems, other considerations should also be considered in the cost evaluation. These factors include construction duration, quality of finish, weight of the structure, mechanical & electrical cost, safety, etc. These could be something worth further study for their association with the project cost.

The costing method is also worth further investigation. The unit rates were used in this study because they were probably the only accessible comprehensive cost data in Singapore. More detailed costing breakdown could possibly give better inside view of the cost implications of the various structural systems if the cost data is comprehensive enough.

The cost information for post-tensioning tendons was not obtained from the same source as the other unit rates; there was a possibility that the cost comparison on PT flat slab construction was not as fair as other structural systems. Because this study provided the detailed material quantities associated with each design configuration, updated unit rates or more insightful cost information could always be applied onto the building material quantities to derive the cost of the trial-building superstructure.

The design requirement could also influence the structural cost. In this study, BS 8110: Structural Use of Concrete was used as the design guide. Others issues like the choice of class 1, 2 or 3 members for PT flat slab design could well result into different structural cost.

References

ADAPT- Floor (1996). Software Manual, ADAPT Structural Concrete Software System. USA.

Ali M. M. and Ang T. C. (1984), “Comparative Evaluation of High-rise Buildings in Singapore”, Technical Report, National Iron and Steel Mills Ltd, Singapore.

Ali M. M. and Ang T. C. (1985), “Influence of Material Selection on tall Building Economics”, The CIDB Review, Singapore, pp. 46-54

Ali M. M. and Ang T. C. (1984), “Cost Effectiveness of Tall Buildings in Singapore: Structural Steel VS Concrete”, Proceedings of International Conference on Tall Buildings, Singapore, pp 845-852.

Aoieong R., Tang S. and Ahmed S. (2002), “A Process Approach in Measuring Quality Costs of Construction Projects: Model Development”, Construction Management and Economics, Vol 20, pp179-192.

BCA (1999). Architecture in Precast Construction, Building and Construction Authority of Singapore.

BS 8110 (1985). British Standard: Structural Use of Concrete, British Standard Institution.

CIDB (1997). Guide to Precast Concrete and Prefabricated Reinforcement for Buildings, Construction Industry Development Board, Singapore.

CPG (2003), CPG Cost Information Quarterly, Issue 49, CPG Corporation, Singapore.

Dagostino, F. R. (1993), Estimating in Building Construction, 4th edition. Prentice Hall.

Dowrick D. J. and Narasimhan N. (1978), "Prestressed VS Reinforced Concrete Flat Slabs", Concrete, Vol. 12, No.9, pp. 16-19.

FIP (1994), FIP Planning and design handbook on precast building structures, SETO Ltd, London

Goodchild C. H. (1997), Economic Concrete Frame Elements, British Cement Association, UK.

Holland, R. (1997), Reinforced Concrete, Thomas Telford, London.

Huntington. W. C. and Mickadeit R.E. (1981) Building Construction, Material and Types of Construction, 5th ed., Wiley, New York.

Hurst, M. K. (1998), Prestressed Concrete Design, E & FN SPON, London.

Hutchison, K. (1993), Building Project Appraisal. The Macmillan Press Ltd, London

John Mo (1998), Comparison between Flat Plate Construction and other Structural Systems: cost and speed, BBR Construction Systems Pte. Ltd, Singapore.

Kouskoulas, V. and Koehn, E. (1974), "Predesign cost estimation function for buildings", ASCE Journal of Construction Division, Dec 1974, pp589-104.

Lau and Ng (1996), "Comparative costs on RC Slabs", M.Sc. dissertation, Nanyang Technological University, Singapore.

Max, Meyer (1998), "An Alternate Cost Efficient Design Solution", BCA Seminar on Flat Slab/Plate Structures, VSL (S) Pte Ltd, Singapore.

Neo, R. (1997), “Precast and Semi-precast cost comparison”, Seminar on Precast Concrete Design for Engineers, Singapore.

Poh, S. H. (1993) “Modelling and Predicting New-build Student Hostel Costs in Singapore”, MBA Dissertation, University of Dundee.

Poh S. H. (1995), “Cost Models for Student Hostels in Singapore”, Proceedings of 1st International Conference on Construction Project Management, Singapore, pp. 541-550.

Raftery, J. (1991), Principle of Building Economics, BSP Professional Books.

Runeson, G. (2000), Building Economics, Deakin University Press.

Skitmore, M. and Marston, V. (1999), Cost Modelling, E & FN SPON, London.

Stone, P. A. (1962), “The Economics of Factory Buildings”, Factory Building Studies, Building research Station, Her Majesty’s Stationary Office, London.

Teh, H.S and Ooi, S.T. (2000,) The Use of Flat Plate in Residential Building, T Y Lin South East Asia Pte Ltd, Singapore

Teng C. W. and Sui W. F. (2003), “An Investigation on Cost Effective Structural Systems in Singapore Construction Industry”, Final Year Project, Nanyang Technological University, 2003.

Tong C. Y. and Tang E. P. (2000), “Flat Plate in Mixed Development”, BCA Seminar on Flat Slab/Plate Structures, ADDP Architects and Tang Ee Ping & Partners, Singapore.

Warszwaski A. and Carmel D. (1984), “Utilization of Precast Concrete Elements in Building”, Journal of Construction Engineering and Management, Vol. 110, No 4, pp. 476-485.

Wilderness Group (1964), “An investigation into building cost relationships of the following design variables: storey height, floor loading, column spacing, number of storeys”, Report to the Royal Institute of Chartered Surveyors.

Wilson, A. J. (1982), “Experiments in probabilistic cost modeling”, Building Cost Techniques –New Direction, E & FN Spon, pp169-180.

Appendices