Design resistance of high strength steel square hollow section K-joints

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**DESIGN RESISTANCE OF
HIGH STRENGTH STEEL SQUARE
HOLLOW SECTION K-JOINTS**

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School of Civil and Environmental Engineering

2015

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School of Civil and Environmental Engineering

A Thesis submitted to the Nanyang Technological University
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ABSTRACT

Steel is widely used in modern building constructions and consequently, extensive research on steel structure is carried out all around the world. Among steel structures, the use of high strength steel is gaining popularity and wider usage. The exact effect of using the high strength steel on the strength of joints has not been investigated extensively so far and there are no published design equations available at present. This study will investigate the influence of steel grade on the strength of Square Hollow Section K-joints. The results from this study mainly will complement the on-going research on the MND-SUL project. In the MND-SUL project, a functional truss bridge across an express way is planned to be built and the mega-truss will be made of S690 steel sections. This thesis presents the numerical studies for assessing the strength of high strength steel SHS gap K-joints. The aim of the numerical analysis is to improve the current design equation in CIDECT Design Guide 3. The results demonstrate the influence of high strength steel on the design resistance of K-joints and two new formulas are proposed to improve the existing equation. Two finite element models are validated with experimental results as the basic verification step.

The parametric study is conducted which comprises 60 models of SHS K-joints made of S690, 60 models of gap SHS K-joints made of S355 and 60 models of SHS K-joints made of S460. Each model is subjected to 3 load cases. The geometric parameters for the joints such as width ratio between braces and chord (β), half width to thickness ratio of chord (γ), the thickness ratio between braces and chord (τ) are varied in the parametric study. The higher the preload is, the lesser the strength of gap SHS K-joints observed. It is found that chord face failure by yielding or buckling is the most common type of failure for β of 0.6 to 0.8, 2γ of 30 to 35 and τ of 0.79 to 1.

The numerical results are compared to existing formula in CIDECT Design Guide 3. It is found that the numerical ultimate capacity of the joints is less than the theoretical results predicted by CIDECT Design Guide 3. Two parametric formulas for predicting the design resistance of gap SHS K-joints with high strength steel are

proposed in the thesis. The results of proposed formulae are compared with the numerical results and they show good agreement.

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LIST OF SYMBOLS

The nomenclatures used in the thesis are listed in alphabetical order in the following list. A symbol whose usage is restricted to only a specific analysis is not mentioned here, and it is explained at the appropriate area in the thesis.

b_0	= chord width
b_1, b_2	= brace width
E	= Young's modulus
g	= the gap distance of the gaped K-joint
l_c	= chord length
P	= applied load
t	= attachment thickness in plate-to-plate joints
t_0	= chord wall thickness
t_1, t_2	= brace wall thickness
T	= chord wall thickness
β	= brace to chord width ratio
2γ	= chord width to chord wall thickness ratio
ε	= principle strain
ν	= Poisson's ratio
θ_1, θ_2	= brace to chord angle
σ	= applied stress
σ_y	= yield stress

N^*	=design resistance of joints
f_y	=yield stress
$F_{u,non}$	=non-dimensional strength
$F_{u,nu}$	=non-dimensional strength derived from numerical result
$F_{u,p}$	=non-dimensional strength calculated by proposed formula
$F_{u,th}$	= the theoretical non-dimensional ultimate strength calculated based on the equation in CIDECT Design Guide 3 (Eq. 2.1)
τ	= brace wall thickness to chord wall thickness ratio
F_{y0}	= yield capacity of the chord

CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

1.1.1 Project overview

Due to limited land area and an ever increasing population, Singapore faces the challenge of maintaining a sustainable living environment. This problem is however not unique to Singapore, modern cities all around the world such as London, New York, Tokyo and Shanghai are all facing similar problems on sustainable urban living due to limited land area. Subways and overpasses are also being built to save time for people. As a land-scarce and highly developed country, Singapore has set out to explore the possibility of erecting offices, light industries, walkways and communal spaces on a kind of bridging mega-trusses system (BMS) above major roads and expressways (Chia, 2014).

The current project is a functional bridging structure which will be built at Buona Vista in Singapore, across the Ayer Rajah Expressway (AYE) (Figure 1.1). It will be built with a width of 80m to serve as carparks and common area. In addition, there will be office building, vehicle road and other facilities. The structural system of the mega truss is shown in Figure 1.2. The span of this functional bridging building is 80 m with beam depth less than 5m and clear height under the BMS is 5m.

There are totally 21 mega transfer trusses with spacing of 5m along 100m transverse distance. The size of bottom chord is as large as 600mm*600mm (Figure 1.3). The 3D view, top view and upward view of the bridge truss system is shown in Figure 1.4 to Figure 1.6. In such big span and limited structure height, high strength steel (HSS) S690 steel is chosen to fabricate the truss structure in order to save the cost of steel and to reduce the weight of the structures for the ease of construction. The advantages and the application of HSS are presented in the following sections.

Figure 1.1 Bridging mega-truss system site (JTC, 2014)

Figure 1.2 The structural system of the mega truss

Member	Stack-up building	Green belt	Driveway
Top Chord	650*650*50	600*600*50	500*300*20
Bottom Chord	600*600*32	600*600*30	300*300*10
Diagonal Web Member	600*600*30	600*600*20	300*300*16
Vertical Web Member	500*500*46	500*500*40	500*300*16
Stiffened Top Chord	800*800*60	600*600*40	400*400*34
Stiffened Bottom Chord	600*600*40	600*600*36	400*400*12.5
Stiffened Web Member	600*600*42	600*600*34	350*350*12.5

Figure 1.3 Dimensions of square hollow sections (SHS) (Zeng, 2015)

Figure 1.4 3D view of the joint with tendon

Figure 1.5 Top view rendering of the Bridge Mega-truss System

Figure 1.6 Upward view rendering of the Bridge Mega-truss System

1.1.2 Applications of HSS

There has been an increasing interest in the use of high strength steels (HSS), which generally has yield strengths higher than 460MPa, for installation recognizing the benefits from an increase in the strength to weight ratio and savings in the cost of materials. This is particularly applicable to truss structures to reduce weight which can lead to achievement of considerable saving in supporting substructures. Since the self-weight of the structure and superstructure is huge, the critical stress at critical area will be very big. In order to make the structure lighter and force allocation more balanced, tendons will also be used in the structure.

One major application of HSS is in Jack-ups. In the topside areas of jacket structures, the weight saving can not only produce overall saving in materials but also allow crane barge installation of more complete topside processing and accommodation units with significant savings. Some HSSs whose yield strengths up to 700MPa have also been used in mobile jack-up drilling rigs to minimize weight during the transportation stage. A survey undertaken in 1995 indicted that the proportion of HSS used in offshore structure increased from less than 10% to over 40% in a short decade (Healy and Billingham, 1996).

Another application of HSS is the BP Harding Jack-up, consisting of a triangular hull supported by three 152m high legs on a fixed concrete base, which was installed on the continental shelf of UK. The lower sections of each leg and the forged nodes are fabricated from 400MPa steel. Higher yield strength steel, 450MPa, is used for the chords in seawater and the splash zone while steel with yield strength of 550MPa is used in the air chord. The highest strength steel with yield strength of 700MPa is employed in the racks. Another example is Siri field production Jack-up which is located in Danish sector of the North Sea and consists of a three legs standing on the top of a steel storage tank. Parts of the tubular legs are made of high strength steel with minimum yield strength of 690MPa (Billingham and Sharp et al. 2003).

The roof truss of the Sony Center in Berlin sets an example for the use of HSS S690 in buildings. This HSS is aimed to protect an old masonry building by suspending

several story of the building. The truss structure is made of steel S460 and S690 and is formed in solid rectangular shape to keep the dimensions of the cross section small.

Application in bridges is also available. Rhine Bridge in Düsseldorf and Millau-Viaduct in France are two instances for application of steel S460 in bridges (Sedlacek and Muller, 2004).

Generally, HSS can be defined as steel with minimum yield strength of greater than 460MPa and it is produced by quenching and tempering procedure. In the worldwide, high strength steel was firstly used in Japan in the 1960s and after that more and more countries showed great enthusiasm on this area. For instance, the first UK project to use HSS is the Hutton Field floating structure, 200km off the coast of Norway. The tension-leg platform was fabricated from steel with minimum yield strength of 795MPa. Extensive research into steel with tensile strength of 600MPa have involved since 1988 in Japan for looking for benefits in the prevention of damage caused by earthquakes. Landmark Tower in central Yokohama is the first project using HSS in the construction of building in Japan. Another application case of HSS with minimum tensile strength 600MPa is the Shimizu super high rise building which is 550m high comprising 127 levels for reducing the column section size. HSS research in Australia was firstly launched by Rosier and Croll and it was firstly used in the project of Grosvenor Place in Sydney in 1989 (Pocock, 2006). In the America, a research program was initiated to develop a better performance steel specifically for use in bridges to improve the weldability, toughness and weathering resistance of existing steel grade.

With the increasing construction needs, many steel manufacture companies are producing high performance high strength steel plates for multi-level building and large span steel structures. High strength steel is more and more widely used in the prominent structures such as Olympic stadium and large span bridges. The Bird' Nest (Figure 1.7), which is well known as the main stadium of Olympic 2008 in China, have large span and good aesthetic appearance. The impressive appearance is owing to the use of high strength steel Q460E/Z35 (Huang, 2007). It is the made

of high strength steel plates and the largest thickness of the steel plate in use is up to 110mm.

Figure 1.7 The Bird's Nest (google)

Figure 1.8 Tokyo Sky Tree & Ryomo (train)

Tokyo sky tree (Figure 1.8) with the height of 634m uses the steel tube with the yield strength of 490N/mm^2 to 500N/mm^2 . The highest part of it, Gain tower, is made of steel tube with the yield strength of 780N/mm^2 with the thickness of 80mm (Shigeru, 2010).

The influence of welding in joints on static strength is found insignificant (Khurshid et al, 2015). Therefore, the influence of welding and welding process is not considered in this thesis.

The high strength steel is applied in the structure and offshore field in a great pace owing to its excellent performance. The advantages of high strength steel are given in the following section.

1.1.3 Advantage of HSS

Figure 1.9 The relationship between the yield strength and the use of steel (Qiu, 2014)

High-strength steel means the steel with the tensile yield strength above 400 MPa and with high strength and excellent overall performance characteristics. According to estimates, replacing S355 to S460 save an average of 12% ~ 14% in amount of steel; replacing S460 to S690 will have additional savings of 5% to 7% (Qiu, 2014). When high strength steel is applied to high-rise buildings or large span structures, the effect is more obvious, it can save 30% of steel consumption.

Through using of high strength steel, the thickness of the material and the weight of the structure can be largely reduced. The decrease is the highest when the structure is subjected to multiple load types. By doubling the yield strength, half the wall thickness is enough to bear the same loading. In the same time, the amount of the decrease is more obvious when the bending moment and torsion stress exist. The Figure 1.9 shows that the using of higher yield strength steel can obviously decrease the high cost of the steel. Furthermore, the decrease of weight can lead to the saving of manufacture, transportation and treatment. It can also release the workload in welding process.

To summarize, the advantages of high strength steel is listed as following,

1. High strength: the ultimate strength of the standard value can reach 400MPa; the tensile strength of the design is above 360MPa.
2. Ductility: Elongation $\geq 14\%$, in fact, the average elongation rate of 20%, compared with HRB335 grade steel (strength design value of 300MPa) can save steel by 10% to 15%.
3. Stable, low sensitivity to strain aging, security reserve is larger than HRB335 grade steel.
4. Yield strength ratio: greater than 1.25, the yield strength σ_s / strength standard value ≤ 1.30 , good seismic performance.
5. Good cold bending performance.

To sum up, using high-strength steel and materials as energy saving products can not only effectively reduce the amount of steel, but also reduce cost of transportation and welding process as a consequence.

1.1.4 Hollow section joints

In the steel truss bridge, Warren truss is chosen as the main structure in this study and rectangular hollow section (RHS) serve as the chord and braces. Rectangular joints are critical structure components in mega-truss structure because it may be fail before the structure's failure. This study will focus on the influence of using

high strength steel to the ultimate strength of SHS K-joints, which will be the basis of study for the whole high strength steel mega truss.

In some cases, the joints are fabricated in rectangular hollow section connections. The brace is welded to the chord members to make sure the load can transfer through the connection. In some cases, some treatments such as concrete encasement and tendons are used to increase the capacity of the joint and reduce the stress concentration effect.

In addition, using of hollow sections saves material and alleviates the weight of steel structure. Compared to the I-beams, a square hollow section has about 2/3 the surface area of the same size I-section shape, and the ratio between cross-section and surface area is also smaller. Based on the high structural efficiency, the protection against corrosion and fire becomes more economical and the neater connections also prevent the accumulation of dirt and water.

There are two main types of hollow sections, one is circular hollow sections (CHS), and the other is rectangular hollow sections (RHS). The former ones have more efficient shape and less resistance to fluid than RHS, but it is more convenient to join the latter ones together rather than the CHS. As a consequence, RHS have evolved as a practical choice in engineering due to its easy connections of flat faces in form of columns and trusses.

There are various types of trusses made from hollow section. In order to minimize the number of joints, a Warren type truss with K-joints is usually adapted rather than a Pratt type truss with N-joints. There are two kinds of K-joints named gap joints and overlap joints. The fabrication of gap joints is easy with regards to end cutting, fitting and welding. However the excessive chord wall deformation of gap joints sometimes leads to insufficient joint strength. In the similar fabrication, fully overlap joints show better joint strength than the gap joints.

1.2 OBJECTIVES AND SCOPES

Since the huge static load including the self-weight of the mega truss and of superstructure would be applied to the mega truss, high strength steel is being used

in the structure to make the section of structure smaller and economical. Currently, there are no formulae for the ultimate strength of high strength hollow section K-joints found in standard codes. This study is mainly aimed at coping with this problem and proposing a formula for calculating ultimate strength of high strength hollow section K-joints.

The objectives of the present study are:

1. to build two models similar to the experimental models (Thong, 2005) as verification models;
2. to conduct a parametric study by varying the geometric parameters, material and preload;
3. to record the ultimate capacities and observe the failure modes of gap SHS K-joints in the research program;
4. to compare the numerical results of normal strength steel with the formulae results to confirm the validity of the finite element models;
5. to find the trend of the change of the ultimate strength under different load combinations;
6. to propose the new formulae which can be used in high strength steels;
7. to propose the new formulae for the normal strength steel which is outside the range of existing formulae;
8. to give a quick check table of corrective factor which can be used in certain kind of materials and load cases.

To achieve the above objectives, numerical studies are carried out. The modeling of common strength steel results is used to verify the proposed finite element modelling techniques. The verified finite element analysis is used to conduct a series of parametric studies. The influences of the geometric parameters and chord preload are investigated throughout.

The finite element analysis software, the commercial FEA package ABAQUS and data analysis software MATLAB is used to build the models and develop the new formulae, respectively.

In the whole process of study, the main function of software is as follows,

1. build the certain number of models in details as required, such as in different sizes, materials and load cases;
2. predict the ultimate strength of joints under different situations;
3. find out the failure modes of each joint under separate conditions;
4. find out the trend of changes of the design resistance and propose a new formulae.

1.3 LAYOUT OF THIS REPORT

This thesis consists of five chapters.

In Chapter 1, an introduction is given on the research background, goals and scope.

In Chapter 2, a literature review on SHS K-joints is given. Some basic definition and classification about the joints, the advantages of hollow section, characteristics, historical development and application are provided. A brief introduction of the recent application of the high strength steel and the advantages of using high strength steel are discussed.

In Chapter 3, the methodology of the finite element analysis is described. The mesh generation procedure, types of element employed, options and parameters used in the analysis are summarized. The numerical method is verified by comparing the numerical results with experimental results such as load-displacement curve and failure mode which showed a reasonably good agreement.

In Chapter 4, a parametric study is conducted by varying the geometric parameters within the validity range specified in CIDECT Design Guide 3, varying material,

geometric parameters and chord preload. The results of parametric study are used to develop the parametric design equations for SHS K-joints.

Finally, Chapter 5 presents the conclusions as well as recommendations for future research work.

CHAPTER 2 LITERATURE REVIEW

2.1 JOINT GEOMETRICAL CLASSIFICATION AND PARAMETERS

Box hollow section (BHS) joints have sparked extensively considerable interest in supporting structures in offshore and onshore structures. A typical BHS joint is made up of one or several smaller rectangular tubes called braces, and one larger rectangular tube called chord. Unlike the traditional rectangular hollow section and circular hollow section joints which are made of mild steel, the braces and chord in box hollow section made of high strength steel are formed by welding rather than rolling. It is because HSS cannot be easily bended to form rolled hollow section and is only available in the form of sheet. After the braces and chord are formed, the braces are jointed with the chord by welding the braces onto the outer surface of the chord.

The connection between the braces and the chord in the form of box is called a hollow section joint, which is the most critical part of the entire structural system. The joint intersection is much simpler compared with circle-to-circle hollow section (CCHS) joints since it needs to be cut straightly, which is one of the reasons why box tube and rectangular tube are widely used in engineering. These joints can be classified into many types according to their geometries. Using this classification, BHS joints can be classified as T-joints, Y-joints, K-joints, X-joints, TT-joints, XX-joints, TX-joints and KK-joints. The configurations of these common hollow section joints are illustrated in Figure 2.1. Although other classifications, such as by the load path, have also been proposed, geometry classification is adopted frequently because it is easier to be understood by designers.

For brevity in design and analysis, the geometry of a BHS joint can be simplified by expressing it as non-dimensional parameters. Figure 2.2 shows the definition of these parameters which are commonly used in practice. Hence, the characteristics of a K-joint can be described by some normalized parameters, such as α , β , γ and ζ .

$\beta = b_1 / b_0$, ratio of brace width to chord width;

$\eta = h_1 / b_0$, ratio of brace depth to chord width;

$\tau = t_1 / t_0$, ratio of brace wall thickness to chord wall thickness;

and $2\gamma = b_0 / t_0$, ratio of chord width to chord wall thickness.

Figure 2.1 Common rectangular joint configurations (Wardenier and Stark, 1978)

Figure 2.2 Parametric notations in box hollow section K-joint (Wardenier and Stark, 1978)

2.2 ULTIMATE STRENGTH AND FAILURE MODE

2.2.1 Ultimate Strength

Ultimate tensile strength, often shortened to tensile strength (UTS) or ultimate strength, is the maximum stress that a material can withstand while being stretched or pulled before failing or breaking. The UTS is usually found by performing a tensile test and recording the engineering stress versus strain. The highest point of the stress-strain curve is the UTS. It is an intensive property; therefore its value does not depend on the size of the test specimen. However, it is dependent on other factors, such as the preparation of the specimen, the presence or otherwise of surface defects, and the temperature of the test environment and material.

2.2.2 Modes of Failure

An added difficulty in the prediction of SHS joint ultimate strength is due to presence of different failure modes. Depending on the type of joint, joint parameters, and whether the loading is tensile or compressive, the mode of failure may shift from one to another.

The strength of RHS joints can, depending on the type of joint, geometric parameters and loading be governed by various criteria.

The majority of truss joints have one compression brace member and one tension brace member welded to the chord as shown in Figure 2.2. Experimental research on welded truss joints (for example, Wardenier and Stark, 1978) has shown that different failure modes exist depending on the type of joint, loading conditions, and various geometric parameters. Failure modes for RHS joints have been described by Wardenier (1982) as illustrated in Figure 2.3, and the design of welded RHS joints is thus based on these potential limit states. These failure modes are:

Mode (a): Plastic failure of the chord face (one brace member pushes the face in, and the other pulls it out)

Mode (b): Punching shear failure of the chord face around a brace member (either compression or tension)

Mode (c): Rupture of the tension brace or its weld, due to an uneven load distribution (also termed “local yielding of the brace”)

Mode (d): Local buckling of the compression brace, due to an uneven load distribution (also termed “local yielding of the brace”)

Mode (e): Shear failure of the chord member in the gap region (for a gapped K joint)

Mode (f): Chord side wall bearing or local buckling failure, under the compression brace

Mode (g): Local buckling of the connecting chord face behind the heel of the tension brace.

Figure 2.3 Failure modes for K and N type of RHS (SHS) truss joints (Wardenier, 1982)

Failure in test specimens has also been observed to be a combination of more than one failure mode.

It should be noted here that modes (c) and (d) are generally combined together under the term “local yielding of the brace” failures and are treated identically since the joint resistance in both cases is determined by the effective cross section of the

critical brace member, with some brace member walls possibly being only partially effective.

Plastic failure of the chord face (mode (a)) is the most common failure mode for gap joints with small to medium ratios of the brace member widths to the chord width β . For medium width ratios ($\beta = 0.6$ to 0.8), this mode generally occurs in combination with tearing in the chord (mode (b)) or the tension brace member (mode (c)) although the latter is only observed in joints with relatively thin walled brace members.

Mode (d), involving local buckling of the compression brace member, is the most common failure mode for overlap joints.

Shear failure of the entire chord section (mode (e)) is observed in gap joints where the width (or diameter) of brace members is close to that of the chord ($\beta \approx 1.0$), or where $h_0 < b_0$.

Local buckling failure (modes (f) and (g)) occurs occasionally in RHS joints with high chord width (or depth) to thickness ratios (b_0/t_0 or h_0/t_0). Mode (g) is taken into account by considering the total normal stress in the chord connecting face, via the term n in the function Q_f .

Wardenier (1982) concluded that in selected cases, just one or two governing modes can be used to predict joint resistance.

A common failure mode of all hollow section joints is the significant residual strength beyond first yield, provided the joint has sufficient deformation capacity to allow the necessary stress redistribution to occur.

2.3 THE PREVIOUS RESEARCH ON K-JOINTS

In 1948, the former West Germany started the research work and the experiment on the design resistance of tubular joints. In 1967, Japanese scholars studied force characteristics and stability of the joints of the steel truss. Kurobane etc. (1970) carried out finite element analysis on the circular hollow section K-joints. In 1973, Japanese scholars studied the fatigue performance circular hollow section K-joints.

Kuang etc. (1977) put forward a stress concentration factor formula of K-joints without considering the impact of welding process. The downside to this approach is that the formula does not consider the impact of the weld, and therefore, unable to accurately calculate the stress distribution around the weld area. Packer etc. (1980) obtained K-joints capacity calculation formula according to plastic hinge line model, and the formula to calculate the results were shown to be in good agreement with experimental results.

Morgan and Lee (1998) proposed formulae for calculating the stress concentration factor of K-joints under in plane bending moment by numerical simulation. The experimental data produced by Shen (1998) revealed that bending stress of the main truss should also be considered in addition to axial force in brace. K-joints with welded steel have good plastic deformation capacity; ultimate strength to take when the main chord wall have the local compression or raised maximum plastic deformation reaches $0.05D$ (D =chord diameter). Chan and Fung (1999) carried out the experimental and theoretical studies on the ultimate capacity of Double Plate-Reinforced Tubular Joints, and showed that additional plate can reduce stress concentration problems, and increase the design resistance of the joints. Gazzola et, al. (2000) used the finite element software to study the overlap K-joints, and proposed the design equation of the ultimate strength of overlap K-joints. Liu and Guo (2000) used numerical analysis methods to study ultimate bearing capacity of the joint between the main chord and the circular brace. Fung (2001) studied the ultimate capacity of the completely overlapped tubular joints, by considering the influence of parameters. Wu (2004) did the finite element analysis on the static performance of rectangular and square hollow section K-type joints, and studied the influence of parameters on the stiffness and the ultimate strength, and observed different types of K-joint failure modes.

Lee (2005) used the finite element software to analyze the Ring-Stiffened DT-Joints in Offshore Jacket Structures and proposed a theoretical model which can accurately analyze the bearing capacity of the joints. Choo (2006) studied the effects of boundary conditions and chord stresses on the ultimate strength of thick-walled CHS K-joints. He proposed the influence factor of the ultimate strength with

the influence of the main chord force changes. Cao (2006) made a comparison between the experimental and numerical analysis of K-joint with stiffening and non-stiffening plates. He subsequently proposed the capacity formula for stiffened K-joint. Sun (2009) conducted a parametric study to find out the effect of parameters on ultimate strength and proposed the ultimate bearing capacity formula for both gap and overlap K-joints. Chen and Tang (2011) conducted static test research on the K-joint of the main circular chord and experimental studies show that according to the formula value of design resistance of the RHS and CHS joint is very conservative, compared with the experimental values, there is a certain error; when the brace wall thickness increased, failure mode is changed, and the strength and ductility of the joints is improved. Li (2013) studied small angle K-joints of steel pipe tower. Studies have shown that the ultimate strength should be the lower one of the ultimate strength and deformation limit. The study also gave the design suggestion of the joint with the angle of not less than 20° in the steel truss tower.

Deng (2015) studied the cuff reinforcement effect to K-joints in the ferrule enhance K-joints, as a theoretical basis for the ferrule reinforcement applications of K-joints. He used the non-linear finite element ABAQUS software to analysis the ordinary K-joints and ferrule reinforcement member K-joints with one brace in tension and another in compression. Force-displacement curves were obtained for different diameters and different thickness of the brace. The results showed that the cuff between main chord and brace can improve force transmission path in common K-joints, reduces stress concentration around welds, and effectively improve the bearing capacity of the joints. Yang (2015) studied the three ways to strengthen Q690 high-strength steel hollow section joints with tile-shaped plate, inner spacer ring, and reinforcing the inner sleeve and obtained the influence of the three strengthening. The study shows that Q690 high strength steel joints with pillar reinforcement K-joints should be designed as semi-rigid joints.

2.4 DESIGN RESISTANCE FORMULA

Formulae are presented for the determination of the ultimate strength of statically loaded structural hollow section lattice girder joints. These strength formulae depend on the type of connection (i.e. gap or overlap).

2.4.1 Formulas based on CIDECT Design Guide 3

According to CIDECT Design Guide 3, the design resistance of uniplanar RHS braces to RHS chord joints is dependent on the failure mode.

Figure 2.4 The typical figure of K-joint (Packer et al., 2009)

For chord face plastification, the general resistance equation is

$$N^* = Q_u Q_f f_{y0} t_0^2 / \sin \theta_i \quad (\text{Eq. 2.1})$$

In which,

$$Q_u = 14\beta\gamma^{0.3} \quad (\text{Eq. 2.2})$$

The parameter Q_u gives the influence function for the parameters β and γ , while the parameter Q_f accounts for the influence of the chord stress on the joint capacity.

Q_f can be achieved by the Figure 2.5.

N^* represents design resistance of joints.

f_{y0} represents the yield stress of the chord.

t_0 represents the thickness of the chord.

θ represents the angle between brace and the chord.

Figure 2.5 Chord axial stress function Q_f for K gap joints (Packer et al, 2009)

For the joint validity, the following chart is being given,

Table 2.1 Range of validity for K-joints (Packer et al., 2009)

		Range of validity	
		T, Y or X joints	K gap joints
Brace-to-chord ratio	RHS braces	$b_i/b_0 \geq 0.1 + 0.01b_0/t_0$ but ≥ 0.25	
	CHS braces	$d_i/b_0 \geq 0.1 + 0.01b_0/t_0$ and $0.25 \leq d_i/b_0 \leq 0.80$	
RHS chord	Compression	class 1 or 2 and $b_0/t_0 \leq 40$ and $h_0/t_0 \leq 40$	
	Tension	$b_0/t_0 \leq 40$ and $h_0/t_0 \leq 40$	
RHS braces	Compression	class 1 or 2 and $b_i/t_i \leq 40$ and $h_i/t_i \leq 40$	
	Tension	$b_i/t_i \leq 40$ and $h_i/t_i \leq 40$	
CHS braces	Compression	class 1 or 2 and $d_i/t_i \leq 50$	
	Tension	$d_i/t_i \leq 50$	
Gap		N/A	$0.5(1-\beta) \leq g/b_0 \leq 1.5(1-\beta)$ (*) and $g \geq t_1 + t_2$
Eccentricity		N/A	$e \leq 0.25h_0$
Aspect ratio		$0.5 \leq h_i/b_i \leq 2.0$	
Brace angle		$\theta_i \geq 30^\circ$	
Yield stress		$f_{yi} \leq f_{y0}$ $f_y \leq 0.8f_u$ $f_y \leq 460 \text{ N/mm}^2$ (**)	

The validity limits of the equations covering the strength of gap K-joints described in this section are also listed in Table 2.1. The limitations are based on test evidence and practical experience. The factored resistance of axially loaded SHS K-connections is also given in Table 2.2.

2.4.2 The application scope of the formulas based on different codes

The joint resistances given in CIDECT Design Guide 3 (Packer et al., 2009) are for hollow sections with nominal yield strength of up to 355 N/mm^2 (MPa). For nominal yield strengths greater than 355 N/mm^2 (MPa), the joint resistances should be multiplied by 0.9. This provision considers the relatively larger deformations that take place in joints with nominal yield strengths of approximately 450 to 460 N/mm^2 (MPa), when plastification of the connecting RHS face occurs. (Hence, if other failure modes govern, it may be conservative). Furthermore, for any formula, the “design yield stress” used for computations should not be taken higher than 0.8 of the nominal ultimate tensile strength. This provision allows for ample connection ductility in cases where punching shear failure or failure due to local yielding of the brace govern, since strength formulae for these failure modes are based on the yield stress. For S460 steel hollow sections in Europe, the reduction factor of 0.9, combined with the limitation on f_y to $0.8f_u$, results in a total reduction in joint resistance of about 15%, relative to just directly using a yield stress of 460 N/mm^2 (MPa) (Liu and Wardenier, 2004).

It is obvious that the formula in CIDECT Design Guide 3 can only be used in the material with the $f_y < 460 \text{ N/mm}^2$. For high strength steel, the reduce rule of the formulae is described as, for S460 steel hollow sections in Europe, the reduction factor of 0.9, combined with the limitation on f_y to $0.8f_u$, results in a total reduction in joint resistance of about 15%, relative to just directly using a yield stress of 460 N/mm^2 (MPa) (Liu and Wardenier, 2004).

Some codes, e.g. Eurocode 3 (CEN, 2005b) give additional rules for the use of steel S690. These rules prescribe an elastic global analysis for structures with partial-strength joints. Further, a reduction factor of 0.8 to the joint capacity equations has to be used instead of the 0.9 factor, which is used for S460.

The author also notices the application scope of EN1993-1-8-2005(E). For hot finished hollow sections and cold formed hollow sections, the nominal yield strength of the product should not exceed 460N/mm^2 . For end products with a nominal yield strength higher than 355N/mm^2 , the static design resistance given should be reduced by a factor 0.9. The nominal wall thickness of hollow sections should not be less than 2.5mm. The nominal wall stickiness of a hollow section chord should not be greater than 25mm unless special measures have been taken to ensure that the through thickness properties of the material will be adequate.

2.5 CURRENT RESEARCH GAPS

From the section discussed above, it is obvious that high strength steel is more and more widely being accepted and used in the important structures. The advantages of high strength steel is also being studied. However, there is limited research on K-joints made of high strength steel. In the term of the formula and rules listed in the current codes, the equations for calculating high strength steel K-joints are also limited. The current researches on K-joints are mainly for ordinary strength grades of steel. Considering all these, it is of great importance to study the joints with high-strength steel and develop the design codes.

CHAPTER 3 FINITE ELEMENT ANALYSIS

3.1 INTRODUCTION

The finite element method is an extraordinarily useful tool in solving engineering problems. It has been more and more widely used in almost all aspect of analysis, ranging from structural, thermal, electrical, mechanical and magnetic field problems. With the assistance of programs like MARC (2003), MENTAT II (2003) and ABAQUS, the finite element analysis is made even simpler than in the past. The program ABAQUS has the experience of simulating complex problems with material and geometry non-linearity, as well as a variety of loading and boundary conditions. The program ABAQUS is a graphical user interface program that allows a user to execute a finite element analysis process from start to finish. The finite element model can be viewed and checked interactively and the results (stresses, displacements etc.) can be visualized graphically.

In this chapter, the modeling techniques for SHS K-joints are discussed. The considerations include finite element mesh layout, boundary and loading condition, element types, joint material properties as well as the options being used in the finite element analysis. A preliminary study was done to fine tune the model devised. The validation of the finite element analysis results was verified by comparing the numerical results with the experimental test results of overlap SHS K-joints S1 and S2.

3.2 FINITE ELEMENT PROGRAM

The finite element analysis was done using a well-established general purpose finite element program ABAQUS. It can solve simple linear and complex nonlinear problems. ABAQUS is widely accepted as one of the most powerful finite element analysis software. This software runs on workstation with 32 cores. The calculation time can largely be saved by the workstation. The mesh density can be increased for the purpose of modeling the joints behavior more accurately. The mesh generation and boundary condition as well as load cases will be introduced in the following sections.

3.3 MESH GENERATION

The mesh design can exert huge influence on the accuracy of the results for finite element analysis. Generally speaking, meshes should be designed in such a manner that smallest elements are used in regions of high stress gradients, with gradually increasing element sizes further away from the high stress gradients regions. In addition, the element aspect ratio between the largest and the smallest element dimensions should also be considered.

For this propose, the mesh density near the connecting face between the chord and the tow braces of the SHS gap K-joints be defined higher than the other area. According to Section 3.8, with the change of the density of the dense region, the calculation time changes within a small range around 30 minutes. The global mesh generation is used in the following parametric study. The largest mesh size is 20mm.

3.4 CHOISES OF ELEMENTS

In this study, a four-node thick shell element is used throughout the joint modeling. Since the difference of the thickness and width between brace and chord is comparably large, the element type of S4R (a 4-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains) is used. Bilinear interpolation functions are used for co-ordinates, displacements and rotations. Each node has six degrees of freedom. S4R is a commonly used shell element which is suitable for modeling both thin shell and thick shell. In Section 3.9, this type of element is proved to be accurate for the modeling.

3.5 MATERIAL PROPERTIES

In this thesis, S355 is supposed to be the common grade of steel and S460 and S690 are supposed to be high strength steel.

In modeling process, there are totally three material properties used for S355, S460 and S690, respectively.

S460 and S690 are defined as high strength steel and have been discussed in Chapter 1.

The true stress-strain curve of S460 used in this study is shown in Figure 3.1.

The true stress-strain curve of S355 used in this study is shown in Figure 3.2.

Figure 3.1 Strain-stress curve for S460

Figure 3.2 Strain-stress curve for S355

The non-linear material property of steel is represented by a multi-linear stress versus strain relationship, as shown in Figure 3.3. It was entered in the MARC analysis as true stress versus logarithmic strain because of the large displacement, large strain and updated Lagrange option used in the finite element analysis. In this

study, the yield stress of S355, f_y , and the ultimate stress of S355, f_u , were assumed to be 355 N/mm² and 528 N/mm² respectively. The yield stress of S460, f_y , and the ultimate stress of S460, f_u , were assumed to be 460 N/mm² and 640 N/mm² respectively. The yield stress of S690, f_y , and the ultimate stress of S690, f_u , were assumed to be 690 N/mm² and 931 N/mm² respectively. The stress-strain curve, which was based on that used by Paul et al. (1989), as shown in Figure 3.3, was used for all the joints in the parametric study.

The Young's Modulus, $E=210$ kN/mm², and the Poisson ratio, $\nu=0.3$ were used in the finite element analysis.

Figure 3.3 Engineering stress-strain curves assumed in parametric study

3.6 BOUNDARY CONDITIONS

The choice of boundary condition is important to the modeling result. The boundary condition should reflect the joint constraint in the structure. The boundary condition used throughout the study is as shown in Figure 3.4. In Thong (2005) modeling, the x , y , z three displacements is restrained in lower chord. In upper chord, the displacement is restrained in x and y -direction and in z -direction (the chord length

direction) the upper chord can move freely. For brace 1, in the direction perpendicular to the brace length, the displacement is restrained, and the brace can move freely in the brace length direction. For brace 2, the displacement in all directions is restrained. This boundary condition can reflect the joint force condition in the realistic structures. The same kind of boundary condition can make the verification easier. It can also make sure the brace 1 is in compressive axial force and brace 2 is in tensile axial force.

There will be a total of three load cases for the models. The three load cases are as shown in the Figure 3.4.

Figure 3.4 Load cases of chord preload considered in parametric study for gap SHS K-joints (Thong, 2005)

3.7 LOAD CONTROL

In general, there are mainly two kinds of methods to apply incremental load in finite element analysis, namely load-control and displacement-control. The load control method implies that external load is applied to the nodes or edges. On the other hand, the displacement control method suggests that the nodal displacements are prescribed by a fix amount. In both cases, the total applied external load can be calculated by summing up all the external forces or reactions at the prescribed nodes and the supports.

In this study both of them were used. Load control method used for chord preload, while the brace was set up through displacement-control.

The following techniques, options and assumptions had been applied in the finite element analysis:

Full Newton-Raphson technique was applied due to its fast quadratic convergence. The stiffness matrix was re-assembled and decomposed for every iteration.

The convergence ratio (maximum force/moment of node divided by the maximum residual force/moment of another node) had been set to 1% to maintain accuracy. This implied that if the convergence ratio exceeded 1%, recycling would continue within an increment until the criteria were satisfied.

The maximum number of iterations had been set to 1.

The number of increments was set from 80 to 100 depending on the type of load applied and the occurrence of the peak in the load-displacement curve.

3.8 CONVEGENCE STUDY

Although the accuracy would increase with a denser mesh, the computing resources requirement, such as CPU time and disk storage space, would increase substantially as well for models with denser mesh. As such, preliminary runs were performed by varying the mesh density of the model (mainly in the brace/chord intersection region) to identify an optimal number of elements to obtain a converged result without using excessive computational time. As the region near the brace/chord intersection region was critical, various mesh densities were examined. An optimal mesh density was obtained when the change of the ultimate capacity became insignificant.

In order to determine the optimal mesh density, a convergence study was performed in this section. In this study, 4 finite element models of the model J59 ($\beta=0.75$, $\gamma=13.64$, and $\tau=0.65$) made of S690 K-joints were considered. Different number of elements and mesh densities the brace/chord intersection regions were analyzed using Element Type No 59. Models 1 to model 4 are shown in Figure 3.5

(a) to Figure 3.5 (d). The chord ends were assumed to be pin, as in test set-up, in this convergence study.

(a) Model 1 with 29520 elements

(b) Model 2 with 49016 elements

(c) Model 3 with 75022 elements

(d) Model 4 with 118080 elements

Figure 3.5 Finite element models for convergence study

Table 3.1 Results of convergence test using 4-node Element Type No. 59

Model	No. of Elements	CPU time(sec)	Ultimate Load(kN)
Model 1	29521	180	11982.8
Model2	49016	480	11981.3
Model3	75022	1260	11980.6
Model4	118080	2940	11980.12

The summary of the results of the convergence test are shown in Table 3.1. In the meantime, the ultimate load and the CPU time required for the analysis are plotted against the number of elements in Figures 3.6 and 3.7, respectively.

Figure 3.6 Ultimate strength vs number of elements used in convergence study
(J59 made of S690)

Figure 3.7 CPU time vs number of elements used in convergence study (J59 made of S690)

From Figure 3.6, it is obvious that with the number of element increases, the ultimate load doesn't change much. For the models with the number of elements, ranging from 29521 to 118080 the ultimate load is constant. However, Figure 3.7 shows that as the number of elements increases, the CPU time required for the analysis increases tremendously. In general, an increase in the number of elements will result in a significant increase in the rate of increase of the CPU time, which is represented by the gradient of curve. By taking the effect of increasing the number of elements in the ultimate load and the CPU time, the optimal number of elements is selected to be around 29521. In the following parametric study, similar mesh density is used.

3.9 FINITE ELEMENT MODEL VERIFICATION

3.9.1 Introduction

Before performing finite element analysis of the models in parametric study, it is important to prove that the finite element method can show the good agreement to the realistic conditions. To achieve this, the finite element results are compared with the results of experimental test. Once the numerical results agree the experimental results well, the finite element method can used with confidence for the parametric

study. The experiment tests on SHS K-joints carried out by Thong (2005) is the most well-recorded in recent years. The finite element results are compared with the experimental test results of Thong (2005).

3.9.2 Parameter of the verification joint

For the purpose of doing verification, building the finite element model which can reflect the real load condition is the first step. Thong (2005) tested the large scale overlap K-joints made of hollow section. The experiment frame is as shown in Figure 3.8 and geometric parameters of measured specimen S1 is as shown in Table 3.2. The simplified constraint condition is as shown in Figure 3.9 and the material stress-strain curve of the S1 is shown in Figure 3.10. The finite element model of specimen S1 with 4-node thick shell element is shown as Figure 3.11.

Figure 3.8 Overlap K-joint specimens on the rig frame (Thong, 2005)

Figure 3.9 Load case of S1 (Thong, 2005)

Figure 3.10 Typical engineering stress-strain curve of S1 (Thong, 2005)

Table 3.2 Geometric parameters of measured specimen S1 (Thong, 2005)

Joint Ref.	Braces $h_i \times b_i \times t_i$	Chord $h_0 \times b_0 \times t_0$	$\theta_{1,2}$	β	τ	γ	Ov %	Remark
S1	150x150x5.75	200x200x6.1	45°	0.75	0.77	16.47	100	No Chord Preload

Figure 3.11 Numerical model of overlap SHS K-joint specimen S1

3.9.3 Numerical results of S1

After the finite element analysis, the displacement-load curve is derived from ABAQUS and failure mode can be seen clearly from Figure 3.12 to 3.13.

From the Figure 3.12 to Figure 3.14 it can be proved that failure mode of joint specimen is chord face failure.

Figure 3.12 Left side view of failure joint S1 (Thong, 2005)

Figure 3.13 Left side view of failure joint S1 in ABAQUS ($\beta=0.75$, $\gamma=16.47$, and $\tau=0.77$)

Figure 3.14 Right side view of failure joint S1 in ABAQUS ($\beta=0.75$, $\gamma=16.47$, and $\tau=0.77$)

Figure 3.15 Experimental and numerical load-displacement curves of S1

3.9.4 Comparison between the numerical results and experimental results

Figure 3.15 show the experimental and numerical load-displacement curves for overlap SHS K-joint S1 tested. It can be seen that the curves began with a straight line from the origin and reach the peak point and then go down fast and then keep a slight slope for a long distance and then go down again. The two curves exhibited good agreement.

The ultimate strength of the numerical modeling is 840kN. The ultimate strength derived from the experiment is 800kN. The experimentally derived ultimate capacity is 5% less than the numerically derived value.

From Figures 3.13 and 3.14, it can be proved that the failure mode of the joint is the same mode of chord face failure. This means that the numerical model not only has a good agreement in ultimate strength, but also in the failure mode.

It can be concluded that the numerical modeling method is valid and proved to be reliable and close to the real result.

3.9.5 Details of the model S2

The experiment frame is the same as S1 and shown in Figure 3.8. The geometric parameters of measured specimen S2 is as shown in Table 3.3. The simplified constraint condition is the same as S1 and shown in Figure 3.9. The material properties are derived from the coupon test result in the thesis of Thong (2005). The finite element model of specimen S2 with 4-node thick shell element is shown in Figure 3.16.

Table 3.3 Geometric parameters of measured specimen S2 (Thong, 2005)

Joint Ref.	Braces $h_i \times b_i \times t_i$	Chord $h_0 \times b_0 \times t_0$	$\theta_{1,2}$	β	τ	γ	O_v %	Remark
S2	120x120x5	200x200x6	45°	0.6	0.83	16.67	100	Chord Preload

Figure 3.16 Numerical model of overlap SHS K-joint specimen S2

3.9.6 Numerical result of S2

After the finite element analysis, the displacement-load curve for S2 model is derived from ABAQUS and failure mode can be seen clearly.

From the Figs. 3.17 to 3.21, it can be proved that failure mode of joint specimen is chord face failure.

Figure 3.17 Left side view of failure joint S2 (Thong, 2005)

Figure 3.18 Left side view of failure joint S2 in ABAQUS ($\beta=0.6$, $\gamma=16.67$, and $\tau=0.83$)

Figure 3.19 Right side view of failure joint S2 (Thong, 2005)

Figure 3.20 Right side view of failure joint S2 in ABAQUS ($\beta=0.6$, $\gamma=16.67$, and $\tau=0.83$)

Figure 3.21 Experimental and numerical load-displacement curves of S2

3.9.7 Comparison between the numerical results and experimental results

Figure 3.21 shows the experimental and numerical load-displacement curves for overlap SHS K-joint S2 tested. The origin point of the experimental curve is not from 0 kN, but the tensile force instead. This is because of at the beginning of the experiment, there is the preload in chord and the brace 1 is restrained in the brace length direction. However, in the modeling process, the brace 1 can move in the brace length. So there is no force in the beginning of the experiment in brace1.

The ultimate strength of the numerical modeling is 671.3kN. The ultimate strength derived from the experiment is 649.4kN. The experimentally derived ultimate capacity is 3.3% less than the numerically derived value.

From Figures 3.17 to 3.20, it can be proved that the failure mode of the joint is the same mode of chord face failure. This means that the numerical model not only has a good agreement in ultimate strength, but also in the failure mode.

It can be concluded again that the numerical modeling method is valid and can be used with confidence in the following parametric study.

3.9.8 Conclusion

The 4-node thick shell element is proved to be accurate in modeling the joints behavior. The two of the overlap joints are modeled as verification joints. The comparison between the experimental and numerical results shows good agreement with each other, with the difference of 3%-5% in ultimate strength value.

Although the verification is overlap joints, the parametric study will be done to gap K-joints, the good agreement can show the Abaqus can give the very similar result with the experimental results. Considering the small difference between overlap joints and K-joints, as the numerical method is verified successfully, a parametric study can be carried out for studying the ultimate strength of SHS K-joints.

CHAPTER 4 PARAMETRIC STUDY

4.1 INTRODUCTION

Chapter 3 shows that the simulation of the actual joint behavior using finite element method has a good agreement with the experimental results. Therefore, the numerical results has been proved accurate and reliable. Thus, a parametric study for SHS gap K-joints can be carried out with finite element method confidently.

In this study, essentially the influences of using of high strength steel, geometric parameter of the joints and load of chord are studied. At the meantime, other parameters are kept constant. There are mainly three significant factors contributing to the variation of the ultimate strength of the square hollow sections gap K-joints i.e. geometric parameters and the loading in the chord members. The geometric parameters are β , γ and τ . The ratio of loading to the yield capacity of the main chord also plays an important role on the changing of the ultimate strength. In order to study the effect of the preload in the chord, two types of preload in chord members are considered. Furthermore, the material is the focus of this study, and S355, S460 and S690 are studied in this study so as to find out the influence of high strength steel to the joint load capacities.

After doing all the simulation mentioned above, the huge number of numerical results could be used to derive a series ultimate strength formulae based on chord face failure of SHS K-joints in different grades of materials. For achieving the formulae from the numerical results, data analysis software called MATLAB is used and the results are presented in the following parts.

4.2 RANGE OF PARAMETERS

The configuration dimensions and geometric parameters of gap SHS K-joints are shown in Figures 4.1. Note that the length of the brace and chord is consistently taken as 3000mm and 6000mm and as the consequence, there will no boundary effect and end effects. In all cases, the brace to chord angle remains 45°.

Figure 4.1 Typical figure of K-joint (Packer et al, 2009)

Table 4.1 Range of parameters

β	τ	γ				
		7.5	9.375	11.538	13.636	16.667
0.5	1	J1	J2	J3	J4	J5
	0.8	J21	J22	J23	J24	J25
	0.65	J41	J42	J43	J44	J45
0.58	1	J6	J7	J8	J9	J10
	0.8	J26	J27	J28	J29	J30
	0.65	J46	J47	J48	J49	J50
0.66	1	J11	J12	J13	J14	J15
	0.8	J31	J32	J33	J34	J35
	0.65	J51	J52	J53	J54	J55
0.75	1	J16	J17	J18	J19	J20
	0.8	J36	J37	J38	J39	J40
	0.65	J56	J57	J58	J59	J60

The research program is listed in Table 4.1. The research program can be divided into 4 groups by changing parameter β . Within each group, they can be divided again with the change τ ranging from 0.65 to 1.0 into 3 groups. Thus, a total number of 12 joints are studied for the variation of β and τ . With the variation of γ from 7.5, 9.375, 11.538, 13.636 and 16.667, the research program can be divided further into

5 groups. Therefore, a total number of 60 joints is studied for a particular load case. Therefore, a total number of 60 joints are studied for a particular load case.

Figure 4.2 Design chart for K-joints (Packer et al, 2009)

In CIDECT Design Guide3 as shown in Figure 4.2, 2γ between 15 to 20 will be more efficient and higher C_k value. In this research, 2γ between 15 to 33 will be studied in order to make extension for the CIDECT Design Guide 3 to be applied into larger range.

Each of the joint is subjected to 3 different combinations of axial loadings, the chord without preload, the compressive preload in the chord equal to the thirty percent of the yield capacity of the chord section, and the compressive preload in the chord equal to the fifty percent of the yield capacity of the chord section. Each joint is modeled in three kinds of steels in the meantime. Common steel S355, High strength steel S460 and high strength steel S690. In total, 540 models are studied in the research.

4.3 FINITE ELEMENT ANALYSIS

In this study, a four-node thick shell element is used throughout the joint modeling. Since the difference of the thickness and width between brace and chord is comparably large, the element type of S4R (a 4-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains) is used.

Bilinear interpolation functions are used for co-ordinates, displacements and rotations. Each node has six degrees of freedom.

The ultimate strength will depend quite significantly on the initial welding distortions and residual stresses. The distribution of transverse shrinkage and angular distribution along the welding line is nearly not influenced by the flange thickness (Dean, 2007). The influence of welding in joints on static strength is found insignificant (Khurshid. et al, 2015). Therefore, the influence of welding and welding process is not considered in this thesis.

4.4 NUMERICAL RESULTS

4.4.1 Ultimate capacity

Ultimate tensile strength, often shortened to tensile strength (UTS) or ultimate strength, is the maximum stress that a material can withstand while being stretched or pulled before failing or breaking. The UTS is usually found by performing a tensile test and recording the engineering stress versus strain. The highest point of the stress-strain curve is the UTS.

For the basic 60 model research program, under 3 loading cases and 3 materials, each will have one displacement-load curve. The ultimate strength is the highest point of the load-displacement curve. Comparison of ultimate strength results of S460 in different load cases are shown in the Table 4.2.

The theoretical results derived from the CIDECT Design Guide 3 are filled in the row of effective width criteria formulae. The percentage of difference between them is also calculated. The failure mode is listed as well.

joint no	b0	t0	b	t	β	γ	τ	Load case 1			Load case 2			Load case 3			
								Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Failure Mode
J1	600	40	300	40	0.50	7.50	1	102192.23	108750.28	-6.03	14679.18	12044.26	21.88	188320.45	133375.12	41.20	-
J2		32		32		9.38		68337.85	74418.92	-8.17	10258.72	8242.01	24.47	148615.48	91269.95	62.83	-
J3		26		26		11.54		43722.03	52285.72	-16.38	6769.01	5790.72	16.89	107197.59	64125.02	67.17	CF
J4		22		22		13.64		31153.72	39359.26	-20.85	4996.04	4359.10	14.61	83013.05	48271.57	71.97	CF
J5		18		18		16.67		18541.33	27982.83	-33.74	3150.29	3099.14	1.65	57549.63	34319.12	67.69	CF
J6		40		40		7.50		118334.34	131265.70	-9.85	16114.75	14292.54	12.75	229586.51	155604.31	47.55	CF
J7		32		32		9.38		75082.75	89826.45	-16.41	10765.31	9780.53	10.07	163580.82	106481.60	53.62	CF
J8		26		26		11.54		50364.99	63110.84	-20.20	7560.98	6871.67	10.03	118922.02	74812.53	58.96	CF
J9		22		22		13.64		33909.00	47508.12	-28.62	5255.93	5172.80	1.61	87801.25	56316.83	55.91	CF
J10		18		18		16.67		21509.98	33776.33	-36.32	3504.78	3677.65	-4.70	64592.72	40038.97	61.32	CF
J11		40		40		7.50		134362.60	155209.13	-13.43	16778.26	16614.37	0.99	231206.05	177833.49	30.01	CF
J12		32		32		9.38		86697.49	106211.18	-18.37	11302.65	11369.38	-0.59	163706.31	121693.26	34.52	CF
J13		26		26		11.54		56426.62	74622.53	-24.38	7811.21	7987.97	-2.21	118966.22	85500.03	39.14	CF
J14		22		22		13.64		39543.70	56173.80	-29.60	5809.08	6013.13	-3.39	92583.22	64362.09	43.85	CF
J15		18		18		16.67		23644.86	39937.29	-40.80	3706.97	4275.09	-13.29	64265.08	45758.82	40.44	CF
J16		40		40		7.50		155397.37	180652.45	-13.98	18132.80	19011.61	-4.62	228282.84	200062.68	14.11	CF
J17		32		32		9.38		104711.91	123622.31	-15.30	12126.43	13009.83	-6.79	163371.04	136904.92	19.33	CF
J18		26		26		11.54		67814.70	86855.35	-21.92	8323.96	9140.53	-8.93	118328.80	96187.53	23.02	CF
J19		22		22		13.64		46761.08	65382.34	-28.48	6081.30	6880.74	-11.62	91015.70	72407.35	25.70	CF
J20		18		18		16.67		29386.70	46484.18	-36.78	4075.30	4891.93	-16.69	65539.15	51478.67	27.31	CF
J21		40		32		7.50	0.8	101326.22	108750.28	-6.83	14311.82	12044.26	18.83	166277.29	133375.12	24.67	-
J22		32		25.6		9.38		67708.21	74418.92	-9.02	9992.54	8242.01	21.24	128696.21	91269.95	41.01	-
J23		26		20.8		11.54		43473.42	52285.72	-16.85	6695.10	5790.72	15.62	99298.67	64125.02	54.85	CF
J24		22		17.6		13.64		30921.26	39359.26	-21.44	4934.89	4359.10	13.21	80146.37	48271.57	66.03	CF
J25		18		14.4		16.67		18574.06	27982.83	-33.62	3151.69	3099.14	1.70	56017.63	34319.12	63.23	CF
J26		40		32		7.50		115616.63	131265.70	-11.92	15594.14	14292.54	9.11	198283.86	155604.31	27.43	-
J27		32		25.6		9.38		73900.24	89826.45	-17.73	10463.26	9780.53	6.98	148717.33	106481.60	39.66	CF
J28		26		20.8		11.54		49748.66	63110.84	-21.17	7449.36	6871.67	8.41	113653.54	74812.53	51.92	CF
J29		22		17.6		13.64		33615.92	47508.12	-29.24	5189.56	5172.80	0.32	83749.38	56316.83	48.71	CF
J30		18		14.4		16.67		21368.91	33776.33	-36.73	3440.44	3677.65	-6.45	61694.66	40038.97	54.09	CF

BF=Brace Failure

CF=Chord Face Failure

Continue on Appendix B for the rest of the joints

4.4.2 Failure mode of the SHS K-joints

The most common failure mode for the studied models is chord face failure, which is shown in Figures 4.3a to 4.3d. Meanwhile, some of the studied model fails as local yielding of brace and are shown in Figures 4.3e to 4.3g.

(a) Chord face failure (Joint no.9, $\beta=0.58$, $\gamma=13.636$ and $\tau=1$, Load Case 1)

(b) Chord face failure (Joint no.9, $\beta=0.58$, $\gamma=13.636$ and $\tau=1$, Load Case 2)

(c) Chord face failure (Joint no.9, $\beta=0.58$, $\gamma=13.636$ and $\tau=1$, Load Case 3)

(d) Chord face failure (Joint no.9, $\beta=0.58$, $\gamma=13.636$ and $\tau=1$, Load Case 3)

(e) Local yielding of brace (Joint no.52, $\beta=0.66$, $\gamma=9.375$ and $\tau=0.65$, Load Case 1)

(f) Local yielding of brace (Joint no.52, $\beta=0.66$, $\gamma=9.375$ and $\tau=0.65$, Load Case 2)

(g) Local yielding of brace (Joint no.52, $\beta=0.66$, $\gamma=9.375$ and $\tau=0.65$, Load Case 3)

Figure 4.3 Failure modes of S460 gap joints

4.4.3 Non-Dimensional Ultimate Load Versus τ

To investigate the influence of τ on the non-dimensional ultimate load of the K-joint, the τ is selected from 0.65 to 1.0. The vertical axis is calculated from the ultimate strength by the yield strength multiplied by the square of thickness, and the horizontal axis is the value of τ . The values of β and γ are kept constant. Non-dimensional strength ($F/f_y T^2$) versus τ is shown in Figure 4.4. The figures for other load cases and materials are shown in Appendix G.

Figure 4.4 Non-dimensional strength ($F/f_y T^2$) versus τ

Figure 4.4 shows that with the increasing of the value of τ , the non-dimensional strength don't change much. A general conclusion can be drawn from the figure that non-dimensional strength is insensitive to the variation of τ .

In the following parts, only the joints with $\tau=1$ will be shown in Figures 4.5 and 4.6 to find the other conclusions due to the small influence of τ .

4.4.4 Non-Dimensional Ultimate Load Versus γ

To investigate the influence of γ on the non-dimensional ultimate load of the K-joint, the γ is selected from 7.5 to 16.67. The vertical axis is calculated from the ultimate strength by the yield strength multiplied by the square of thickness, and the horizontal axis is the value of γ . The values of β and τ are kept constant. The figures for other load cases and materials are shown in Appendix G.

Figure 4.5 Non-dimensional strength ($F/f_y T^2$) versus γ

Figure 4.5 shows that with the increasing of the value of γ , the non-dimensional strength increase fast until γ reaches around 11, there will be a peak point for the non-dimensional strength. A general conclusion can be drawn from the figure that non-dimensional strength is sensitive to the variation of γ to some extent. It should be taken into consideration when the new formula is proposed.

4.4.5 Non-Dimensional Ultimate Load Versus β

Similar to the geometric parameters γ and τ , β is another important parameter which influences the ultimate strength of the joints. In order to investigate the influence of β on the non-dimensional ultimate load of the K-joint, the β is selected from 0.5 to 0.75. The vertical axis is calculated from the ultimate strength by the yield strength multiplied by the square of thickness, and the horizontal axis is the value of β . The values of τ and γ are kept constant. The figures for other load cases and materials are shown in Appendix G.

Figure 4.6 Non-dimensional strength ($F/f_y T^2$) versus β

Figure 4.6 shows that with the increasing of the value of β , the non-dimensional strength change very much and shows the linear relationship. β is the most influential geometric parameter compared to τ and γ for the strength of gap K-joint. A slight change of β can lead to the big change of the non-dimensional strength, when comparing with the minor influence of γ and τ . Therefore, β should be chosen as the primary variable parameter in dealing with the ultimate strength formulae.

4.4.6 Strength Ratio

Strength ratio is defined as the ratio of the numerical ultimate strength to the theoretical ultimate strength calculated based on the equation in CIDECT Design Guide 3 (Eq. 2.1).

In order to find out the relationship between the strength ratios between the parameters, the ratio value and different parameters are listed in Table 4.3 and shown in the Figures 4.7 to 4.9.

Table 4.3 Non-dimensional ultimate strength obtained from the numerical analysis and the computed strength ratio ($\tau=1$)

$\beta=0.5$		Non-dimensional strength		Strength ratio	
Joint No	γ	LC2	LC1	LC2	LC1
J1	7.5	19.62	13.85	1.20	0.94
J2	9.375	22.00	14.71	1.26	0.93
J3	11.538	21.33	13.50	1.15	0.80
J4	13.636	21.65	13.36	1.11	0.76
J5	16.667	19.83	10.61	0.95	0.57

$\beta=0.58$		Non-dimensional strength		Strength ratio	
Joint No	γ	LC2	LC1	LC2	LC1
J6	7.5	22.09	16.43	1.14	0.92
J7	9.375	22.15	15.65	1.07	0.82
J8	11.538	24.21	15.88	1.10	0.78
J9	13.636	21.84	13.91	0.94	0.65
J10	16.667	22.47	12.74	0.91	0.56

$\beta=0.66$		Non-dimensional strength		Strength ratio	
Joint No	γ	LC2	LC1	LC2	LC1
J11	7.5	22.93	18.40	1.02	0.87
J12	9.375	23.45	17.73	0.97	0.79
J13	11.538	24.16	17.01	0.94	0.71
J14	13.636	24.28	15.88	0.90	0.63
J15	16.667	22.69	13.72	0.79	0.51

$\beta=0.75$		Non-dimensional strength		Strength ratio	
Joint No	γ	LC2	LC1	LC2	LC1
J16	7.5	24.59	20.95	0.95	0.85
J17	9.375	24.95	20.96	0.90	0.80
J18	11.538	25.76	20.28	0.88	0.73
J19	13.636	25.66	19.17	0.83	0.65
J20	16.667	24.97	17.60	0.76	0.56

4.4.6.1 Effect of τ on the strength ratio

From the Figure 4.7 between τ and strength ratio, it is obvious to draw the conclusion that the strength ratio keep constant with the change of τ . A general conclusion can be drawn from the figure that strength ratio is insensitive to the variation of τ .

In the following parts, only the joints with $\tau=1$ is shown in the figures to find the other conclusions.

4.4.6.2 Effect of γ on the strength ratio

Figure 4.8 show the relationship between the strength ratio and γ for different values of β and 3 different load cases. It is apparent that the variation of strength ratio with respect to γ is insignificant for all load cases for the range of β studied.

4.4.6.3 Effect of β on the strength ratio

Figure 4.9 show the relationship between the strength ratio and β for different values of γ . It can be seen obviously that β influence the strength ratio largely. When a minor change happens to β , the strength ratio can decrease for a large scale.

Figure 4.7 Strength ratio versus τ for gap K-joints

Figure 4.8 Strength ratio versus γ for gap K-joints Figure 4.9 Strength ratio versus β for gap K-joints

4.5 FAILURE MODES OF K-JOINTS IN DIFFERENT MATERIALS

The importance of investigating the failure modes of gap K-joints lies in the ability to explain the difference in the strength of joints subjected to various loads and also the ability to understand the trend of the load-displacement curves.

Two basic failure modes can be detected from all the results obtained from parametric study:

- (1) Plastic failure of the chord face. The most common failure mode for gap joints with all the joints studied. This mode occurred for joints with high τ

($\tau=0.8\sim1.0$) in load case 3 in all the three materials and for all the joints studied for load case 1 and load case 2.

- (2) Local buckling of the compression brace, due to an uneven load distribution (also termed local yielding of the brace). This mode happens in joints with low or medium γ ($\gamma=7.5\sim13.636$) and low τ ($\tau=0.65$) in load case 3. When β is low ($\beta=0.5\sim0.58$), this mode happen in joint with low γ ($\gamma=7.5\sim9.375$) and medium to high τ ($\tau=0.8\sim1$).

Table 4.4 shows the failure modes of joints in different load cases and materials. The failure modes of other joints are given in the Appendix H. All of the brace failure happened when $\tau=0.65$ in load case 3. Some joints have the combination of the two failure modes, brace failure and chord plastification. In the same joint, when using high strength steel, the failure mode can be transferred from brace failure to chord face plastification, i.e. J23 J45 J49 J50 and J59.

Table 4.4 The failure modes of joints in different load cases and materials

J16	355	LC3	CF	J17	355	LC3	CF	J18	355	LC3	CF
		LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF
	460	LC3	CF		460	LC3	CF		460	LC3	CF
		LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF
	690	LC3	CF		690	LC3	CF		690	LC3	CF
		LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF
J36	355	LC3	CF	J37	355	LC3	CF	J38	355	LC3	CF
		LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF
	460	LC3	CF		460	LC3	CF		460	LC3	CF
		LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF
	690	LC3	CF		690	LC3	CF		690	LC3	CF
		LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF
J56	355	LC3	BF	J57	355	LC3	BF	J58	355	LC3	BF
		LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF
	460	LC3	BF		460	LC3	BF		460	LC3	BF
		LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF
	690	LC3	BF		690	LC3	BF		690	LC3	BF
		LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF

BF=Brace Failure

CF=Chord Face Failure

Continue on Appendix H for the rest of the joints

LC1=Load Case 1

LC2=Load Case 2

LC3=Load Case 3

Table 4.5 shows the probability of the occurrence of the two failure modes for different load cases and variation of τ (t/t_0). For those joints with two failure modes, the results are shown in the form of interaction curve in Figure 4.10. Figure 4.10 shows the plot of τ versus β for load cases 3 and $\gamma=11.538$. Both the two zones of failure mode can be observed. There were not enough data to define the exact

boundary but sufficient to provide a rough estimation of the failure modes. The interaction figure of other joints in load case 3 can be found in Appendix H.

Table 4.5 Failure modes related to load cases and τ (t/t_0) for gap K-joints

LC	1			2			3		
τ	1	0.8	0.65	1	0.8	0.65	1	0.8	0.65
CF	✓	✓	✓	✓	✓	✓	✓	✓	✓
BF							✓	✓	✓
LC=Load Case, CF=Chord Failure, BF=Brace Failure

Figure 4.10 Interaction between τ and β for k-joints subjected to load case 3;
 $\gamma=13.636$

4.6 COMPARISON OF NUMERICAL RESULTS WITH CIDECT DESIGN GUIDE 3

Although some of the numerical results of ultimate strength of the model in the research program exceed the theoretical result of the ultimate strength for S355, the majority of the numerical results are less than the theoretical results derived from the formulae in CIDECT Design Guide 3. This means that it is not conservative to use the design resistance of joint formulae for S355 in the CIDECT Design Guide 3. For S460 and S690, there is no exact formula to calculate the ultimate strength in CIDECT or any existing codes. However, from the comparison between the numerical ultimate capacities and theoretical ultimate capacities that derived from the CIDECT formulae, the majority of the numerical results are less than the theoretical results derived from the formulae in CIDECT Design Guide 3. This means that it is not safe for the S460 and S690 joint to use the formula in CIDECT Design Guide 3. Therefore, it is necessary, significant and in great urgency to propose a new formula considering this case.

For the S355 gap SHS K-joints, the strength differences under high compressive load can be very large as the parameter combination changes. The formulae can be used with confidence when the chord is under no force. However, the conditions that the chord is under high compressive load can be very common in the realistic design, so there is an urgent need to consider how to improve the formulae to make it suitable to a larger scope of force conditions.

Table 4.6 Comparison of strength results of the three materials in load case 1

joint no	b0	t0	b	t	β	γ	τ	S355			S460			S690		
								Numerical strength of joints (KN)	Theoretical strength of joints (KN)	ratio	Numerical strength of joints (KN)	Theoretical strength of joints (KN)	ratio	Numerical strength of joints (KN)	Theoretical strength of joints (KN)	ratio
J1	600	40	300	40	0.50	7.50	1	8123.58	8392.68	0.97	10219.22	10875.03	0.94	15289.88	16312.54	0.94
J2		32		32		9.38		5414.32	5743.20	0.94	6833.78	7441.89	0.92	10395.76	11162.84	0.93
J3		26		26		11.54		3488.36	4035.09	0.86	4372.20	5228.57	0.84	6298.67	7842.86	0.80
J4		22		22		13.64		2334.37	3037.51	0.83	3115.37	3935.93	0.79	4462.75	5903.89	0.76
J5		18		18		16.67		1509.14	2159.54	0.70	1854.13	2798.28	0.66	2372.46	4197.42	0.57
J6		40	350	40	0.58	7.50		9282.77	10130.29	0.92	11833.43	13126.57	0.90	18138.30	19689.85	0.92
J7		32		32		9.38		6126.36	6932.26	0.88	7508.27	8982.64	0.84	11057.58	13473.97	0.82
J8		26		26		11.54		4053.21	4870.51	0.83	5036.50	6311.08	0.80	7405.31	9466.63	0.78
J9		22		22		13.64		2711.95	3666.39	0.74	3390.90	4750.81	0.71	4645.01	7126.22	0.65
J10		18		18		16.67		1776.37	2606.65	0.68	2151.00	3377.63	0.64	2849.26	5066.45	0.56
J11		40	400	40	0.67	7.50		10761.45	11978.10	0.90	13436.26	15520.91	0.87	20314.42	23281.37	0.87
J12		32		32		9.38		7133.42	8196.73	0.87	8669.75	10621.12	0.82	12525.45	15931.68	0.79
J13		26		26		11.54		4485.74	5758.91	0.78	5642.66	7462.25	0.76	7934.97	11193.38	0.71
J14		22		22		13.64		3265.87	4335.15	0.75	3954.37	5617.38	0.70	5302.28	8426.07	0.63
J15		18		18		16.67		1955.15	3082.12	0.63	2364.49	3993.73	0.59	3067.29	5990.59	0.51
J16		40	450	40	0.75	7.50	0.8	12972.20	13941.66	0.93	15539.74	18065.25	0.86	23126.11	27097.87	0.85
J17		32		32		9.38		8358.00	9540.42	0.88	10471.19	12362.23	0.85	14807.48	18543.35	0.80
J18		26		26		11.54		5833.46	6702.97	0.87	6781.47	8885.53	0.78	9459.69	13028.30	0.73
J19		22		22		13.64		3789.29	5045.81	0.75	4676.11	6538.23	0.72	6402.19	9807.35	0.65
J20		18		18		16.67		2376.13	3587.37	0.66	2938.67	4648.42	0.63	3933.81	6972.63	0.56
J21		40	300	32	0.50	7.50		8010.88	8392.68	0.95	10132.62	10875.03	0.93	15351.82	16312.54	0.94
J22		32		25.6		9.38		5366.96	5743.20	0.93	6770.82	7441.89	0.91	10313.79	11162.84	0.92
J23		26		20.8		11.54		3470.83	4035.09	0.86	4347.34	5228.57	0.83	6268.57	7842.86	0.80
J24		22		17.6		13.64		2522.07	3037.51	0.83	3092.13	3935.93	0.79	4399.60	5903.89	0.75
J25		18		14.4		16.67		1500.65	2159.54	0.69	1857.41	2798.28	0.66	2329.10	4197.42	0.55
J26		40	350	32	0.58	7.50		9061.28	10130.29	0.89	11561.66	13126.57	0.88	17772.45	19689.85	0.90
J27		32		25.6		9.38		6044.43	6932.26	0.87	7390.02	8982.64	0.82	10928.13	13473.97	0.81
J28		26		20.8		11.54		4026.52	4870.51	0.83	4974.87	6311.08	0.79	7299.98	9466.63	0.77
J29		22		17.6		13.64		2694.54	3666.39	0.73	3361.59	4750.81	0.71	4601.62	7126.22	0.65
J30		18		14.4		16.67		1767.92	2606.65	0.68	2136.89	3377.63	0.63	2817.78	5066.45	0.56

joint no	b0	t0	b	t	β	γ	τ	S355			S460			S690		
								Numerical strength of joints (KN)	Theoretical strength of joints (KN)	ratio	Numerical strength of joints (KN)	Theoretical strength of joints (KN)	ratio	Numerical strength of joints (KN)	Theoretical strength of joints (KN)	ratio
J31	600	40	400	32	0.67	7.50	0.8	10482.67	11978.10	0.88	13045.93	15520.91	0.84	19873.96	23281.37	0.85
J32		32		25.6		9.38		7027.08	8196.73	0.86	8515.68	10621.12	0.80	12345.44	15931.68	0.77
J33		26		20.8		11.54		4444.51	5738.91	0.77	5566.12	7462.25	0.75	7831.98	11193.38	0.70
J34		22		17.6		13.64		3233.16	4335.15	0.75	3909.20	5617.38	0.70	5234.54	8426.07	0.62
J35		18		14.4		16.67		1933.58	3082.12	0.63	2338.31	3993.73	0.59	2988.54	5990.59	0.50
J36		40		32		7.50		12533.11	13941.66	0.90	15013.13	18065.25	0.83	22581.27	27097.87	0.83
J37		32		25.6		9.38		8207.76	9540.42	0.86	10200.86	12362.23	0.83	14498.45	18543.35	0.78
J38		26		20.8		11.54		5714.36	6702.97	0.85	6662.33	8685.53	0.77	9237.67	13028.30	0.71
J39		22	450	17.6	0.75	13.64		3739.51	5045.81	0.74	4599.08	6338.23	0.70	6226.67	9807.35	0.63
J40		18		14.4		16.67		2336.50	3587.37	0.65	2859.64	4648.42	0.62	3792.65	6972.63	0.54
J41		40		26		7.50		7834.06	8392.68	0.93	9942.25	10875.03	0.91	14981.66	16312.54	0.92
J42		32		20.8		9.38		5297.04	5743.20	0.92	6650.93	7441.89	0.89	10104.96	11162.84	0.91
J43		26	300	16.9	0.50	11.54		3438.99	4035.09	0.85	4372.20	5228.57	0.84	6224.70	7842.86	0.79
J44		22		14.3		13.64		2498.97	3037.51	0.82	3060.16	3935.93	0.78	4357.90	5903.89	0.74
J45		18		11.7		16.67		1485.67	2159.54	0.69	1838.57	2798.28	0.66	2331.72	4197.42	0.56
J46		40		26		7.50		8765.68	10130.29	0.87	11202.22	13126.57	0.85	17229.92	19689.85	0.88
J47	600	32	350	20.8	0.58	9.38	0.65	5903.89	6932.26	0.85	7210.65	8982.64	0.80	10747.40	13473.97	0.80
J48		26		16.9		11.54		3956.06	4870.51	0.81	4861.29	6311.08	0.77	7154.70	9466.63	0.76
J49		22		14.3		13.64		2675.22	3666.39	0.73	3310.76	4750.81	0.70	4536.78	7126.22	0.64
J50		18		11.7		16.67		1752.82	2606.65	0.67	2111.80	3377.63	0.63	2763.85	5066.45	0.55
J51		40		26		7.50		10065.74	11978.10	0.84	12508.85	15520.91	0.81	19204.25	23281.37	0.82
J52		32		20.8		9.38		6786.56	8196.73	0.83	8236.24	10621.12	0.78	12081.82	15931.68	0.76
J53		26	400	16.9	0.67	11.54		4380.20	5738.91	0.76	5436.57	7462.25	0.73	7672.78	11193.38	0.69
J54		22		14.3		13.64		3183.11	4335.15	0.73	3834.25	5617.38	0.68	5154.53	8426.07	0.61
J55		18		11.7		16.67		1920.57	3082.12	0.62	2302.77	3993.73	0.58	2944.38	5990.59	0.49
J56		40		26		7.50		11934.64	13941.66	0.86	14288.15	18065.25	0.79	21639.19	27097.87	0.80
J57		32	450	20.8	0.75	9.38		7919.64	9540.42	0.83	9737.56	12362.23	0.79	14060.70	18543.35	0.76
J58		26		16.9		11.54		5459.89	6702.97	0.81	6411.01	8685.53	0.74	9899.40	13028.30	0.69
J59		22		14.3		13.64		3664.21	5045.81	0.73	4452.99	6338.23	0.68	6005.52	9807.35	0.61
J60		18		11.7		16.67		2298.74	3587.37	0.64	2764.67	4648.42	0.59	3553.39	6972.63	0.51

Table 4.7 Comparison of strength results of the three materials in load case 2

joint no	b0	t0	b	t	β	γ $b0/(2t0)$	τ $t1/t0$	S355			S460			S690		
								Numerical strength of joints (KN)	Theoretical strength of joints (KN)	ratio	Numerical strength of joints (KN)	Theoretical strength of joints (KN)	ratio	Numerical strength of joints (KN)	Theoretical strength of joints (KN)	ratio
J1	600	40	300	40	0.50	7.50	1	11688.12	9295.03	1.26	14679.18	12044.26	1.22	21657.65	18066.39	1.20
J2		32		32		9.38		8029.41	6360.68	1.26	10258.72	8242.01	1.24	15544.18	12363.02	1.26
J3		26		26		11.54		5398.86	4468.93	1.21	6769.01	5790.72	1.17	9947.85	8686.09	1.15
J4		22		22		13.64		4051.49	3364.09	1.20	4996.04	4359.10	1.15	7231.21	6538.65	1.11
J5		18		18		16.67		2597.15	2391.73	1.09	3150.29	3099.14	1.02	4432.47	4648.71	0.95
J6		40		40		7.50		12732.23	11030.11	1.15	16114.75	14292.54	1.13	24381.85	21438.81	1.14
J7		32		32		9.38		8713.61	7548.02	1.15	10765.31	9780.53	1.10	15646.88	14670.80	1.07
J8		26		26		11.54		6014.35	5303.13	1.13	7560.98	6871.67	1.10	11292.09	10307.50	1.10
J9		22		22		13.64		4162.56	3992.06	1.04	5255.93	5172.80	1.02	7294.65	7759.21	0.94
J10		18		18		16.67		2901.08	2838.19	1.02	3504.78	3677.65	0.95	5023.15	5516.48	0.91
J11	600	40	400	40	0.67	7.50	0.8	13290.60	12821.96	1.04	16778.26	16614.37	1.01	25314.10	24921.55	1.02
J12		32		32		9.38		9214.89	8774.20	1.05	11302.65	11369.38	0.99	16567.18	17054.07	0.97
J13		26		26		11.54		6169.13	6164.63	1.00	7811.21	7987.97	0.98	11269.11	11981.96	0.94
J14		22		22		13.64		4683.09	4640.57	1.01	5809.08	6013.13	0.97	8109.34	9019.69	0.90
J15		18		18		16.67		3037.62	3299.25	0.92	3706.97	4275.09	0.87	5071.53	6412.63	0.79
J16		40		40		7.50		14991.62	14672.00	1.02	18132.80	19011.61	0.95	27152.67	28517.41	0.95
J17		32		32		9.38		9684.03	10040.20	0.96	12126.43	13009.83	0.93	17628.25	19514.75	0.90
J18		26		26		11.54		6951.23	7054.11	0.99	8323.96	9140.53	0.91	12014.22	13710.80	0.88
J19		22		22		13.64		4874.08	5310.14	0.92	6081.30	6880.74	0.88	8569.90	10321.11	0.83
J20		18		18		16.67		3290.10	3775.29	0.87	4075.30	4891.93	0.83	5581.65	7337.89	0.76
J21	600	40	300	32	0.50	7.50	0.8	11326.11	9295.03	1.22	14311.82	12044.26	1.19	21304.30	18066.39	1.18
J22		32		25.6		9.38		7889.72	6360.68	1.24	9992.54	8242.01	1.21	15160.68	12363.02	1.23
J23		26		20.8		11.54		5323.95	4468.93	1.19	6695.10	5790.72	1.16	9791.83	8686.09	1.13
J24		22		17.6		13.64		4025.55	3364.09	1.20	4934.89	4359.10	1.13	7131.87	6538.65	1.09
J25		18		14.4		16.67		2575.04	2391.73	1.08	3151.69	3099.14	1.02	4409.63	4648.71	0.95
J26		40		32		7.50		12326.77	11030.11	1.12	15594.14	14292.54	1.09	23663.19	21438.81	1.10
J27		32		25.6		9.38		8562.03	7548.02	1.13	10463.26	9780.53	1.07	15368.71	14670.80	1.05
J28		26		20.8		11.54		5936.66	5303.13	1.12	7449.36	6871.67	1.08	11103.78	10307.50	1.08
J29		22		17.6		13.64		4115.80	3992.06	1.03	5189.56	5172.80	1.00	7251.96	7759.21	0.93
J30		18		14.4		16.67		2886.54	2838.19	1.02	3440.44	3677.65	0.94	4970.19	5516.48	0.90

joint no	b0	t0	b	t	β (b/b0)	γ $b0/(2t0)$	τ t1/t0	S355			S460			S690		
								Numerical strength of joints (KN)	Theoretical strength of joints (KN)	ratio	Numerical strength of joints (KN)	Theoretical strength of joints (KN)	ratio	Numerical strength of joints (KN)	Theoretical strength of joints (KN)	ratio
J31	600	40	32	25.6	0.67	7.50	0.8	13047.20	12821.96	1.02	16439.79	16614.37	0.99	24753.51	24921.55	0.99
J32		32				9.38		9102.06	8774.20	1.04	11190.46	11369.38	0.98	16387.38	17054.07	0.96
J33		26				11.54		6139.01	6164.63	1.00	7756.30	7987.97	0.97	11198.76	11981.96	0.93
J34		22				13.64		4647.82	4640.57	1.00	5755.16	6013.13	0.96	8062.18	9019.69	0.89
J35		18	14.4	14.4	0.75	16.67		3016.11	3299.25	0.91	3677.85	4275.09	0.86	5089.98	6412.63	0.79
J36		40				7.50		14613.21	14672.00	1.00	17735.60	19011.61	0.93	26308.49	28517.41	0.92
J37		32				9.38		9573.85	10040.20	0.95	11968.43	13009.83	0.92	17408.97	19514.75	0.89
J38		26				11.54		6867.31	7054.11	0.97	8230.11	9140.53	0.90	11876.33	13710.80	0.87
J39		22	17.6	20.8	0.58	13.64		4835.61	5310.14	0.91	6029.59	6880.74	0.88	8492.23	10321.11	0.82
J40		18				16.67		3267.52	3775.29	0.87	4055.95	4891.93	0.83	5336.10	7337.89	0.75
J41		40				7.50		10889.34	9295.03	1.17	13846.51	12044.26	1.15	20703.01	18066.39	1.15
J42		32				9.38		7634.33	6360.68	1.20	9668.06	8242.01	1.17	14612.54	12363.02	1.18
J43		26	300	16.9	0.50	11.54		5209.06	4468.93	1.17	6769.01	5790.72	1.17	9566.01	8686.09	1.10
J44		22				13.64		3958.52	3364.09	1.18	4832.69	4359.10	1.11	6934.17	6338.65	1.06
J45		18				16.67		2538.24	2391.73	1.06	3114.80	3099.14	1.01	4348.83	4648.71	0.94
J46		40				7.50		11795.99	11030.11	1.07	14980.06	14292.54	1.05	22733.43	21438.81	1.06
J47		32	350	20.8	0.58	9.38		8252.08	7548.02	1.09	10131.38	9780.53	1.04	14980.02	14670.80	1.02
J48		26				11.54		5767.84	5303.13	1.09	7211.17	6871.67	1.05	10771.03	10307.50	1.04
J49		22				13.64		4076.62	3992.06	1.02	5081.85	5172.80	0.98	7164.63	7759.21	0.92
J50		18				16.67		2852.25	2838.19	1.00	3420.28	3677.65	0.93	4882.01	5516.48	0.88
J51		40	26	20.8	0.67	7.50	0.65	12700.64	12821.96	0.99	15999.50	16614.37	0.96	24098.73	24921.55	0.97
J52		32				9.38		8875.53	8774.20	1.01	10917.15	11369.38	0.96	16021.81	17054.07	0.94
J53		26				11.54		6023.82	6164.63	0.98	7572.53	7987.97	0.95	10967.60	11981.96	0.92
J54		22				13.64		4563.49	4640.57	0.98	5638.87	6013.13	0.94	7909.93	9019.69	0.88
J55		18	14.3	11.7	0.75	16.67		2960.93	3299.25	0.90	3622.34	4275.09	0.85	5022.63	6412.63	0.78
J56		40				7.50		13956.09	14672.00	0.95	17027.04	19011.61	0.90	25557.05	28517.41	0.90
J57		32				9.38		9366.19	10040.20	0.93	11723.58	13009.83	0.90	17177.71	19514.75	0.88
J58		26				11.54		6698.82	7054.11	0.95	8091.40	9140.53	0.89	11711.44	13710.80	0.85
J59		22	14.3	14.3	0.75	13.64		4774.62	5310.14	0.90	5938.10	6880.74	0.86	8385.55	10321.11	0.81
J60		18				16.67		3235.79	3775.29	0.86	3985.61	4891.93	0.81	5492.62	7337.89	0.75

Table 4.8 Comparison of strength results of the three materials in load case 3

joint no	b0	t0	b	t	β	γ	τ	S355			S460			S690		
								Numerical strength of joints (KN)	Theoretical strength of joints (KN)	ratio	Numerical strength of joints (KN)	Theoretical strength of joints (KN)	ratio	Numerical strength of joints (KN)	Theoretical strength of joints (KN)	ratio
J1		40		40		7.50	1	16010.99	10293.08	1.56	18832.04	13337.51	1.41	28555.55	20006.27	1.43
J2		32		32		9.38		12292.93	7043.66	1.75	14861.55	9126.99	1.63	21825.76	13690.49	1.59
J3		26	300	26	0.50	11.54		8654.64	4948.78	1.75	10719.76	6412.50	1.67	13965.51	9618.75	1.45
J4		22		22		13.64		6740.63	3725.31	1.81	8301.30	4827.16	1.72	12339.76	7240.73	1.70
J5		18		18		16.67		4400.33	2648.54	1.66	5754.96	3431.91	1.68	7779.50	5147.87	1.51
J6		40		40		7.50		18489.22	12008.59	1.54	22958.65	15560.43	1.48	33800.02	23340.65	1.45
J7		32		32		9.38		13327.96	8217.60	1.62	16358.08	10648.16	1.54	20998.05	15972.24	1.31
J8		26	350	26	0.58	11.54		9656.68	5773.58	1.67	11892.20	7481.25	1.59	17553.80	11221.88	1.56
J9		22		22		13.64		6928.96	4346.19	1.59	8780.12	5631.68	1.56	11930.98	8447.52	1.41
J10		18		18		16.67		5239.10	3089.96	1.70	6459.27	4003.90	1.61	9598.16	6005.85	1.60
J11	600	40		40		7.50	0.8	18460.04	13724.11	1.35	23120.61	17783.35	1.30	34881.01	26675.02	1.31
J12		32		32		9.38		13433.10	9391.55	1.43	16370.63	12169.33	1.35	24260.99	18253.99	1.33
J13		26	400	26	0.67	11.54		9562.26	6598.37	1.45	11896.62	8550.00	1.39	17456.71	12825.00	1.36
J14		22		22		13.64		7567.82	4967.07	1.52	9258.32	6436.21	1.44	13114.14	9654.31	1.36
J15		18		18		16.67		5148.33	3531.39	1.46	6426.51	4575.88	1.40	9403.93	6863.82	1.37
J16		40		40		7.50		18669.01	15439.62	1.21	22828.28	20006.27	1.14	34254.09	30009.40	1.14
J17		32		32		9.38		13051.85	10565.49	1.24	16337.10	13690.49	1.19	24491.81	20535.74	1.19
J18		26	450	26	0.75	11.54		9831.84	7423.17	1.32	11832.88	9618.75	1.23	17675.05	14428.13	1.23
J19		22		22		13.64		7406.29	5587.96	1.33	9101.57	7240.73	1.26	13361.46	10861.10	1.23
J20		18		18		16.67		5354.54	3972.81	1.35	6553.92	5147.87	1.27	9581.78	7721.80	1.24
J21		40		32		7.50	0.8	13789.80	10293.08	1.34	16627.73	13337.51	1.25	23450.91	20006.27	1.17
J22		32		25.6		9.38		10754.10	7043.66	1.53	12869.62	9126.99	1.41	19677.50	13690.49	1.44
J23		26	300	20.8	0.50	11.54		7991.64	4948.78	1.61	9929.87	6412.50	1.55	13447.02	9618.75	1.40
J24		22		17.6		13.64		6502.07	3725.31	1.75	8014.64	4827.16	1.66	11814.31	7240.73	1.63
J25		18		14.4		16.67		4281.09	2648.54	1.62	5601.76	3431.91	1.63	7538.92	5147.87	1.46
J26		40		32		7.50		16463.12	12008.59	1.37	19828.39	15560.43	1.27	30508.60	23340.65	1.31
J27		32		25.6		9.38		12573.40	8217.60	1.53	14871.73	10648.16	1.40	20335.17	15972.24	1.27
J28		26	350	20.8	0.58	11.54		9133.27	5773.58	1.58	11365.35	7481.25	1.52	16543.97	11221.88	1.47
J29		22		17.6		13.64		6635.00	4346.19	1.53	8374.94	5631.68	1.49	11929.06	8447.52	1.41
J30		18		14.4		16.67		5013.15	3089.96	1.62	6169.47	4003.90	1.54	9132.12	6005.85	1.52

joint no	b0	t0	b	t	β	γ $(b_0/(2t_0))$	τ t_1/t_0	S355			S460			S690		
								Numerical strength of joints (kN)	Theoretical strength of joints (kN)	ratio	Numerical strength of joints (kN)	Theoretical strength of joints (kN)	ratio	Numerical strength of joints (kN)	Theoretical strength of joints (kN)	ratio
J31	600	40	400	32	0.67	7.50	0.8	17601.31	13724.11	1.28	21934.09	17783.35	1.23	32861.96	26675.02	1.23
J32		32		25.6		9.38		12772.97	9391.55	1.36	15551.66	12169.33	1.28	22860.48	18253.99	1.25
J33		26		20.8		11.54		9111.51	6598.37	1.38	11305.66	8550.00	1.32	16533.85	12825.00	1.29
J34		22		17.6		13.64		7203.01	4967.07	1.45	8805.12	6436.21	1.37	12538.67	9654.31	1.30
J35		18		14.4		16.67		4916.82	3531.39	1.39	6108.08	4575.88	1.33	8831.09	6863.82	1.29
J36		40		32		7.50		18117.69	15439.62	1.17	22079.19	20006.27	1.10	33022.92	30009.40	1.10
J37		32		25.6		9.38		12693.10	10565.49	1.20	15835.18	13690.49	1.16	23505.04	20535.74	1.14
J38		26		20.8		11.54		9507.13	7423.17	1.28	11397.13	9618.75	1.18	16833.92	14428.13	1.17
J39		22	450	17.6	0.75	13.64		7030.01	5587.96	1.26	8706.97	7240.73	1.20	12685.52	10861.10	1.17
J40		18		14.4		16.67		5049.79	3972.81	1.27	6247.81	5147.87	1.21	8981.89	7721.80	1.16
J41		40		26		7.50		12007.97	10293.08	1.17	14358.29	13337.51	1.08	21413.93	20006.27	1.07
J42		32		20.8		9.38		9305.22	7043.66	1.32	11109.31	9126.99	1.22	16862.78	13690.49	1.23
J43		26		16.9		11.54		6841.00	4948.78	1.38	8505.82	6412.50	1.33	12746.31	9618.75	1.33
J44		22		14.3		13.64		5533.17	3725.31	1.49	6691.91	4827.16	1.39	10350.55	7240.73	1.43
J45		18		11.7		16.67		3950.84	2648.54	1.49	4839.45	3431.91	1.41	7489.77	5147.87	1.45
J46		40		26		7.50	0.65	13985.70	12008.59	1.16	17261.96	15560.43	1.11	26157.03	23340.65	1.12
J47		32		20.8		9.38		10131.82	8217.60	1.23	12546.09	10648.16	1.18	19265.88	15972.24	1.21
J48		26	350	16.9	0.58	11.54		7609.66	5773.58	1.32	9301.17	7481.25	1.24	14522.09	11221.88	1.29
J49		22		14.3		13.64		5929.85	4346.19	1.36	7240.37	5631.68	1.29	11088.59	8447.52	1.31
J50		18		11.7		16.67		4405.41	3089.96	1.43	5315.75	4003.90	1.33	8548.39	6005.85	1.42
J51		40		26		7.50		15089.18	13724.11	1.10	18922.51	17783.35	1.06	29031.93	26675.02	1.09
J52		32		20.8		9.38		10871.66	9391.55	1.16	13302.76	12169.33	1.09	21479.08	18253.99	1.18
J53		26		16.9		11.54		8082.50	6598.37	1.22	9726.35	8550.00	1.14	15606.62	12825.00	1.22
J54		22		14.3		13.64		6405.59	4967.07	1.29	7667.54	6436.21	1.19	11854.99	9654.31	1.23
J55		18		11.7		16.67		4619.11	3531.39	1.31	5752.54	4575.88	1.26	8246.32	6863.82	1.20
J56	600	40	400	26	0.67	7.50	0.8	16309.47	15439.62	1.06	20132.47	20006.27	1.01	30751.00	30009.40	1.02
J57		32		20.8		9.38		11638.68	10565.49	1.10	14217.68	13690.49	1.04	21705.14	20535.74	1.06
J58		26		16.9		11.54		8503.71	7423.17	1.15	10295.24	9618.75	1.07	15802.73	14428.13	1.10
J59		22		14.3		13.64		6647.17	5587.96	1.19	7938.81	7240.73	1.10	11980.12	10861.10	1.10
J60		18		11.7		16.67		4807.27	3972.81	1.21	5771.31	5147.87	1.12	8513.07	7721.80	1.10

4.7 COMPARISON BETWEEN MATERIALS

As shown in the Figures 4.11 to 4.13, the ultimate strength of the joint can increase largely when it is constructed using high strength steel.

As shown in Figure 4.11, the forces are similar to each other when the displacement is below 10mm. However, the ultimate force sees an increase from 3438kN to 6228kN as the steel strength rises from S335 to S690. When the force exceeds the ultimate point, it declines rapidly as the displacement keeps on increasing.

It is also concluded that the deformation is almost the same in different grade of steel when reached the ultimate strength. The ultimate deformation is all around 75mm when reach the ultimate strength.

The strength ratio of numerical results to theoretical results ($\frac{F_{u,nu}}{F_{u,th}}$) decreases when using high strength steel. The strength ratio of S355 for J43 in load case 1 is 0.852. The strength ratio of S460 for J43 in load case 1 is 0.836. The strength ratio of S690 for J43 in load case 1 is 0.794. From S355 to S690, the non-dimensional strength decrease by 5%.

The non-dimensional strength (N^*/F_{yt0}^2) don't change much with the change of material. The $F_{u,non}$ (non-dimensional strength) of S355 for J43 in load case 1 is 14.33. The $F_{u,non}$ (non-dimensional strength) of S460 for J43 in load case 1 is 14.06. The $F_{u,non}$ (non-dimensional strength) of S690 for J43 in load case 1 is 13.34. From S355 to S690, the non-dimensional strength decrease by 6.9%.

The comparison of non-dimensional strength and strength ratio for other joints in the three grades of materials is shown in Tables 4.9 to 4.11.

Figure 4.11 The force-displacement curve of J43 with load case 1 in chord in different grades of steel

Figure 4.12 The force-displacement curve of J43 with load case 2 in chord in different grades of steel

Figure 4.13 The force-displacement curve of J43 with load case 3 in chord in different grades of steel

Table 4.9 Comparison non-dimensional strength results of the three materials in load case 1

joint no	b0	t0	b	t	β	γ	τ	S355			S460			S690		
								Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio	Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio	Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio
J1	600	40	300	40	0.50	7.50	1	14.30	14.78	0.97	13.88	14.78	0.94	13.85	14.78	0.94
J2		32		32		9.38		14.89	15.80	0.94	14.51	15.80	0.92	14.71	15.80	0.93
J3		26		26		11.54		14.54	16.81	0.86	14.06	16.81	0.84	13.50	16.81	0.80
J4		22		22		13.64		14.75	17.68	0.83	13.99	17.68	0.79	13.36	17.68	0.76
J5		18		18		16.67		13.12	18.78	0.70	12.44	18.78	0.66	10.61	18.78	0.57
J6		40		40		7.50		16.34	17.84	0.92	16.08	17.84	0.90	16.43	17.84	0.92
J7		32		32		9.38		16.85	19.07	0.88	15.94	19.07	0.84	15.65	19.07	0.82
J8		26		26		11.54		16.89	20.30	0.83	16.20	20.30	0.80	15.88	20.30	0.78
J9		22		22		13.64		15.78	21.34	0.74	15.23	21.34	0.71	13.91	21.34	0.65
J10		18		18		16.67		15.44	22.66	0.68	14.43	22.66	0.64	12.74	22.66	0.56
J11		40	400	40	0.67	7.50		18.95	21.09	0.90	18.26	21.09	0.87	18.40	21.09	0.87
J12		32		32		9.38		19.62	22.55	0.87	18.41	22.55	0.82	17.73	22.55	0.79
J13		26		26		11.54		18.69	24.00	0.78	18.15	24.00	0.76	17.01	24.00	0.71
J14		22		22		13.64		19.01	25.23	0.75	17.76	25.23	0.70	15.88	25.23	0.63
J15		18		18		16.67		17.00	26.80	0.63	15.86	26.80	0.59	13.72	26.80	0.51
J16		40		40		7.50		22.84	24.55	0.93	21.11	24.55	0.86	20.95	24.55	0.85
J17		32		32		9.38		22.99	26.24	0.88	22.23	26.24	0.85	20.96	26.24	0.80
J18		26		26		11.54		24.31	27.93	0.87	21.81	27.93	0.78	20.28	27.93	0.73
J19		22		22		13.64		22.05	29.37	0.75	21.00	29.37	0.72	19.17	29.37	0.65
J20		18		18		16.67		20.66	31.19	0.66	19.72	31.19	0.63	17.60	31.19	0.56
J21		40	300	32	0.50	7.50	0.8	14.10	14.78	0.95	13.77	14.78	0.93	13.91	14.78	0.94
J22		32		25.6		9.38		14.76	15.80	0.93	14.37	15.80	0.91	14.60	15.80	0.92
J23		26		20.8		11.54		14.46	16.81	0.86	13.98	16.81	0.83	13.44	16.81	0.80
J24		22		17.6		13.64		14.68	17.68	0.83	13.89	17.68	0.79	13.17	17.68	0.75
J25		18		14.4		16.67		13.05	18.78	0.69	12.46	18.78	0.66	10.42	18.78	0.55
J26		40		32		7.50		15.95	17.84	0.89	15.71	17.84	0.88	16.10	17.84	0.90
J27		32		25.6		9.38		16.63	19.07	0.87	15.69	19.07	0.82	15.47	19.07	0.81
J28		26		20.8		11.54		16.78	20.30	0.83	16.00	20.30	0.79	15.65	20.30	0.77
J29		22		17.6		13.64		15.68	21.34	0.73	15.10	21.34	0.71	13.78	21.34	0.65
J30		18		14.4		16.67		15.37	22.66	0.68	14.34	22.66	0.63	12.60	22.66	0.56

joint no	b0	t0	b	t	β	γ	τ	S355			S460			S690		
								Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio	Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio	Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio
J31	600	40	400	32	0.67	7.50	0.8	18.46	21.09	0.88	17.73	21.09	0.84	18.00	21.09	0.85
J32		32		25.6		9.38		19.33	22.55	0.86	18.08	22.55	0.80	17.47	22.55	0.77
J33		26		20.8		11.54		18.52	24.00	0.77	17.90	24.00	0.75	16.79	24.00	0.70
J34		22		17.6		13.64		18.82	25.23	0.75	17.56	25.23	0.70	15.67	25.23	0.62
J35		18		14.4		16.67		16.81	26.80	0.63	15.69	26.80	0.59	13.37	26.80	0.50
J36		40	450	32	0.75	7.50		22.07	24.55	0.90	20.40	24.55	0.83	20.45	24.55	0.83
J37		32		25.6		9.38		22.58	26.24	0.86	21.66	26.24	0.83	20.52	26.24	0.78
J38		26		20.8		11.54		23.81	27.93	0.85	21.43	27.93	0.77	19.80	27.93	0.71
J39		22		17.6		13.64		21.76	29.37	0.74	20.66	29.37	0.70	18.64	29.37	0.63
J40		18		14.4		16.67		20.31	31.19	0.65	19.19	31.19	0.62	16.96	31.19	0.54
J41		40	300	26	0.50	7.50	0.65	13.79	14.78	0.93	13.51	14.78	0.91	13.57	14.78	0.92
J42		32		20.8		9.38		14.57	15.80	0.92	14.12	15.80	0.89	14.30	15.80	0.91
J43		26		16.9		11.54		14.33	16.81	0.85	14.06	16.81	0.84	13.35	16.81	0.79
J44		22		14.3		13.64		14.54	17.68	0.82	13.74	17.68	0.78	13.05	17.68	0.74
J45		18		11.7		16.67		12.92	18.78	0.69	12.34	18.78	0.66	10.43	18.78	0.56
J46		40	350	26	0.58	7.50	0.85	15.43	17.84	0.87	15.22	17.84	0.85	15.61	17.84	0.88
J47		32		20.8		9.38		16.24	19.07	0.85	15.31	19.07	0.80	15.21	19.07	0.80
J48		26		16.9		11.54		16.48	20.30	0.81	15.63	20.30	0.77	15.34	20.30	0.76
J49		22		14.3		13.64		15.57	21.34	0.73	14.87	21.34	0.70	13.58	21.34	0.64
J50		18		11.7		16.67		15.24	22.66	0.67	14.17	22.66	0.63	12.36	22.66	0.55
J51		40	400	26	0.67	7.50	0.65	17.72	21.09	0.84	17.00	21.09	0.81	17.40	21.09	0.82
J52		32		20.8		9.38		18.67	22.55	0.83	17.49	22.55	0.78	17.10	22.55	0.76
J53		26		16.9		11.54		18.25	24.00	0.76	17.48	24.00	0.73	16.45	24.00	0.69
J54		22		14.3		13.64		18.53	25.23	0.73	17.22	25.23	0.68	15.43	25.23	0.61
J55		18		11.7		16.67		16.70	26.80	0.62	15.45	26.80	0.58	13.17	26.80	0.49
J56		40	450	26	0.75	7.50	0.64	21.01	24.55	0.86	19.41	24.55	0.79	19.60	24.55	0.80
J57		32		20.8		9.38		21.79	26.24	0.83	20.67	26.24	0.79	19.90	26.24	0.76
J58		26		16.9		11.54		22.75	27.93	0.81	20.62	27.93	0.74	19.27	27.93	0.69
J59		22		14.3		13.64		21.33	29.37	0.73	20.00	29.37	0.68	17.98	29.37	0.61
J60		18		11.7		16.67		19.99	31.19	0.64	18.55	31.19	0.59	15.89	31.19	0.51

Table 4.10 Comparison non-dimensional strength results of the three materials in load case 2

joint no	b0	t0	b	t	β	γ	τ	S355			S460			S690		
								Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio	Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio	Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio
J1	600	40	300	40	0.50	7.50	1	20.58	16.36	1.26	19.94	16.36	1.22	19.62	16.36	1.20
J2		32		32		9.38		22.09	17.50	1.26	21.78	17.50	1.24	22.00	17.50	1.26
J3		26		26		11.54		22.50	18.62	1.21	21.77	18.62	1.17	21.33	18.62	1.15
J4		22		22		13.64		23.58	19.58	1.20	22.44	19.58	1.15	21.65	19.58	1.11
J5		18		18		16.67		22.58	20.79	1.09	21.14	20.79	1.02	19.83	20.79	0.95
J6		40	350	40	0.58	7.50		22.42	19.42	1.15	21.90	19.42	1.13	22.09	19.42	1.14
J7		32		32		9.38		23.97	20.76	1.15	22.85	20.76	1.10	22.15	20.76	1.07
J8		26		26		11.54		25.06	22.10	1.13	24.31	22.10	1.10	24.21	22.10	1.10
J9		22		22		13.64		24.23	23.23	1.04	23.61	23.23	1.02	21.84	23.23	0.94
J10		18		18		16.67		25.22	24.68	1.02	23.52	24.68	0.95	22.47	24.68	0.91
J11		40	400	40	0.67	7.50		23.40	22.57	1.04	22.80	22.57	1.01	22.93	22.57	1.02
J12		32		32		9.38		25.35	24.14	1.05	24.00	24.14	0.99	23.45	24.14	0.97
J13		26		26		11.54		25.71	25.69	1.00	25.12	25.69	0.98	24.16	25.69	0.94
J14		22		22		13.64		27.26	27.01	1.01	26.09	27.01	0.97	24.28	27.01	0.90
J15		18		18		16.67		26.41	28.68	0.92	24.87	28.68	0.87	22.69	28.68	0.79
J16	600	40	450	40	0.75	7.50		26.39	25.83	1.02	24.64	25.83	0.95	24.59	25.83	0.95
J17		32		32		9.38		26.64	27.62	0.96	25.74	27.62	0.93	24.95	27.62	0.90
J18		26		26		11.54		28.97	29.39	0.99	26.77	29.39	0.91	25.76	29.39	0.88
J19		22		22		13.64		28.37	30.91	0.92	27.31	30.91	0.88	25.66	30.91	0.83
J20		18		18		16.67		28.60	32.82	0.87	27.34	32.82	0.83	24.97	32.82	0.76
J21		40	300	32	0.50	7.50		19.94	16.36	1.22	19.45	16.36	1.19	19.30	16.36	1.18
J22		32		25.6		9.38		21.70	17.50	1.24	21.21	17.50	1.21	21.46	17.50	1.23
J23		26		20.8		11.54		22.18	18.62	1.19	21.53	18.62	1.16	20.99	18.62	1.13
J24		22		17.6		13.64		23.43	19.58	1.20	22.17	19.58	1.13	21.36	19.58	1.09
J25		18		14.4		16.67		22.39	20.79	1.08	21.15	20.79	1.02	19.72	20.79	0.95
J26	600	40	350	32	0.58	7.50	0.8	21.70	19.42	1.12	21.19	19.42	1.09	21.43	19.42	1.10
J27		32		25.6		9.38		23.55	20.76	1.13	22.21	20.76	1.07	21.75	20.76	1.05
J28		26		20.8		11.54		24.74	22.10	1.12	23.96	22.10	1.08	23.81	22.10	1.08
J29		22		17.6		13.64		23.95	23.23	1.03	23.31	23.23	1.00	21.72	23.23	0.93
J30		18		14.4		16.67		25.10	24.68	1.02	23.08	24.68	0.94	22.23	24.68	0.90

joint no	b0	t0	b	t	β	γ	τ	S355			S460			S690		
								Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio	Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio	Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio
J31	600	40	400	32	0.67	7.50	0.8	22.97	22.57	1.02	22.34	22.57	0.99	22.42	22.57	0.99
J32		32		25.6		9.38		25.04	24.14	1.04	23.76	24.14	0.98	23.19	24.14	0.96
J33		26		20.8		11.54		25.58	25.69	1.00	24.94	25.69	0.97	24.01	25.69	0.93
J34		22		17.6		13.64		27.05	27.01	1.00	25.85	27.01	0.96	24.14	27.01	0.89
J35		18		14.4		16.67		26.22	28.68	0.91	24.68	28.68	0.86	22.77	28.68	0.79
J36		40		32		7.50		25.73	25.83	1.00	24.10	25.83	0.93	23.83	25.83	0.92
J37		32		25.6		9.38		26.34	27.62	0.95	25.41	27.62	0.92	24.64	27.62	0.89
J38		26		20.8		11.54		28.62	29.39	0.97	26.47	29.39	0.90	25.46	29.39	0.87
J39		22	450	17.6	0.75	13.64		28.14	30.91	0.91	27.08	30.91	0.88	25.43	30.91	0.82
J40		18		14.4		16.67		28.41	32.82	0.87	27.21	32.82	0.83	24.76	32.82	0.75
J41		40		26		7.50		19.17	16.36	1.17	18.81	16.36	1.15	18.75	16.36	1.15
J42		32		20.8		9.38		21.00	17.50	1.20	20.52	17.50	1.17	20.68	17.50	1.18
J43		26		16.9		11.54		21.71	18.62	1.17	21.77	18.62	1.17	20.51	18.62	1.10
J44		22		14.3		13.64		23.04	19.58	1.18	21.71	19.58	1.11	20.76	19.58	1.06
J45		18		11.7		16.67		22.07	20.79	1.06	20.90	20.79	1.01	19.45	20.79	0.94
J46		40		26		7.50		20.77	19.42	1.07	20.35	19.42	1.05	20.59	19.42	1.06
J47		32	350	20.8	0.58	9.38		22.70	20.76	1.09	21.51	20.76	1.04	21.20	20.76	1.02
J48		26		16.9		11.54		24.03	22.10	1.09	23.19	22.10	1.05	23.09	22.10	1.04
J49		22		14.3		13.64		23.73	23.23	1.02	22.83	23.23	0.98	21.45	23.23	0.92
J50		18		11.7		16.67		24.80	24.68	1.00	22.95	24.68	0.93	21.84	24.68	0.88
J51		40		26		7.50	0.65	22.36	22.57	0.99	21.74	22.57	0.96	21.83	22.57	0.97
J52		32		20.8		9.38		24.42	24.14	1.01	23.18	24.14	0.96	22.68	24.14	0.94
J53		26		16.9		11.54		25.10	25.69	0.98	24.35	25.69	0.95	23.51	25.69	0.92
J54		22		14.3		13.64		26.56	27.01	0.98	25.33	27.01	0.94	23.69	27.01	0.88
J55		18		11.7		16.67		25.74	28.68	0.90	24.30	28.68	0.85	22.47	28.68	0.78
J56		40		26		7.50		24.57	25.83	0.95	23.13	25.83	0.90	23.15	25.83	0.90
J57		32	450	20.8	0.75	9.38		25.77	27.62	0.93	24.89	27.62	0.90	24.31	27.62	0.88
J58		26		16.9		11.54		27.91	29.39	0.95	26.02	29.39	0.89	25.11	29.39	0.85
J59		22		14.3		13.64		27.79	30.91	0.90	26.67	30.91	0.86	25.11	30.91	0.81
J60		18		11.7		16.67		28.13	32.82	0.86	26.74	32.82	0.81	24.57	32.82	0.75

Table 4.11 Comparison non-dimensional strength results of the three materials in load case 3

joint no	b_0	t_0	b	t	β	γ	τ	S355			S460			S690			Failure Mode
								Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio	Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio	Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio	
J1	600	40	300	40	0.50	7.50	1	28.19	18.12	1.56	25.59	18.12	1.41	25.87	18.12	1.43	CF
J2		32		32		9.38		33.82	19.38	1.75	31.55	19.38	1.63	30.89	19.38	1.59	CF
J3		26		26		11.54		36.06	20.62	1.75	34.47	20.62	1.67	29.94	20.62	1.45	CF
J4		22		22		13.64		39.23	21.68	1.81	37.29	21.68	1.72	36.95	21.68	1.70	CF
J5		18		18		16.67		38.26	23.03	1.66	38.61	23.03	1.68	34.80	23.03	1.51	CF
J6		40	350	40		7.50		32.55	21.14	1.54	31.19	21.14	1.48	30.62	21.14	1.45	CF
J7		32		32		9.38		36.66	22.61	1.62	34.73	22.61	1.54	29.72	22.61	1.31	CF
J8		26		26		11.54		40.24	24.06	1.67	38.24	24.06	1.59	37.63	24.06	1.56	CF
J9		22		22		13.64		40.33	25.30	1.59	39.44	25.30	1.56	35.73	25.30	1.41	CF
J10		18		18		16.67		45.55	26.86	1.70	43.34	26.86	1.61	42.93	26.86	1.60	CF
J11		40	400	40	0.67	7.50		32.50	24.16	1.35	31.41	24.16	1.30	31.60	24.16	1.31	CF
J12		32		32		9.38		36.95	25.84	1.43	34.75	25.84	1.35	34.34	25.84	1.33	CF
J13		26		26		11.54		39.85	27.50	1.45	38.26	27.50	1.39	37.43	27.50	1.36	CF
J14		22		22		13.64		44.05	28.91	1.52	41.58	28.91	1.44	39.27	28.91	1.36	CF
J15		18		18		16.67		44.76	30.70	1.46	43.12	30.70	1.40	42.06	30.70	1.37	CF
J16		40	450	40		7.50		32.87	27.18	1.21	31.02	27.18	1.14	31.03	27.18	1.14	CF
J17		32		32		9.38		35.90	29.06	1.24	34.68	29.06	1.19	34.66	29.06	1.19	CF
J18		26		26		11.54		40.97	30.93	1.32	38.05	30.93	1.23	37.89	30.93	1.23	CF
J19		22		22		13.64		43.10	32.52	1.33	40.88	32.52	1.26	40.01	32.52	1.23	CF
J20		18		18		16.67		46.55	34.54	1.35	43.97	34.54	1.27	42.86	34.54	1.24	CF
J21		40	300	32	0.50	7.50		24.28	18.12	1.34	22.59	18.12	1.25	21.24	18.12	1.17	CF
J22		32		25.6		9.38		29.58	19.38	1.53	27.32	19.38	1.41	27.85	19.38	1.44	CF
J23		26		20.8		11.54		33.30	20.62	1.61	31.93	20.62	1.55	28.83	20.62	1.40	CF
J24		22		17.6		13.64		37.84	21.68	1.75	36.00	21.68	1.66	35.38	21.68	1.63	CF
J25		18		14.4		16.67		37.22	23.03	1.62	37.59	23.03	1.63	33.72	23.03	1.46	CF
J26		40	350	32		7.50		28.98	21.14	1.37	26.94	21.14	1.27	27.63	21.14	1.31	-
J27		32		25.6		9.38		34.59	22.61	1.53	31.57	22.61	1.40	28.78	22.61	1.27	CF
J28		26		20.8		11.54		38.06	24.06	1.58	36.55	24.06	1.52	35.47	24.06	1.47	CF
J29		22		17.6		13.64		38.62	25.30	1.53	37.62	25.30	1.49	35.72	25.30	1.41	CF
J30		18		14.4		16.67		43.59	26.86	1.62	41.39	26.86	1.54	40.85	26.86	1.52	CF

joint no	b_0	t_0	b	t	β	γ	τ	S355			S460			S690			Failure Mode
								Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio	Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio	Numerical non-dimensional strength (KN)	Theoretical non-dimensional strength (KN)	ratio	
J31	600	40	400	32	0.67	7.50	0.8	30.99	24.16	1.28	29.80	24.16	1.23	29.77	24.16	1.23	CF
J32		32		25.6		9.38		35.14	25.84	1.36	33.02	25.84	1.28	32.35	25.84	1.25	CF
J33		26		20.8		11.54		37.97	27.50	1.38	36.36	27.50	1.32	35.45	27.50	1.29	CF
J34		22		17.6		13.64		41.92	28.91	1.45	39.55	28.91	1.37	37.55	28.91	1.30	CF
J35		18		14.4		16.67		42.75	30.70	1.39	40.98	30.70	1.33	39.50	30.70	1.29	CF
J36		40		32		7.50		31.90	27.18	1.17	30.00	27.18	1.10	29.91	27.18	1.10	CF
J37		32		25.6		9.38		34.92	29.06	1.20	33.62	29.06	1.16	33.27	29.06	1.14	CF
J38		26		20.8		11.54		39.62	30.93	1.28	36.65	30.93	1.18	36.09	30.93	1.17	CF
J39		22		17.6		13.64		40.91	32.52	1.26	39.11	32.52	1.20	37.99	32.52	1.17	CF
J40		18		14.4		16.67		43.90	34.54	1.27	41.92	34.54	1.21	40.18	34.54	1.16	CF
J41		40	300	26	0.50	7.50	0.65	21.14	18.12	1.17	19.51	18.12	1.08	19.40	18.12	1.07	-
J42		32		20.8		9.38		25.60	19.38	1.32	23.58	19.38	1.22	23.87	19.38	1.23	BF
J43		26		16.9		11.54		28.51	20.62	1.38	27.35	20.62	1.33	27.33	20.62	1.33	BF
J44		22		14.3		13.64		32.20	21.68	1.49	30.06	21.68	1.39	30.99	21.68	1.43	BF
J45		18		11.7		16.67		34.35	23.03	1.49	32.47	23.03	1.41	33.50	23.03	1.45	CF
J46		40		26		7.50		24.62	21.14	1.16	23.45	21.14	1.11	23.69	21.14	1.12	-
J47		32		20.8		9.38		27.87	22.61	1.23	26.63	22.61	1.18	27.27	22.61	1.21	BF
J48		26		16.9		11.54		31.71	24.06	1.32	29.91	24.06	1.24	31.13	24.06	1.29	BF
J49		22		14.3		13.64		34.51	25.30	1.36	32.52	25.30	1.29	33.20	25.30	1.31	CF
J50		18		11.7		16.67		38.30	26.86	1.43	35.67	26.86	1.33	38.24	26.86	1.42	CF
J51		40	400	26	0.67	7.50		26.57	24.16	1.10	25.71	24.16	1.06	26.30	24.16	1.09	BF
J52		32		20.8		9.38		29.91	25.84	1.16	28.24	25.84	1.09	30.40	25.84	1.18	BF
J53		26		16.9		11.54		33.68	27.50	1.22	31.38	27.50	1.14	33.46	27.50	1.22	BF
J54		22		14.3		13.64		37.28	28.91	1.29	34.44	28.91	1.19	35.50	28.91	1.23	BF
J55		18		11.7		16.67		40.16	30.70	1.31	38.60	30.70	1.26	36.89	30.70	1.20	CF
J56		40		26		7.50		28.71	27.18	1.06	27.35	27.18	1.01	27.85	27.18	1.02	BF
J57		32		20.8		9.38		32.02	29.06	1.10	30.18	29.06	1.04	30.72	29.06	1.06	BF
J58		26		16.9		11.54		35.44	30.93	1.15	33.11	30.93	1.07	33.88	30.93	1.10	BF
J59		22		14.3		13.64		38.69	32.52	1.19	35.66	32.52	1.10	35.87	32.52	1.10	CF
J60		18		11.7		16.67		41.80	34.54	1.21	38.72	34.54	1.12	38.08	34.54	1.10	CF

4.8 DEVELOPMENT OF THE DESIGN RESISTANCE EQUATIONS

The purpose of developing ultimate strength equation is to quantify the amount of ultimate load presented graphically in Section 4.4 for design purpose. As it can be seen in Section 4.4, for a certain number of joints the numerical results which received from finite element analyses are quite different from strength capacity predicted by CIDECT Design Guide 3. Thus, there is an urgent need to propose a new formula for chord face failure case.

To assist in the development of ultimate strength equations, curve-fitting was done on the numerical ultimate capacities using MATLAB. MATLAB is a science and end engineering tool that simplifies the tasks of data plotting, regression analysis (curve fitting) and statistical analysis. Regression model was used in the format of K-joint with gap formula for chord failure case. Based on that regression model the best coefficient was determined.

The proposed equations consist of both non-dimensional strength equation for three materials and the corrective factor (strength ratio) for three materials in three load cases. The corrective factor (strength ratio) should be multiplied by the value calculated from the equation in CIDECT Design Guide 3 (Eq. 2.1)

The proposed SHS gap K-joint formula in the form of non-dimensional strength is presented below:

$$\frac{F_u}{f_y * t_0^2} = p_1\beta + p_2\beta^2 + p_3\beta^3 + p_4\gamma + p_5\tau + p_6$$

(Eq. 4.1)

F_u is the design resistance of the joint

f_y is the yield stress of the joint

t_0 is the thickness of the chord

Table 4.12 The values of p1~p6 in different load cases in the Eq. 4.1

p	Load Case 1	Load Case 2	Load Case 3
p1	84.75	88.13	206.03
p2	-148.45	-144.10	-169.53
p3	105.17	60.24	25.05
p4	-0.41	0.06	1.28
p5	1.76	2.09	12.23
p6	-1.90	-4.93	-59.41

The correction factor equation is in the form of strength ratio-the ratio of the numerical ultimate strength to the theoretical ultimate strength calculated based on the equation in CIDECT Design Guide 3 (Eq. 2.1).

The proposed SHS gap K-joint formula in the form of Strength ratio is presented below:

$$\frac{F_{u,nu}}{F_{u,th}} = k_1\beta + k_2\beta^2 + k_3\beta^3 + k_4\gamma + k_5\tau + k_6$$

(Eq. 4.2)

$F_{u,nu}$ is the numerical non-dimensional ultimate strength

$F_{u,th}$ is the theoretical non-dimensional ultimate strength calculated based on the equation in CIDECT Design Guide 3 (Eq. 2.1)

Table 4.13 The values of k1~k6 in different load cases in the Eq. 4.2

k	Load Case 1	Load Case 2	Load Case 3
k1	1.36	0.66	5.77
k2	-5.21	-4.22	-8.00
k3	4.01	3.01	2.63
k4	-0.04	-0.02	0.018
k5	0.08	0.096	0.49
k6	1.28	1.64	-0.40

4.8.1 Application of the proposed formulae

In the current existing code the steel is limited from S235 to S355. The proposed formula 4.1 is applicable on S690 SHS K-joints. For this purpose 60 numerical models of S690 SHS K-joints and 60 numerical models of S460 SHS K-joints are built with different geometric parameters and 3 load cases. The numerical results, which compare with the strength of proposed formulae, are shown in the Figures 4.14 to 4.22 and Tables 4.14 to 4.22. It is also important to note that they all suffered chord face failure mode. It can be seen from Table 4.15, the equation based on S690 can be used for S460 and S355 well.

For the design purpose, the safe factor γ_M can be multiplied to the Eq. 4.1.

$\gamma_M=1.05$ (with 95% Confidence Intervals)

Figure 4.14 Comparison of proposed formula with numerical results for S355 in load case 1

Figure 4.15 Comparison of proposed formula with numerical results for S355 in load case 2

Figure 4.16 Comparison of proposed formula with numerical results for S355 in load case 3

Figure 4.17 Comparison of proposed formula with numerical results for S460 in load case 1

Figure 4.18 Comparison of proposed formula with numerical results for S460 in load case 2

Figure 4.19 Comparison of proposed formula with numerical results for S460 in load case 3

Figure 4.20 Comparison of proposed formula with numerical results for S690 in load case 1

Figure 4.21 Comparison of proposed formula with numerical results for S690 in load case 2

Figure 4.22 Comparison of proposed formula with numerical results for S690 in load case 3

Table 4.14 Comparison of numerical results with the proposed formula results for S355 in load case 1

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)	Proposed formula $F_{u,p}$ (kN)	Ratio
J1	600	40	300	40	0.50	7.50	1	14.30	15.19	0.94
J2		32		32		9.38		14.89	14.42	1.03
J3		26		26		11.54		14.54	13.53	1.07
J4		22		22		13.64		14.75	12.67	1.16
J5		18		18		16.67		13.12	11.43	1.15
J6		40	350	40	0.58	7.50		16.34	16.58	0.99
J7		32		32		9.38		16.85	15.81	1.07
J8		26		26		11.54		16.89	14.92	1.13
J9		22		22		13.64		15.78	14.06	1.12
J10		18		18		16.67		15.44	12.82	1.20
J11		40	400	40	0.67	7.50		18.95	18.47	1.03
J12		32		32		9.38		19.62	17.70	1.11
J13		26		26		11.54		18.69	16.81	1.11
J14		22		22		13.64		19.01	15.95	1.19
J15		18		18		16.67		17.00	14.71	1.16
J16		40	450	40	0.75	7.50		22.84	21.21	1.08
J17		32		32		9.38		22.99	20.44	1.12
J18		26		26		11.54		24.31	19.55	1.24
J19		22		22		13.64		22.05	18.69	1.18
J20		18		18		16.67		20.66	17.45	1.18
J21		40	300	32	0.50	7.50	0.8	14.10	14.84	0.95
J22		32		25.6		9.38		14.76	14.07	1.05
J23		26		20.8		11.54		14.46	13.18	1.10
J24		22		17.6		13.64		14.68	12.32	1.19
J25		18		14.4		16.67		13.05	11.08	1.18
J26		40	350	32	0.58	7.50		15.95	16.23	0.98
J27		32		25.6		9.38		16.63	15.46	1.08
J28		26		20.8		11.54		16.78	14.57	1.15
J29		22		17.6		13.64		15.68	13.71	1.14
J30		18		14.4		16.67		15.37	12.47	1.23

Joint No	b ₀	t ₀	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b ₀)	b ₀ /(2t ₀)	t ₁ /t ₀	Numerical results F _{u,nu} (kN)	Proposed formula F _{u,p} (kN)	Ratio
J31	600	40	400	32	0.67	7.50	0.8	18.46	18.11	1.02
J32		32		25.6		9.38		19.33	17.34	1.11
J33		26		20.8		11.54		18.52	16.46	1.13
J34		22		17.6		13.64		18.82	15.60	1.21
J35		18		14.4		16.67		16.81	14.36	1.17
J36		40	450	32	0.75	7.50		22.07	20.86	1.06
J37		32		25.6		9.38		22.58	20.09	1.12
J38		26		20.8		11.54		23.81	19.20	1.24
J39		22		17.6		13.64		21.76	18.34	1.19
J40		18		14.4		16.67		20.31	17.10	1.19
J41		40	300	26	0.50	7.50	0.65	13.79	14.84	0.93
J42		32		20.8		9.38		14.57	13.81	1.06
J43		26		16.9		11.54		14.33	12.92	1.11
J44		22		14.3		13.64		14.54	12.06	1.21
J45		18		11.7		16.67		12.92	10.82	1.19
J46		40	350	26	0.58	7.50		15.43	15.96	0.97
J47		32		20.8		9.38		16.24	15.20	1.07
J48		26		16.9		11.54		16.48	14.31	1.15
J49		22		14.3		13.64		15.57	13.45	1.16
J50		18		11.7		16.67		15.24	12.21	1.25
J51	40	400	26	0.67	7.50	17.72		17.85	0.99	
J52	32		20.8		9.38	18.67		17.08	1.09	
J53	26		16.9		11.54	18.25		16.19	1.13	
J54	22		14.3		13.64	18.53		15.33	1.21	
J55	18		11.7		16.67	16.70		14.09	1.18	
J56	40	450	26	0.75	7.50	21.01		20.59	1.02	
J57	32		20.8		9.38	21.79		19.83	1.10	
J58	26		16.9		11.54	22.75		18.94	1.20	
J59	22		14.3		13.64	21.33		18.08	1.18	
J60	18		11.7		16.67	19.99		16.84	1.19	

Table 4.15 Comparison of numerical results with the proposed formula results for S355 in load case 2

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)		
J1	600	40	300	40	0.50	7.50	1	20.58	20.66	1.00
J2		32		32		9.38		22.09	20.77	1.06
J3		26		26		11.54		22.50	20.89	1.08
J4		22		22		13.64		23.58	21.01	1.12
J5		18		18		16.67		22.58	21.19	1.07
J6		40	350	40	0.58	7.50		22.42	22.13	1.01
J7		32		32		9.38		23.97	22.24	1.08
J8		26		26		11.54		25.06	22.36	1.12
J9		22		22		13.64		24.23	22.48	1.08
J10		18		18		16.67		25.22	22.66	1.11
J11		40	400	40	0.67	7.50		23.40	23.48	1.00
J12		32		32		9.38		25.35	23.59	1.07
J13		26		26		11.54		25.71	23.71	1.08
J14		22		22		13.64		27.26	23.83	1.14
J15		18		18		16.67		26.41	24.01	1.10
J16		40	450	40	0.75	7.50		26.39	24.92	1.06
J17		32		32		9.38		26.64	25.03	1.06
J18		26		26		11.54		28.97	25.15	1.15
J19		22		22		13.64		28.37	25.27	1.12
J20		18		18		16.67		28.60	25.45	1.12
J21		40	300	32	0.50	7.50	0.8	19.94	20.24	0.99
J22		32		25.6		9.38		21.70	20.35	1.07
J23		26		20.8		11.54		22.18	20.47	1.08
J24		22		17.6		13.64		23.43	20.59	1.14
J25		18		14.4		16.67		22.39	20.77	1.08
J26		40	350	32	0.58	7.50		21.70	21.71	1.00
J27		32		25.6		9.38		23.55	21.82	1.08
J28		26		20.8		11.54		24.74	21.94	1.13
J29		22		17.6		13.64		23.95	22.06	1.09
J30		18		14.4		16.67		25.10	22.24	1.13

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)	Proposed formula $F_{u,p}$ (kN)	Ratio
J31	600	40	400	32	0.67	7.50	0.8	22.97	23.06	1.00
J32		32		25.6		9.38		25.04	23.17	1.08
J33		26		20.8		11.54		25.58	23.29	1.10
J34		22		17.6		13.64		27.05	23.41	1.16
J35		18		14.4		16.67		26.22	23.59	1.11
J36		40	450	32	0.75	7.50		25.73	24.50	1.05
J37		32		25.6		9.38		26.34	24.61	1.07
J38		26		20.8		11.54		28.62	24.73	1.16
J39		22		17.6		13.64		28.14	24.85	1.13
J40		18		14.4		16.67		28.41	25.03	1.14
J41		40	300	26	0.50	7.50	0.65	19.17	20.24	0.95
J42		32		20.8		9.38		21.00	20.03	1.05
J43		26		16.9		11.54		21.71	20.16	1.08
J44		22		14.3		13.64		23.04	20.28	1.14
J45		18		11.7		16.67		22.07	20.46	1.08
J46		40	350	26	0.58	7.50		20.77	21.40	0.97
J47		32		20.8		9.38		22.70	21.51	1.06
J48		26		16.9		11.54		24.03	21.63	1.11
J49		22		14.3		13.64		23.73	21.75	1.09
J50		18		11.7		16.67		24.80	21.93	1.13
J51		40	400	26	0.67	7.50		22.36	22.75	0.98
J52		32		20.8		9.38		24.42	22.86	1.07
J53		26		16.9		11.54		25.10	22.98	1.09
J54		22		14.3		13.64		26.56	23.10	1.15
J55		18		11.7		16.67		25.74	23.28	1.11
J56		40	450	26	0.75	7.50		24.57	24.19	1.02
J57		32		20.8		9.38		25.77	24.29	1.06
J58		26		16.9		11.54		27.91	24.42	1.14
J59		22		14.3		13.64		27.79	24.54	1.13
J60		18		11.7		16.67		28.13	24.72	1.14

Table 4.16 Comparison of numerical results with the proposed formula results for S355 in load case 3

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)	Proposed formula $F_{u,p}$ (kN)	Ratio
J1	600	40	300	40	0.50	7.50	1	28.19	26.15	1.08
J2		32		32		9.38		33.82	28.54	1.18
J3		26		26		11.54		36.06	31.30	1.15
J4		22		22		13.64		39.23	33.98	1.15
J5		18		18		16.67		38.26	37.85	1.01
J6		40	350	40	0.58	7.50		32.55	29.86	1.09
J7		32		32		9.38		36.66	32.25	1.14
J8		26		26		11.54		40.24	35.01	1.15
J9		22		22		13.64		40.33	37.69	1.07
J10		18		18		16.67		45.55	41.55	1.10
J11		40	400	40	0.67	7.50		32.50	31.82	1.02
J12		32		32		9.38		36.95	34.21	1.08
J13		26		26		11.54		39.85	36.97	1.08
J14		22		22		13.64		44.05	39.65	1.11
J15		18		18		16.67		44.76	43.51	1.03
J16		40	450	40	0.75	7.50		32.87	32.12	1.02
J17		32		32		9.38		35.90	34.51	1.04
J18		26		26		11.54		40.97	37.27	1.10
J19		22		22		13.64		43.10	39.95	1.08
J20		18		18		16.67		46.55	43.81	1.06
J21		40	300	32	0.50	7.50	0.8			
J22		32		25.6		9.38				
J23		26		20.8		11.54		33.30	28.86	1.15
J24		22		17.6		13.64		37.84	31.53	1.20
J25		18		14.4		16.67		37.22	35.40	1.05
J26		40	350	32	0.58	7.50		28.98	27.41	1.06
J27		32		25.6		9.38		34.59	29.80	1.16
J28		26		20.8		11.54		38.06	32.56	1.17
J29		22		17.6		13.64		38.62	35.24	1.10
J30		18		14.4		16.67		43.59	39.11	1.11

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)	Proposed formula $F_{u,p}$ (kN)	Ratio
J31	600	40	400	32	0.67	7.50	0.8	30.99	29.37	1.06
J32		32		25.6		9.38		35.14	31.76	1.11
J33		26		20.8		11.54		37.97	34.52	1.10
J34		22		17.6		13.64		41.92	37.20	1.13
J35		18		14.4		16.67		42.75	41.07	1.04
J36		40	450	32	0.75	7.50		31.90	29.67	1.08
J37		32		25.6		9.38		34.92	32.06	1.09
J38		26		20.8		11.54		39.62	34.82	1.14
J39		22		17.6		13.64		40.91	37.50	1.09
J40		18		14.4		16.67		43.90	41.37	1.06
J41		40	300	26	0.50	7.50	0.65			
J42		32		20.8		9.38				
J43		26		16.9		11.54		28.51	27.02	1.05
J44		22		14.3		13.64		32.20	29.70	1.08
J45		18		11.7		16.67		34.35	33.57	1.02
J46		40	350	26	0.58	7.50				
J47		32		20.8		9.38		27.87	27.97	1.00
J48		26		16.9		11.54		31.71	30.73	1.03
J49		22		14.3		13.64		34.51	33.41	1.03
J50		18		11.7		16.67		38.30	37.27	1.03
J51		40	400	26	0.67	7.50		26.57	27.54	0.96
J52		32		20.8		9.38		29.91	29.93	1.00
J53		26		16.9		11.54		33.68	32.69	1.03
J54		22		14.3		13.64		37.28	35.37	1.05
J55		18		11.7		16.67		40.16	39.23	1.02
J56		40	450	26	0.75	7.50		28.71	27.84	1.03
J57		32		20.8		9.38		32.02	30.23	1.06
J58		26		16.9		11.54		35.44	32.99	1.07
J59		22		14.3		13.64		38.69	35.67	1.08
J60		18		11.7		16.67		41.80	39.53	1.06

Table 4.17 Comparison of numerical results with the proposed formula results for S460 in load case 1

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)	Proposed formula $F_{u,p}$ (kN)	Ratio
J1	600	40	300	40	0.50	7.50	1	13.88	15.19	0.91
J2		32		32		9.38		14.51	14.42	1.01
J3		26		26		11.54		14.06	13.53	1.04
J4		22		22		13.64		13.99	12.67	1.10
J5		18		18		16.67		12.44	11.43	1.09
J6		40	350	40	0.58	7.50		16.08	16.58	0.97
J7		32		32		9.38		15.94	15.81	1.01
J8		26		26		11.54		16.20	14.92	1.09
J9		22		22		13.64		15.23	14.06	1.08
J10		18		18		16.67		14.43	12.82	1.13
J11		40	400	40	0.67	7.50		18.26	18.47	0.99
J12		32		32		9.38		18.41	17.70	1.04
J13		26		26		11.54		18.15	16.81	1.08
J14		22		22		13.64		17.76	15.95	1.11
J15		18		18		16.67		15.86	14.71	1.08
J16		40	450	40	0.75	7.50		21.11	21.21	1.00
J17		32		32		9.38		22.23	20.44	1.09
J18		26		26		11.54		21.81	19.55	1.12
J19		22		22		13.64		21.00	18.69	1.12
J20		18		18		16.67		19.72	17.45	1.13
J21		40	300	32	0.50	7.50	0.8	13.77	14.84	0.93
J22		32		25.6		9.38		14.37	14.07	1.02
J23		26		20.8		11.54		13.98	13.18	1.06
J24		22		17.6		13.64		13.89	12.32	1.13
J25		18		14.4		16.67		12.46	11.08	1.12
J26		40	350	32	0.58	7.50		15.71	16.23	0.97
J27		32		25.6		9.38		15.69	15.46	1.01
J28		26		20.8		11.54		16.00	14.57	1.10
J29		22		17.6		13.64		15.10	13.71	1.10
J30		18		14.4		16.67		14.34	12.47	1.15

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)	Proposed formula $F_{u,p}$ (kN)	Ratio
J31	600	40	400	32	0.67	7.50	0.8	17.73	18.11	0.98
J32		32		25.6		9.38		18.08	17.34	1.04
J33		26		20.8		11.54		17.90	16.46	1.09
J34		22		17.6		13.64		17.56	15.60	1.13
J35		18		14.4		16.67		15.69	14.36	1.09
J36		40	450	32	0.75	7.50		20.40	20.86	0.98
J37		32		25.6		9.38		21.66	20.09	1.08
J38		26		20.8		11.54		21.43	19.20	1.12
J39		22		17.6		13.64		20.66	18.34	1.13
J40		18		14.4		16.67		19.19	17.10	1.12
J41		40	300	26	0.50	7.50	0.65	13.51	14.84	0.91
J42		32		20.8		9.38		14.12	13.81	1.02
J43		26		16.9		11.54		14.06	12.92	1.09
J44		22		14.3		13.64		13.74	12.06	1.14
J45		18		11.7		16.67		12.34	10.82	1.14
J46		40	350	26	0.58	7.50		15.22	15.96	0.95
J47		32		20.8		9.38		15.31	15.20	1.01
J48		26		16.9		11.54		15.63	14.31	1.09
J49		22		14.3		13.64		14.87	13.45	1.11
J50		18		11.7		16.67		14.17	12.21	1.16
J51		40	400	26	0.67	7.50		17.00	17.85	0.95
J52		32		20.8		9.38		17.49	17.08	1.02
J53		26		16.9		11.54		17.48	16.19	1.08
J54		22		14.3		13.64		17.22	15.33	1.12
J55		18		11.7		16.67		15.45	14.09	1.10
J56		40	450	26	0.75	7.50		19.41	20.59	0.94
J57		32		20.8		9.38		20.67	19.83	1.04
J58		26		16.9		11.54		20.62	18.94	1.09
J59		22		14.3		13.64		20.00	18.08	1.11
J60		18		11.7		16.67		18.55	16.84	1.10

Table 4.18 Comparison of numerical results with the proposed formula results for S460 in load case 2

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)	Proposed formula $F_{u,p}$ (kN)	Ratio
J1	600	40	300	40	0.50	7.50	1	19.94	20.66	0.97
J2		32		32		9.38		21.78	20.77	1.05
J3		26		26		11.54		21.77	20.89	1.04
J4		22		22		13.64		22.44	21.01	1.07
J5		18		18		16.67		21.14	21.19	1.00
J6		40	350	40	0.58	7.50		21.90	22.13	0.99
J7		32		32		9.38		22.85	22.24	1.03
J8		26		26		11.54		24.31	22.36	1.09
J9		22		22		13.64		23.61	22.48	1.05
J10		18		18		16.67		23.52	22.66	1.04
J11		40	400	40	0.67	7.50		22.80	23.48	0.97
J12		32		32		9.38		24.00	23.59	1.02
J13		26		26		11.54		25.12	23.71	1.06
J14		22		22		13.64		26.09	23.83	1.09
J15		18		18		16.67		24.87	24.01	1.04
J16		40	450	40	0.75	7.50		24.64	24.92	0.99
J17		32		32		9.38		25.74	25.03	1.03
J18		26		26		11.54		26.77	25.15	1.06
J19		22		22		13.64		27.31	25.27	1.08
J20		18		18		16.67		27.34	25.45	1.07
J21		40	300	32	0.50	7.50	0.8	19.45	20.24	0.96
J22		32		25.6		9.38		21.21	20.35	1.04
J23		26		20.8		11.54		21.53	20.47	1.05
J24		22		17.6		13.64		22.17	20.59	1.08
J25		18		14.4		16.67		21.15	20.77	1.02
J26		40	350	32	0.58	7.50		21.19	21.71	0.98
J27		32		25.6		9.38		22.21	21.82	1.02
J28		26		20.8		11.54		23.96	21.94	1.09
J29		22		17.6		13.64		23.31	22.06	1.06
J30		18		14.4		16.67		23.08	22.24	1.04

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)	Proposed formula $F_{u,p}$ (kN)	Ratio
J31	600	40	400	32	0.67	7.50	0.8	22.34	23.06	0.97
J32		32		25.6		9.38		23.76	23.17	1.03
J33		26		20.8		11.54		24.94	23.29	1.07
J34		22		17.6		13.64		25.85	23.41	1.10
J35		18		14.4		16.67		24.68	23.59	1.05
J36		40	450	32	0.75	7.50		24.10	24.50	0.98
J37		32		25.6		9.38		25.41	24.61	1.03
J38		26		20.8		11.54		26.47	24.73	1.07
J39		22		17.6		13.64		27.08	24.85	1.09
J40		18		14.4		16.67		27.21	25.03	1.09
J41		40	300	26	0.50	7.50	0.65	18.81	20.24	0.93
J42		32		20.8		9.38		20.52	20.03	1.02
J43		26		16.9		11.54		21.77	20.16	1.08
J44		22		14.3		13.64		21.71	20.28	1.07
J45		18		11.7		16.67		20.90	20.46	1.02
J46		40	350	26	0.58	7.50		20.35	21.40	0.95
J47		32		20.8		9.38		21.51	21.51	1.00
J48		26		16.9		11.54		23.19	21.63	1.07
J49		22		14.3		13.64		22.83	21.75	1.05
J50		18		11.7		16.67		22.95	21.93	1.05
J51		40	400	26	0.67	7.50		21.74	22.75	0.96
J52		32		20.8		9.38		23.18	22.86	1.01
J53		26		16.9		11.54		24.35	22.98	1.06
J54		22		14.3		13.64		25.33	23.10	1.10
J55		18		11.7		16.67		24.30	23.28	1.04
J56		40	450	26	0.75	7.50		23.13	24.19	0.96
J57		32		20.8		9.38		24.89	24.29	1.02
J58		26		16.9		11.54		26.02	24.42	1.07
J59		22		14.3		13.64		26.67	24.54	1.09
J60		18		11.7		16.67		26.74	24.72	1.08

Table 4.19 Comparison of numerical results with the proposed formula results for S460 in load case 3

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)	Proposed formula $F_{u,p}$ (kN)	Ratio
J1	600	40	300	40	0.50	7.50	1			
J2		32		32		9.38		31.55	28.54	1.11
J3		26		26		11.54		34.47	31.30	1.10
J4		22		22		13.64		37.29	33.98	1.10
J5		18		18		16.67		38.61	37.85	1.02
J6		40	350	40	0.58	7.50		31.19	29.86	1.04
J7		32		32		9.38		34.73	32.25	1.08
J8		26		26		11.54		38.24	35.01	1.09
J9		22		22		13.64		39.44	37.69	1.05
J10		18		18		16.67		43.34	41.55	1.04
J11		40	400	40	0.67	7.50		31.41	31.82	0.99
J12		32		32		9.38		34.75	34.21	1.02
J13		26		26		11.54		38.26	36.97	1.03
J14		22		22		13.64		41.58	39.65	1.05
J15		18		18		16.67		43.12	43.51	0.99
J16		40	450	40	0.75	7.50		31.02	32.12	0.97
J17		32		32		9.38		34.68	34.51	1.01
J18		26		26		11.54		38.05	37.27	1.02
J19		22		22		13.64		40.88	39.95	1.02
J20		18		18		16.67		43.97	43.81	1.00
J21		40	300	32	0.50	7.50	0.8		23.70	0.00
J22		32		25.6		9.38		27.32	26.10	1.05
J23		26		20.8		11.54		31.93	28.86	1.11
J24		22		17.6		13.64		36.00	31.53	1.14
J25		18		14.4		16.67		37.59	35.40	1.06
J26		40	350	32	0.58	7.50			27.41	0.00
J27		32		25.6		9.38		31.57	29.80	1.06
J28		26		20.8		11.54		36.55	32.56	1.12
J29		22		17.6		13.64		37.62	35.24	1.07
J30		18		14.4		16.67		41.39	39.11	1.06

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)	Proposed formula $F_{u,p}$ (kN)	Ratio
J31	600	40	400	32	0.67	7.50	0.8	29.80	29.37	1.01
J32		32		25.6		9.38		33.02	31.76	1.04
J33		26		20.8		11.54		36.36	34.52	1.05
J34		22		17.6		13.64		39.55	37.20	1.06
J35		18		14.4		16.67		40.98	41.07	1.00
J36		40	450	32	0.75	7.50		30.00	29.67	1.01
J37		32		25.6		9.38		33.62	32.06	1.05
J38		26		20.8		11.54		36.65	34.82	1.05
J39		22		17.6		13.64		39.11	37.50	1.04
J40		18		14.4		16.67		41.92	41.37	1.01
J41		40	300	26	0.50	7.50	0.65			
J42		32		20.8		9.38				
J43		26		16.9		11.54		27.35	27.02	1.01
J44		22		14.3		13.64		30.06	29.70	1.01
J45		18		11.7		16.67		32.47	33.57	0.97
J46		40	350	26	0.58	7.50				
J47		32		20.8		9.38		26.63	27.97	0.95
J48		26		16.9		11.54		29.91	30.73	0.97
J49		22		14.3		13.64		32.52	33.41	0.97
J50		18		11.7		16.67		35.67	37.27	0.96
J51		40	400	26	0.67	7.50		25.71	27.54	0.93
J52		32		20.8		9.38		28.24	29.93	0.94
J53		26		16.9		11.54		31.28	32.69	0.96
J54		22		14.3		13.64		34.44	35.37	0.97
J55		18		11.7		16.67		38.60	39.23	0.98
J56		40	450	26	0.75	7.50		27.35	27.84	0.98
J57		32		20.8		9.38		30.18	30.23	1.00
J58		26		16.9		11.54		33.11	32.99	1.00
J59		22		14.3		13.64		35.66	35.67	1.00
J60		18		11.7		16.67		38.72	39.53	0.98

Table 4.20 Comparison of numerical results with the proposed formula results for S690 in load case 1

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)	Proposed formula $F_{u,p}$ (kN)	Ratio
J1	600	40	300	40	0.50	7.50	1	13.85	15.19	0.91
J2		32		32		9.38		14.71	14.42	1.02
J3		26		26		11.54		13.50	13.53	1.00
J4		22		22		13.64		13.36	12.67	1.05
J5		18		18		16.67		10.61	11.43	0.93
J6		40	350	40	0.58	7.50		16.43	16.58	0.99
J7		32		32		9.38		15.65	15.81	0.99
J8		26		26		11.54		15.88	14.92	1.06
J9		22		22		13.64		13.91	14.06	0.99
J10		18		18		16.67		12.74	12.82	0.99
J11		40	400	40	0.67	7.50		18.40	18.47	1.00
J12		32		32		9.38		17.73	17.70	1.00
J13		26		26		11.54		17.01	16.81	1.01
J14		22		22		13.64		15.88	15.95	1.00
J15		18		18		16.67		13.72	14.71	0.93
J16		40	450	40	0.75	7.50		20.95	21.21	0.99
J17		32		32		9.38		20.96	20.44	1.03
J18		26		26		11.54		20.28	19.55	1.04
J19		22		22		13.64		19.17	18.69	1.03
J20		18		18		16.67		17.60	17.45	1.01
J21		40	300	32	0.50	7.50	0.8	13.91	14.84	0.94
J22		32		25.6		9.38		14.60	14.07	1.04
J23		26		20.8		11.54		13.44	13.18	1.02
J24		22		17.6		13.64		13.17	12.32	1.07
J25		18		14.4		16.67		10.42	11.08	0.94
J26		40	350	32	0.58	7.50		16.10	16.23	0.99
J27		32		25.6		9.38		15.47	15.46	1.00
J28		26		20.8		11.54		15.65	14.57	1.07
J29		22		17.6		13.64		13.78	13.71	1.00
J30		18		14.4		16.67		12.60	12.47	1.01

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)	Proposed formula $F_{u,p}$ (kN)	Ratio
J31	600	40	400	32	0.67	7.50	0.8	18.00	18.11	0.99
J32		32		25.6		9.38		17.47	17.34	1.01
J33		26		20.8		11.54		16.79	16.46	1.02
J34		22		17.6		13.64		15.67	15.60	1.00
J35		18		14.4		16.67		13.37	14.36	0.93
J36		40	450	32	0.75	7.50		20.45	20.86	0.98
J37		32		25.6		9.38		20.52	20.09	1.02
J38		26		20.8		11.54		19.80	19.20	1.03
J39		22		17.6		13.64		18.64	18.34	1.02
J40		18		14.4		16.67		16.96	17.10	0.99
J41		40	300	26	0.50	7.50	0.65	13.57	14.84	0.91
J42		32		20.8		9.38		14.30	13.81	1.04
J43		26		16.9		11.54		13.35	12.92	1.03
J44		22		14.3		13.64		13.05	12.06	1.08
J45		18		11.7		16.67		10.43	10.82	0.96
J46		40	350	26	0.58	7.50		15.61	15.96	0.98
J47		32		20.8		9.38		15.21	15.20	1.00
J48		26		16.9		11.54		15.34	14.31	1.07
J49		22		14.3		13.64		13.58	13.45	1.01
J50		18		11.7		16.67		12.36	12.21	1.01
J51		40	400	26	0.67	7.50		17.40	17.85	0.97
J52		32		20.8		9.38		17.10	17.08	1.00
J53		26		16.9		11.54		16.45	16.19	1.02
J54		22		14.3		13.64		15.43	15.33	1.01
J55		18		11.7		16.67		13.17	14.09	0.93
J56		40	450	26	0.75	7.50		19.60	20.59	0.95
J57		32		20.8		9.38		19.90	19.83	1.00
J58		26		16.9		11.54		19.27	18.94	1.02
J59		22		14.3		13.64		17.98	18.08	0.99
J60		18		11.7		16.67		15.89	16.84	0.94

Table 4.21 Comparison of numerical results with the proposed formula results for S690 in load case 2

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)	Proposed formula $F_{u,p}$ (kN)	Ratio
J1	600	40	300	40	0.50	7.50	1	19.62	20.66	0.95
J2		32		32		9.38		22.00	20.77	1.06
J3		26		26		11.54		21.33	20.89	1.02
J4		22		22		13.64		21.65	21.01	1.03
J5		18		18		16.67		19.83	21.19	0.94
J6		40	350	40	0.58	7.50		22.09	22.13	1.00
J7		32		32		9.38		22.15	22.24	1.00
J8		26		26		11.54		24.21	22.36	1.08
J9		22		22		13.64		21.84	22.48	0.97
J10		18		18		16.67		22.47	22.66	0.99
J11		40	400	40	0.67	7.50		22.93	23.48	0.98
J12		32		32		9.38		23.45	23.59	0.99
J13		26		26		11.54		24.16	23.71	1.02
J14		22		22		13.64		24.28	23.83	1.02
J15		18		18		16.67		22.69	24.01	0.94
J16		40	450	40	0.75	7.50		24.59	24.92	0.99
J17		32		32		9.38		24.95	25.03	1.00
J18		26		26		11.54		25.76	25.15	1.02
J19		22		22		13.64		25.66	25.27	1.02
J20		18		18		16.67		24.97	25.45	0.98
J21		40	300	32	0.50	7.50	0.8	19.30	20.24	0.95
J22		32		25.6		9.38		21.46	20.35	1.05
J23		26		20.8		11.54		20.99	20.47	1.03
J24		22		17.6		13.64		21.36	20.59	1.04
J25		18		14.4		16.67		19.72	20.77	0.95
J26		40	350	32	0.58	7.50		21.43	21.71	0.99
J27		32		25.6		9.38		21.75	21.82	1.00
J28		26		20.8		11.54		23.81	21.94	1.08
J29		22		17.6		13.64		21.72	22.06	0.98
J30		18		14.4		16.67		22.23	22.24	1.00

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)	Proposed formula $F_{u,p}$ (kN)	Ratio
J31	600	40	400	32	0.67	7.50	0.8	22.42	23.06	0.97
J32		32		25.6		9.38		23.19	23.17	1.00
J33		26		20.8		11.54		24.01	23.29	1.03
J34		22		17.6		13.64		24.14	23.41	1.03
J35		18		14.4		16.67		22.77	23.59	0.97
J36		40	450	32	0.75	7.50		23.83	24.50	0.97
J37		32		25.6		9.38		24.64	24.61	1.00
J38		26		20.8		11.54		25.46	24.73	1.03
J39		22		17.6		13.64		25.43	24.85	1.02
J40		18		14.4		16.67		24.76	25.03	0.99
J41		40	300	26	0.50	7.50	0.65	18.75	20.24	0.93
J42		32		20.8		9.38		20.68	20.03	1.03
J43		26		16.9		11.54		20.51	20.16	1.02
J44		22		14.3		13.64		20.76	20.28	1.02
J45		18		11.7		16.67		19.45	20.46	0.95
J46		40	350	26	0.58	7.50		20.59	21.40	0.96
J47		32		20.8		9.38		21.20	21.51	0.99
J48		26		16.9		11.54		23.09	21.63	1.07
J49		22		14.3		13.64		21.45	21.75	0.99
J50		18		11.7		16.67		21.84	21.93	1.00
J51		40	400	26	0.67	7.50		21.83	22.75	0.96
J52		32		20.8		9.38		22.68	22.86	0.99
J53		26		16.9		11.54		23.51	22.98	1.02
J54		22		14.3		13.64		23.69	23.10	1.03
J55		18		11.7		16.67		22.47	23.28	0.97
J56		40	450	26	0.75	7.50		23.15	24.19	0.96
J57		32		20.8		9.38		24.31	24.29	1.00
J58		26		16.9		11.54		25.11	24.42	1.03
J59		22		14.3		13.64		25.11	24.54	1.02
J60		18		11.7		16.67		24.57	24.72	0.99

Table 4.22 Comparison of numerical results with the proposed formula results for S690 in load case 3

Joint No	b_0	t_0	b	t	β	γ	τ	Non-dimensional strength results		
					(b/b_0)	$b_0/(2t_0)$	t_1/t_0	Numerical results $F_{u,nu}$ (kN)	Proposed formula $F_{u,p}$ (kN)	Ratio
J1	600	40	300	40	0.50	7.50	1	25.87	26.15	0.99
J2		32		32		9.38		30.89	28.54	1.08
J3		26		26		11.54		29.94	31.30	0.96
J4		22		22		13.64		36.95	33.98	1.09
J5		18		18		16.67		34.80	37.85	0.92
J6		40	350	40	0.58	7.50		30.62	29.86	1.03
J7		32		32		9.38		29.72	32.25	0.92
J8		26		26		11.54		37.63	35.01	1.07
J9		22		22		13.64		35.73	37.69	0.95
J10		18		18		16.67		42.93	41.55	1.03
J11		40	400	40	0.67	7.50		31.60	31.82	0.99
J12		32		32		9.38		34.34	34.21	1.00
J13		26		26		11.54		37.43	36.97	1.01
J14		22		22		13.64		39.27	39.65	0.99
J15		18		18		16.67		42.06	43.51	0.97
J16		40	450	40	0.75	7.50		31.03	32.12	0.97
J17		32		32		9.38		34.66	34.51	1.00
J18		26		26		11.54		37.89	37.27	1.02
J19		22		22		13.64		40.01	39.95	1.00
J20		18		18		16.67		42.86	43.81	0.98
J21		40	300	32	0.50	7.50	0.8			
J22		32		25.6		9.38		27.85	26.10	1.07
J23		26		20.8		11.54		28.83	28.86	1.00
J24		22		17.6		13.64		35.38	31.53	1.12
J25		18		14.4		16.67		33.72	35.40	0.95
J26		40	350	32	0.58	7.50		27.63	27.41	1.01
J27		32		25.6		9.38		28.78	29.80	0.97
J28		26		20.8		11.54		35.47	32.56	1.09
J29		22		17.6		13.64		35.72	35.24	1.01
J30		18		14.4		16.67		40.85	39.11	1.04

Joint No	b ₀	t ₀	b	t	β	γ	τ	Non-dimensional strength results			
					(b/b ₀)	b ₀ /(2t ₀)	t ₁ /t ₀	Numerical results F _{u,nu} (kN)	Proposed formula F _{u,p} (kN)	Ratio	
J31	600	40	400	32	0.67	7.50	0.8	29.77	29.37	1.01	
J32		32		25.6		9.38		32.35	31.76	1.02	
J33		26		20.8		11.54		35.45	34.52	1.03	
J34		22		17.6		13.64		37.55	37.20	1.01	
J35		18		14.4		16.67		39.50	41.07	0.96	
J36		40	450	32	0.75	7.50		29.91	29.67	1.01	
J37		32		25.6		9.38		33.27	32.06	1.04	
J38		26		20.8		11.54		36.09	34.82	1.04	
J39		22		17.6		13.64		37.99	37.50	1.01	
J40		18		14.4		16.67		40.18	41.37	0.97	
J41		40	300	26	0.50	7.50		0.65			
J42		32		20.8		9.38			23.87	24.26	0.98
J43		26		16.9		11.54			27.33	27.02	1.01
J44		22		14.3		13.64			30.99	29.70	1.04
J45		18		11.7		16.67			33.50	33.57	1.00
J46		40	350	26	0.58	7.50					
J47		32		20.8		9.38			27.27	27.97	0.97
J48		26		16.9		11.54			31.13	30.73	1.01
J49		22		14.3		13.64			33.20	33.41	0.99
J50		18		11.7		16.67			38.24	37.27	1.03
J51		40	400	26	0.67	7.50			26.30	27.54	0.96
J52		32		20.8		9.38			30.40	29.93	1.02
J53		26		16.9		11.54			33.46	32.69	1.02
J54		22		14.3		13.64			35.50	35.37	1.00
J55		18		11.7		16.67			36.89	39.23	0.94
J56		40	450	26	0.75	7.50			27.85	27.84	1.00
J57		32		20.8		9.38			30.72	30.23	1.02
J58		26		16.9		11.54			33.88	32.99	1.03
J59		22		14.3		13.64			35.87	35.67	1.01
J60		18		11.7		16.67			38.08	39.53	0.96

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Based on the fact that the high strength steel is more and more frequently used in the modern structure but no existing exact formula can be applied, the influence of high strength steel to the ultimate strength of the gap SHS K-joints has been selected for study. To achieve this purpose, a numerical parametric study using ABAQUS is performed to model the actual behavior of axially loaded gap K-joints with different materials, parameters and loading cases. A verification process is also done to verify the numerical results. The parametric study is applied to sixty joints with various parameters made of three grades of steel in three load cases. Two formulas are proposed with MATLAB for expecting the ultimate strength of high strength steel SHS F-joints. The comparison between the numerical result and the results derived from the proposed equation is performed to prove the validity of the new formula and show good agreement.

5.1.1 Verification of the finite element model

The finite element model corresponding to the experimental parameter and the load case is built. The comparison of experimental and numerical values showed accurate and reliable results. The chord face failure is observed in all the models. These results indicated that the numerical analysis can be used to simulate the real ultimate strength and failure mode with confidence.

5.1.2 Finite Element Analysis

The finite element analysis is carried out using the commercial finite element program ABAQUS. The finite element modelling technique is verified with experimental result. The numerical analyses are used to obtain the load-displacement curves for each model. The numerical results showed a good agreement with the experimental results with discrepancy less than 7%. This

ascertained the accuracy and reliability of finite element modeling techniques used in the parametric study.

5.1.3 Parametric Study

A numerical parametric study is conducted based on 60 models of S355 SHS K-joints, 60 models of S690 SHS K-joints, 60 models of S460 SHS K-joints, subjected to 3 load cases. Three types of loading are considered: without chord preload, with chord preload equal to thirty percent of the axial yield capacity of the chord and with chord preload equal to fifty percent of the axial yield capacity of the chord. The geometric parameters, β varies from 0.65 to 1.0, γ from 7.5 to 16.67, and τ from 0.65 to 1.00. The other parameters such as the length of the braces and chord are kept constant.

5.1.4 Failure modes

There are two distinct failure modes observed from the numerical parametric study:

- (1) Local brace failure-This mode happens in joints with low to medium γ and low τ in load case 3 only. When β is low ($\beta=0.5\sim0.58$), this mode happens in joint with low γ and medium to high τ ($\tau=0.8\sim1$).
- (2) Chord face plastification-The most common failure mode for gap joints with small to medium β . This mode occurred for joints with medium and high τ in load case 3 in all the three materials and all the joints studied in load case 1 and load case 2.

Failure modes for K-joints can be classified into different types of failure according to the loading cases and parameters as listed in the Chapter 2. From the result of the numerical results, it can be concluded that the failure mode of the gap K-joint is dependent on β , τ , γ and load case. The majority of local yielding of brace happens in the load case 3 with $\tau=0.65$ with γ below 13.636.

5.1.5 Comparison with codes

1. There is not the accurate design resistance equation for the high strength steel in any existing codes. In order to make the comparison, the author proposes the equation which can be applied to the high strength steel as well as improve the existing equation.
2. When the chord load under compressive load exceeds the thirty percent of the yield capacity of the chord section, the ultimate strength will be less than the capacity based on the brace effective width criterion predicted by CIDECT design guide 3.
3. When the compressive load in the chord increases, the ultimate strength decreases significantly. The ratio between the ultimate strength to the theoretical result obtained from the CIDECT design guide 3 becomes less and less.
4. When the common grade of steel changes to the high strength steel, the ultimate strength increases significantly but the non-dimensional strength does not change very much.

5.1.6 Proposed ultimate strength equations

Several formulae have been proposed in Section 4.8 to predict the strength of the SHS K-joint with high strength steel under high compression in chord. The strength ratio as a function of τ , β and γ , shown in Eq (4.1) can predict the numerical results very well. Repeatability test shows a very good prediction by the proposed ultimate strength equation with the ratio of the proposed equation to numerical predicted range from 0.95 to 1.10, which show a good agreement.

5.2 RECOMMENDATIONS

The finite element analysis in this study is without considering the welding process and stress concentration factor. If considering the welding defects, an extra decrease factor should be multiplied by the ultimate strength to make the result more similar to the actual situation. The verification model is overlap K-joint but the parametric study is based on gap K-joint, although the joint type is not totally same but the

result show good agreement which make the model result reliable. More experimental testing should be carried out on these joints which cannot be accurately predicted by the numerical analysis.

Research work on gap K-joint can be extended for different load cases. A large number of load cases have not been covered by the present study, namely moment loads either in-plane or out-of-plane or combinations of axial and moment loads. The range of the parameters can be in a larger scope. The K-joint with stiffener, overlapping and repaired joints can also be studied in the future.

The present study for the K-joint is just limited in the square hollow section (SHS) gap joints; the future researchers can explore the circular hollow section (CHS) with high strength as well. As high strength steel is applied increasingly in buildings and structures, the author believes the research on the high strength steel structures, such as vibration and buildability and construction method should be studied extensively in near future.

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APPENDIX A DIMENSIONS, GEOMETRIC PARAMETERS, AND NUMERICAL RESULTS OF S355 GAP K-JOINT

joint no	b_0	t_0	b	t	β	γ	τ	Load case 1			Load case 2			Load case 3		
								Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)
J1	40	40		40		7.50		8123.58	8392.68	-3.21	11688.12	9295.03	25.75	16010.99	10293.08	55.55
J2	32	32		32		9.38		5414.32	5743.20	-5.73	8029.41	6360.68	26.24	12292.93	7043.66	74.52
J3	26	26	300	26	0.50	11.54		3488.36	4035.09	-13.55	5398.86	4468.93	20.81	8654.64	4948.78	74.88
J4	22	22		22		13.64		2534.37	3037.51	-16.56	4051.49	3364.09	20.43	6740.63	3725.31	80.94
J5	18	18		18		16.67		1509.14	2159.54	-30.12	2597.15	2391.73	8.59	4400.33	2648.54	66.14
J6	40	40		40		7.50		9282.77	10130.29	-8.37	12732.23	11030.11	15.43	18489.22	12008.59	53.97
J7	32	32		32		9.38		6126.36	6932.26	-11.63	8713.61	7548.02	15.44	13327.96	8217.60	62.19
J8	26	26	350	26	0.58	11.54		4053.21	4870.51	-16.78	6014.35	5303.13	13.41	9656.68	5773.58	67.26
J9	22	22		22		13.64		2711.95	3666.39	-26.03	4162.56	3992.06	4.27	6928.96	4346.19	59.43
J10	18	18		18		16.67		1776.37	2606.65	-31.85	2901.08	2838.19	2.22	5239.10	3089.96	69.55
J11	40	40		40		7.50	1	10761.45	11978.10	-10.16	13290.60	12821.96	3.66	18460.04	13724.11	34.51
J12	32	32		32		9.38		7133.42	8196.73	-12.97	9214.89	8774.20	5.02	13433.10	9391.55	43.03
J13	26	26	400	26	0.67	11.54		4485.74	5758.91	-22.11	6169.13	6164.63	0.07	9562.26	6598.37	44.92
J14	22	22		22		13.64		3265.87	4335.15	-24.67	4683.09	4640.57	0.92	7567.82	4967.07	52.36
J15	18	18		18		16.67		1955.15	3082.12	-36.56	3037.62	3299.25	-7.93	5148.33	3531.39	45.79
J16	40	40		40		7.50		12972.20	13941.66	-6.95	14991.62	14672.00	2.18	18669.01	15439.62	20.92
J17	32	32		32		9.38		8358.00	9540.42	-12.39	9684.03	10040.20	-3.55	13051.85	10565.49	23.53
J18	26	26	450	26	0.75	11.54		5833.46	6702.97	-12.97	6951.23	7054.11	-1.46	9831.84	7423.17	32.45
J19	22	22		22		13.64		3789.29	5045.81	-24.90	4874.08	5310.14	-8.21	7406.29	5587.96	32.54
J20	18	18		18		16.67		2376.13	3587.37	-33.76	3290.10	3775.29	-12.85	5354.54	3972.81	34.78
J21	40	40		40		7.50		8010.88	8392.68	-4.55	11376.11	9295.03	21.85	13789.80	10293.08	33.97
J22	32	32		32		9.38		5366.96	5743.20	-6.55	7889.72	6360.68	24.04	10754.10	7043.66	52.68
J23	26	26	300	26	0.50	11.54		3470.83	4035.09	-13.98	5323.95	4468.93	19.13	7991.64	4948.78	61.49
J24	22	22		22		13.64		2522.07	3037.51	-16.97	4025.55	3364.09	19.66	6502.07	3725.31	74.54
J25	18	18		18		16.67		1500.65	2159.54	-30.51	2575.04	2391.73	7.66	4281.09	2648.54	61.64
J26	40	40		40		7.50	0.8	9061.28	10130.29	-10.55	12326.77	11030.11	11.76	16463.12	12008.59	37.09
J27	32	32		32		9.38		6044.43	6932.26	-12.81	8562.03	7548.02	13.43	12573.40	8217.60	53.01
J28	26	26	350	26	0.58	11.54		4026.52	4870.51	-17.33	5936.66	5303.13	11.95	9133.27	5773.58	58.19
J29	22	22		22		13.64		2694.54	3666.39	-26.51	4115.80	3992.06	3.10	6635.00	4346.19	52.66
J30	18	18		18		16.67		1767.92	2606.65	-32.18	2886.54	2838.19	1.70	5013.15	3089.96	62.24

joint no	b_0	t_0	b	t	β	γ	τ	Load case 1			Load case 2			Load case 3		
								Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)
J31	600	40	400	32	0.67	7.50	0.8	10482.67	11978.10	-12.48	13047.20	12821.96	1.76	17601.31	13724.11	28.25
J32		32		25.6		9.38		7027.08	8196.73	-14.27	9102.06	8774.20	3.74	12772.97	9391.55	36.01
J33		26		20.8		11.54		4444.51	5758.91	-22.82	6139.01	6164.63	-0.42	9111.51	6598.37	38.09
J34		22		17.6		13.64		3233.16	4335.15	-25.42	4647.82	4640.57	0.16	7203.01	4967.07	45.02
J35		18	450	14.4	0.75	16.67		1933.58	3082.12	-37.26	3016.11	3299.25	-8.58	4916.82	3531.39	39.23
J36		40		32		7.50		12533.11	13941.66	-10.10	14613.21	14672.00	-0.40	18117.69	15439.62	17.35
J37		32		25.6		9.38		8207.76	9540.42	-13.97	9573.85	10040.20	-4.64	12693.10	10565.49	20.14
J38		26		20.8		11.54		5714.36	6702.97	-14.75	6867.31	7054.11	-2.65	9507.13	7423.17	28.07
J39		22	500	17.6	0.85	13.64		3739.51	5045.81	-25.89	4835.61	5310.14	-8.94	7030.01	5587.96	25.81
J40		18		14.4		16.67		2336.50	3587.37	-34.87	3267.52	3775.29	-13.45	5049.79	3972.81	27.11
J41		40		26		7.50		7834.06	8392.68	-6.66	10889.34	9295.03	17.15	12007.97	10293.08	16.66
J42		32		20.8		9.38		5297.04	5743.20	-7.77	7634.33	6360.68	20.02	9305.22	7043.66	32.11
J43		26	550	16.9	0.95	11.54		3438.99	4035.09	-14.77	5209.06	4468.93	16.56	6841.00	4948.78	38.24
J44		22		14.3		13.64		2498.97	3037.51	-17.73	3958.52	3364.09	17.67	5533.17	3725.31	48.53
J45		18		11.7		16.67		1485.67	2159.54	-31.20	2538.24	2391.73	6.13	3950.84	2648.54	49.17
J46		40		26		7.50		8765.68	10130.29	-13.47	11795.99	11030.11	6.94	13985.70	12008.59	16.46
J47	600	32	350	20.8	0.58	9.38	0.65	5903.89	6932.26	-14.83	8252.08	7548.02	9.33	10131.82	8217.60	23.29
J48		26		16.9		11.54		3956.06	4870.51	-18.78	5767.84	5303.13	8.76	7609.66	5773.58	31.80
J49		22		14.3		13.64		2675.22	3666.39	-27.03	4076.62	3992.06	2.12	5929.85	4346.19	36.44
J50		18		11.7		16.67		1752.82	2606.65	-32.76	2852.25	2838.19	0.50	4405.41	3089.96	42.57
J51		40	400	26	0.67	7.50		10065.74	11978.10	-15.97	12700.64	12821.96	-0.95	15089.18	13724.11	9.95
J52		32		20.8		9.38		6786.56	8196.73	-17.20	8875.53	8774.20	1.15	10871.66	9391.55	15.76
J53		26		16.9		11.54		4380.20	5758.91	-23.94	6023.82	6164.63	-2.28	8082.50	6598.37	22.49
J54		22		14.3		13.64		3183.11	4335.15	-26.57	4563.49	4640.57	-1.66	6405.59	4967.07	28.96
J55		18	450	11.7	0.75	16.67		1920.57	3082.12	-37.69	2960.93	3299.25	-10.25	4619.11	3531.39	30.80
J56		40		26		7.50		11934.64	13941.66	-14.40	13956.09	14672.00	-4.88	16309.47	15439.62	5.63
J57		32		20.8		9.38		7919.64	9540.42	-16.99	9366.19	10040.20	-6.71	11638.68	10565.49	10.16
J58		26		16.9		11.54		5459.89	6702.97	-18.55	6698.82	7054.11	-5.04	8503.71	7423.17	14.56
J59		22	500	14.3	0.85	13.64		3664.21	5045.81	-27.38	4774.62	5310.14	-10.08	6647.17	5587.96	18.96
J60		18		11.7		16.67		2298.74	3587.37	-35.92	3235.79	3775.29	-14.29	4807.27	3972.81	21.00

APPENDIX B DIMENSIONS, GEOMETRIC PARAMETERS, AND NUMERICAL RESULTS OF S460 GAP K-JOINT

joint no	b_0	t_0	b	t	β	γ	τ	Load case 1			Load case 2			Load case 3		
								Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)
J1	600	40	300	40	0.50	7.50	1	10219.22	10875.03	-6.03	14679.18	12044.26	21.88	18832.04	13337.51	41.20
J2		32		32		9.38		6833.78	7441.89	-8.17	10258.72	8242.01	24.47	14861.55	9126.99	62.83
J3		26		26		11.54		4372.20	5228.57	-16.38	6769.01	5790.72	16.89	10719.76	6412.50	67.17
J4		22		22		13.64		3115.37	3935.93	-20.85	4996.04	4359.10	14.61	8301.30	4827.16	71.97
J5		18		18		16.67		1854.13	2798.28	-33.74	3150.29	3099.14	1.65	5754.96	3431.91	67.69
J6		40		40		7.50		11833.43	13126.57	-9.85	16114.75	14292.54	12.75	22958.65	15560.43	47.55
J7		32		32		9.38		7508.27	8982.64	-16.41	10765.31	9780.53	10.07	16358.08	10648.16	53.62
J8		26		26		11.54		5036.50	6311.08	-20.20	7560.98	6871.67	10.03	11892.20	7481.25	58.96
J9		22		22		13.64		3390.90	4750.81	-28.62	5255.93	5172.80	1.61	8780.12	5631.68	55.91
J10		18		18		16.67		2151.00	3377.63	-36.32	3504.78	3677.65	-4.70	6459.27	4003.90	61.32
J11		40	400	40	0.67	7.50		13436.26	15520.91	-13.43	16778.26	16614.37	0.99	23120.61	17783.35	30.01
J12		32		32		9.38		8669.75	10621.12	-18.37	11302.65	11369.38	-0.59	16370.63	12169.33	34.52
J13		26		26		11.54		5642.66	7462.25	-24.38	7811.21	7987.97	-2.21	11896.62	8550.00	39.14
J14		22		22		13.64		3954.37	5617.38	-29.60	5809.08	6013.13	-3.39	9258.32	6436.21	43.85
J15		18		18		16.67		2364.49	3993.73	-40.80	3706.97	4275.09	-13.29	6426.51	4575.88	40.44
J16		40		40		7.50		15539.74	18065.25	-13.98	18132.80	19011.61	-4.62	22828.28	20006.27	14.11
J17		32		32		9.38		10471.19	12362.23	-15.30	12126.43	13009.83	-6.79	16337.10	13690.49	19.33
J18		26		26		11.54		6781.47	8685.53	-21.92	8323.96	9140.53	-8.93	11832.88	9618.75	23.02
J19		22		22		13.64		4676.11	6538.23	-28.48	6081.30	6880.74	-11.62	9101.57	7240.73	25.70
J20		18		18		16.67		2938.67	4648.42	-36.78	4075.30	4891.93	-16.69	6553.92	5147.87	27.31
J21		40	300	32	0.8	7.50		10132.62	10875.03	-6.83	14311.82	12044.26	18.83	16627.73	13337.51	24.67
J22		32		25.6		9.38		6770.82	7441.89	-9.02	9992.54	8242.01	21.24	12869.62	9126.99	41.01
J23		26		20.8		11.54		4347.34	5228.57	-16.85	6695.10	5790.72	15.62	9929.87	6412.50	54.85
J24		22		17.6		13.64		3092.13	3935.93	-21.44	4934.89	4359.10	13.21	8014.64	4827.16	66.03
J25		18		14.4		16.67		1857.41	2798.28	-33.62	3151.69	3099.14	1.70	5601.76	3431.91	63.23
J26		40		32		7.50		11561.66	13126.57	-11.92	15594.14	14292.54	9.11	19828.39	15560.43	27.43
J27		32		25.6		9.38		7390.02	8982.64	-17.73	10463.26	9780.53	6.98	14871.73	10648.16	39.66
J28		26		20.8		11.54		4974.87	6311.08	-21.17	7449.36	6871.67	8.41	11365.35	7481.25	51.92
J29		22		17.6		13.64		3361.59	4750.81	-29.24	5189.56	5172.80	0.32	8374.94	5631.68	48.71
J30		18		14.4		16.67		2136.89	3377.63	-36.73	3440.44	3677.65	-6.45	6169.47	4003.90	54.09

joint no	b_0	t_0	b	t	β	γ	τ	Load case 1			Load case 2			Load case 3			
								Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Effective width criteria difference ratio(%)
J31	600	40	400	32	0.67	7.50	0.8	13045.93	15520.91	-15.95	16439.79	16614.37	-1.05	21934.09	17783.35	23.34	CF
J32		25.6		9.38		8515.68		10621.12	-19.82	11190.46	11369.38	-1.57	15551.66	12169.33	27.79	CF	
J33		20.8		11.54		5566.12		7462.25	-25.41	7756.30	7987.97	-2.90	11305.66	8550.00	32.23	CF	
J34		17.6		13.64		3909.20		5617.38	-30.41	5755.16	6013.13	-4.29	8805.12	6436.21	36.81	CF	
J35		14.4		16.67		2338.31		3993.73	-41.45	3677.85	4275.09	-13.97	6108.08	4575.88	33.48	CF	
J36		40		32		7.50		15013.13	18065.25	-16.89	17735.60	19011.61	-6.71	22079.19	20006.27	10.36	CF
J37		32		25.6		9.38		10200.86	12362.23	-17.48	11968.43	13009.83	-8.00	15835.18	13690.49	15.67	CF
J38		26		450		0.75		6662.33	8685.53	-23.29	8230.11	9140.53	-9.96	11397.13	9618.75	18.49	CF
J39		22	17.6	13.64	4599.08	6538.23	-29.66	6029.59	6880.74	-12.37	8706.97	7240.73	20.25	CF			
J40		18	14.4	16.67	2859.64	4648.42	-38.48	4055.95	4891.93	-17.09	6247.81	5147.87	21.37	CF			
J41		40	26	7.50	9942.25	10875.03	-8.58	13846.51	12044.26	14.96	14358.29	13337.51	7.65	-			
J42		32	20.8	9.38	6650.93	7441.89	-10.63	9668.06	8242.01	17.30	11109.31	9126.99	21.72	BF			
J43		26	300	0.50	4372.20	5228.57	-16.38	6769.01	5790.72	16.89	8505.82	6412.50	32.64	BF			
J44		22	14.3	13.64	3060.16	3935.93	-22.25	4832.69	4359.10	10.86	6691.91	4827.16	38.63	BF			
J45		18	11.7	16.67	1838.57	2798.28	-34.30	3114.80	3099.14	0.51	4839.45	3431.91	41.01	CF			
J46		40	26	7.50	11202.22	13126.57	-14.66	14980.06	14292.54	4.81	17261.96	15560.43	10.93	CF			
J47		32	20.8	9.38	7210.65	8982.64	-19.73	10131.38	9780.53	3.59	12546.09	10648.16	17.82	CF			
J48		26	350	0.58	4861.29	6311.08	-22.97	7211.17	6871.67	4.94	9301.17	7481.25	24.33	CF			
J49		22	14.3	13.64	3310.76	4750.81	-30.31	5081.85	5172.80	-1.76	7240.37	5631.68	28.56	CF			
J50		18	11.7	16.67	2111.80	3377.63	-37.48	3420.28	3677.65	-7.00	5315.75	4003.90	32.76	CF			
J51		40	26	400	0.65	7.50	12508.85	15520.91	-19.41	15999.50	16614.37	-3.70	18922.51	17783.35	6.41	BF	
J52		32	20.8			9.38	8236.24	10621.12	-22.45	10917.15	11369.38	-3.98	13302.76	12169.33	9.31	BF	
J53		26	16.9			0.67	5436.57	7462.25	-27.15	7572.53	7987.97	-5.20	9726.35	8550.00	13.76	BF	
J54		22	14.3			13.64	3834.25	5617.38	-31.74	5638.87	6013.13	-6.22	7667.54	6436.21	19.13	BF	
J55		18	11.7			16.67	2302.77	3993.73	-42.34	3622.34	4275.09	-15.27	5752.54	4575.88	25.71	CF	
J56		40	26			7.50	14288.15	18065.25	-20.91	17027.04	19011.61	-10.44	20132.47	20006.27	0.63	BF	
J57		32	20.8			9.38	9737.56	12362.23	-21.23	11723.58	13009.83	-9.89	14217.68	13690.49	3.85	BF	
J58		26	450			0.75	6411.01	8685.53	-26.19	8091.40	9140.53	-11.48	10295.24	9618.75	7.03	BF	
J59		22	14.3			13.64	4452.99	6538.23	-31.89	5938.10	6880.74	-13.70	7938.81	7240.73	9.64	CF	
J60		18	11.7			16.67	2764.67	4648.42	-40.52	3985.61	4891.93	-18.53	5771.31	5147.87	12.11	CF	

APPENDIX C DIMENSIONS, GEOMETRIC PARAMETERS, AND NUMERICAL RESULTS OF S690 GAP K-JOINT

joint no	b ₀	t ₀	b	t	Load case 1			Load case 2			Load case 3						
					β	γ	τ	Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Failure Mode
J1		40				7.50		15289.88	16312.54	-6.27	21657.65	18066.39	19.88	28555.55	20006.27	42.73	CF
J2		32				9.38		10395.76	11162.84	-6.87	15544.18	12363.02	25.73	21825.76	13690.49	59.42	CF
J3		26	300		0.50	11.54		6298.67	7842.86	-19.69	9947.85	8686.09	14.53	13965.51	9618.75	45.19	CF
J4		22				13.64		4462.75	5903.89	-24.41	7231.21	6538.65	10.59	12339.76	7240.73	70.42	CF
J5		18				16.67		2372.46	4197.42	-43.48	4432.47	4648.71	-4.65	7779.50	5147.87	51.12	CF
J6		40				7.50		18138.30	19689.85	-7.88	24381.85	21438.81	13.73	33800.02	23340.65	44.81	CF
J7		32				9.38		11057.58	13473.97	-17.93	15646.88	14670.80	6.65	20998.05	15972.24	31.47	CF
J8		26	350		0.58	11.54		7405.31	9466.63	-21.77	11292.09	10307.50	9.55	17553.80	11221.88	56.42	CF
J9		22				13.64		4645.01	7126.22	-34.82	7294.65	7759.21	-5.99	11930.98	8447.52	41.24	CF
J10		18				16.67	1	2849.26	5066.45	-43.76	5023.15	5516.48	-8.94	9598.16	6005.85	59.81	CF
J11		40				7.50		20314.42	23281.37	-12.74	25314.10	24921.55	1.58	34881.01	26675.02	30.76	CF
J12		32				9.38		12525.45	15931.68	-21.38	16567.18	17054.07	-2.86	24260.99	18253.99	32.91	CF
J13		26	400		0.67	11.54		7934.97	11193.38	-29.11	11269.11	11981.96	-5.95	17456.71	12825.00	36.11	CF
J14		22				13.64		5302.28	8426.07	-37.07	8109.34	9019.69	-10.09	13114.14	9654.31	35.84	CF
J15	600	18				16.67		3067.29	5990.59	-48.80	5071.53	6412.63	-20.91	9403.93	6863.82	37.01	CF
J16		40				7.50		23126.11	27097.87	-14.66	27152.67	28517.41	-4.79	34254.09	30009.40	14.14	CF
J17		32				9.38		14807.48	18543.35	-20.15	17628.25	19514.75	-9.67	24491.81	20535.74	19.26	CF
J18		26	450		0.75	11.54		9459.69	13028.30	-27.39	12014.22	13710.80	-12.37	17675.05	14428.13	22.50	CF
J19		22				13.64		6402.19	9807.35	-34.72	8569.90	10321.11	-16.97	13361.46	10861.10	23.02	CF
J20		18				16.67		3933.81	6972.63	-43.58	5581.65	7337.89	-23.93	9581.78	7721.80	24.09	CF
J21		40				7.50		15351.82	16312.54	-5.89	21304.30	18066.39	17.92	23450.91	20006.27	17.22	CF
J22		32	25.6			9.38		10313.79	11162.84	-7.61	15160.68	12363.02	22.63	19677.50	13690.49	43.73	CF
J23		26	300		0.50	11.54		6268.57	7842.86	-20.07	9791.83	8686.09	12.73	13447.02	9618.75	39.80	CF
J24		22				13.64		4399.60	5903.89	-25.48	7131.87	6538.65	9.07	11814.31	7240.73	63.16	CF
J25		18				16.67		2329.10	4197.42	-44.51	4409.63	4648.71	-5.14	7538.92	5147.87	46.45	CF
J26		40				7.50	0.8	17772.45	19689.85	-9.74	23663.19	21438.81	10.38	30508.60	23340.65	30.71	-
J27		32	25.6			9.38		10928.13	13473.97	-18.89	15368.71	14670.80	4.76	20335.17	15972.24	27.32	CF
J28		26	350		0.58	11.54		7299.98	9466.63	-22.89	11103.78	10307.50	7.73	16543.97	11221.88	47.43	CF
J29		22				13.64		4601.62	7126.22	-35.43	7251.96	7759.21	-6.54	11929.06	8447.52	41.21	CF
J30		18				16.67		2817.78	5066.45	-44.38	4970.19	5516.48	-9.90	9132.12	6005.85	52.05	CF

joint no	b_0	t_0	b	t	β	γ	τ	Load case 1			Load case 2			Load case 3		
								Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)	Numerical strength of joints (KN)	Effective width criteria Formula(KN)	strength difference ratio(%)
J31	600	40	400	32	0.67	7.50	0.8	19873.96	23281.37	-14.64	24753.51	24921.55	-0.67	32861.96	26675.02	23.19
J32		32		25.6		9.38		12345.44	15931.68	-22.51	16387.38	17054.07	-3.91	22860.48	18253.99	25.24
J33		26		20.8		11.54		7831.98	11193.38	-30.03	11198.76	11981.96	-6.54	16533.85	12825.00	28.92
J34		22		17.6		13.64		5234.54	8426.07	-37.88	8062.18	9019.69	-10.62	12538.67	9654.31	29.88
J35		18		14.4		16.67		2988.54	5990.59	-50.11	5089.98	6412.63	-20.63	8831.09	6863.82	28.66
J36		40		32		7.50		22581.27	27097.87	-16.67	26308.49	28517.41	-7.75	33022.92	30009.40	10.04
J37		32		25.6		9.38		14498.45	18543.35	-21.81	17408.97	19514.75	-10.79	23505.04	20535.74	14.46
J38		26		20.8		0.75		9237.67	13028.30	-29.10	11876.33	13710.80	-13.38	16833.92	14428.13	16.67
J39		22	450	17.6	0.75	13.64	0.65	6226.67	9807.35	-36.51	8492.23	10321.11	-17.72	12685.52	10861.10	16.80
J40		18		14.4		16.67		3792.65	6972.63	-45.61	5536.10	7337.89	-24.55	8981.89	7721.80	16.32
J41		40		26		7.50		14981.66	16312.54	-8.16	20703.01	18066.39	14.59	21413.93	20006.27	7.04
J42		32		20.8		9.38		10104.96	11162.84	-9.48	14612.54	12363.02	18.20	16862.78	13690.49	23.17
J43		26		16.9		0.50		6224.70	7842.86	-20.63	9566.01	8686.09	10.13	12746.31	9618.75	32.52
J44		22		14.3		13.64		4357.90	5903.89	-26.19	6934.17	6538.65	6.05	10350.55	7240.73	42.95
J45		18		11.7		16.67		2331.72	4197.42	-44.45	4348.83	4648.71	-6.45	7489.77	5147.87	45.49
J46		40		26		7.50		17229.92	19689.85	-12.49	22733.43	21438.81	6.04	26157.03	23340.65	12.07
J47		32	350	20.8	0.58	9.38		10747.40	13473.97	-20.24	14980.02	14670.80	2.11	19265.88	15972.24	20.62
J48		26		16.9		11.54		7154.70	9466.63	-24.42	10771.03	10307.50	4.50	14522.09	11221.88	29.41
J49		22		14.3		13.64		4536.78	7126.22	-36.34	7164.63	7759.21	-7.66	11088.59	8447.52	31.26
J50		18		11.7		16.67		2763.85	5066.45	-45.45	4882.01	5516.48	-11.50	8548.39	6005.85	42.33
J51		40		26		7.50		19204.25	23281.37	-17.51	24098.73	24921.55	-3.30	29031.93	26675.02	8.84
J52		32		20.8		9.38		12081.82	15931.68	-24.16	16021.81	17054.07	-6.05	21479.08	18253.99	17.67
J53		26		16.9		0.67		7672.78	11193.38	-31.45	10967.60	11981.96	-8.47	15606.62	12825.00	21.69
J54		22		14.3		13.64		5154.53	8426.07	-38.83	7909.93	9019.69	-12.30	11854.99	9654.31	22.79
J55		18		11.7		16.67		2944.38	5990.59	-50.85	5022.63	6412.63	-21.68	8246.32	6863.82	20.14
J56		40	450	26	0.75	7.50		21639.19	27097.87	-20.14	25557.05	28517.41	-10.38	30751.00	30009.40	2.47
J57		32		20.8		9.38		14060.70	18543.35	-24.17	17177.71	19514.75	-11.98	21705.14	20335.74	5.69
J58		26		16.9		11.54		8989.40	13028.30	-31.00	11711.44	13710.80	-14.58	15802.73	14428.13	9.53
J59		22		14.3		13.64		6005.52	9807.35	-38.77	8385.55	10321.11	-18.75	11980.12	10861.10	10.30
J60		18		11.7		16.67		3553.39	6972.63	-49.04	5492.62	7337.89	-25.15	8513.07	7721.80	10.25

APPENDIX D LOAD-DISPLACEMENT CURVES FOR S355 GAP K-JOINTS

(J1) $\beta=0.5$, $\gamma=7.5$ and $\tau=1$

(J2) $\beta=0.5$, $\gamma=9.35$ and $\tau=1$

(J3) $\beta=0.5$, $\gamma=11.538$ and $\tau=1$

(J4) $\beta=0.5$, $\gamma=13.636$ and $\tau=1$

—▲— load case 1

—●— load case 2

—■— load case 3

(J5) $\beta=0.5$, $\gamma=16.676$ and $\tau=1$

(J6) $\beta=0.58$, $\gamma=7.5$ and $\tau=1$

(J7) $\beta=0.58$, $\gamma=9.375$ and $\tau=1$

(J8) $\beta=0.58$, $\gamma=11.538$ and $\tau=1$

—▲— load case 1

—●— load case 2

—■— load case 3

(J9) $\beta=0.58$, $\gamma=13.636$ and $\tau=1$

(J10) $\beta=0.58$, $\gamma=16.676$ and $\tau=1$

(J11) $\beta=0.66$, $\gamma=7.5$ and $\tau=1$

(J12) $\beta=0.66$, $\gamma=9.375$ and $\tau=1$

—▲— load case 1

—●— load case 2

—■— load case 3

(J13) $\beta=0.66$, $\gamma=11.538$ and $\tau=1$

(J14) $\beta=0.66$, $\gamma=13.636$ and $\tau=1$

(J15) $\beta=0.66$, $\gamma=16.667$ and $\tau=1$

(J16) $\beta=0.75$, $\gamma=7.5$ and $\tau=1$

—▲— load case 1

—●— load case 2

—■— load case 3

(J17) $\beta=0.75$, $\gamma=9.375$ and $\tau=1$

(J18) $\beta=0.75$, $\gamma=11.538$ and $\tau=1$

(J19) $\beta=0.75$, $\gamma=13.636$ and $\tau=1$

(J20) $\beta=0.75$, $\gamma=16.667$ and $\tau=1$

—▲— load case 1

—●— load case 2

—■— load case 3

(J21) $\beta=0.5$, $\gamma=7.5$ and $\tau=0.8$

(J22) $\beta=0.5$, $\gamma=9.375$ and $\tau=0.8$

(J23) $\beta=0.5$, $\gamma=11.538$ and $\tau=0.8$

(J24) $\beta=0.5$, $\gamma=13.636$ and $\tau=0.8$

—▲— load case 1

—●— load case 2

—■— load case 3

(J25) $\beta=0.5$, $\gamma=16.667$ and $\tau=0.8$

(J26) $\beta=0.58$, $\gamma=7.5$ and $\tau=0.8$

(J27) $\beta=0.58$, $\gamma=9.375$ and $\tau=0.8$

(J28) $\beta=0.58$, $\gamma=11.538$ and $\tau=0.8$

—▲— load case 1

—●— load case 2

—■— load case 3

(J29) $\beta=0.58$, $\gamma=13.636$ and $\tau=0.65$

(J30) $\beta=0.58$, $\gamma=16.676$ and $\tau=0.8$

(J31) $\beta=0.66$, $\gamma=7.8$ and $\tau=0.8$

(J32) $\beta=0.66$, $\gamma=9.375$ and $\tau=0.8$

—▲— load case 1

—●— load case 2

—■— load case 3

(J33) $\beta=0.66$, $\gamma=11.538$ and $\tau=0.8$

(J34) $\beta=0.66$, $\gamma=13.636$ and $\tau=0.8$

(J35) $\beta=0.66$, $\gamma=16.667$
 $\tau=0.8$

(J36) $\beta=0.75$, $\gamma=7.5$ $\tau=0.8$

—▲— load case 1

—●— load case 2

—■— load case 3

(J37) $\beta=0.75$, $\gamma=9.375$ and $\tau=0.8$

(J38) $\beta=0.75$, $\gamma=11.538$ and $\tau=0.8$

(J39) $\beta=0.75$, $\gamma=13.636$ and $\tau=0.8$

(J40) $\beta=0.75$, $\gamma=16.667$ and $\tau=0.8$

—▲— load case 1

—●— load case 2

—■— load case 3

(J41) $\beta=0.5$, $\gamma=7.5$ and $\tau=0.65$

(J42) $\beta=0.5$, $\gamma=9.375$ and $\tau=0.65$

(J43) $\beta=0.5$, $\gamma=11.538$ and $\tau=0.65$

(J44) $\beta=0.5$, $\gamma=11.636$ and $\tau=0.65$

—▲— load case 1

—●— load case 2

—■— load case 3

(J45) $\beta=0.5$, $\gamma=16.667$ and $\tau=0.65$

(J46) $\beta=0.58$, $\gamma=7.5$ and $\tau=0.65$

(J47) $\beta=0.58$, $\gamma=9.375$ and $\tau=0.65$

(J48) $\beta=0.58$, $\gamma=11.538$ and $\tau=0.65$

—▲— load case 1

—●— load case 2

—■— load case 3

(J49) $\beta=0.58$, $\gamma=13.636$ and $\tau=0.65$

(J50) $\beta=0.58$, $\gamma=16.667$ and $\tau=0.65$

(J51) $\beta=0.66$, $\gamma=7.5$ and $\tau=0.65$

(J52) $\beta=0.66$, $\gamma=9.375$ and $\tau=0.65$

—▲— load case 1

—●— load case 2

—■— load case 3

(J53) $\beta=0.66$, $\gamma=11.538$ and $\tau=0.65$

(J54) $\beta=0.66$, $\gamma=13.636$ and $\tau=0.65$

(J55) $\beta=0.66$, $\gamma=16.667$ and $\tau=0.65$

(J56) $\beta=0.65$, $\gamma=7.5$ and $\tau=0.65$

—▲— load case 1

—●— load case 2

—■— load case 3

(J57) $\beta=0.75, \gamma=9.375$ and $\tau=0.65$

(J58) $\beta=0.65, \gamma=11.538$ and $\tau=0.65$

(J59) $\beta=0.75, \gamma=13.636$ and $\tau=0.65$

(J60) $\beta=0.75, \gamma=16.667$ and $\tau=0.65$

—▲— load case 1

—●— load case 2

—■— load case 3

APPENDIX E LOAD-DISPLACEMENT CURVES FOR S460 GAP K-JOINTS

(J1) $\beta=0.5$, $\gamma=7.5$ and $\tau=1$

(J2) $\beta=0.5$, $\gamma=9.35$ and $\tau=1$

(J3) $\beta=0.5$, $\gamma=11.538$ and $\tau=1$

(J4) $\beta=0.5$, $\gamma=13.636$ and $\tau=1$

—▲— load case 1

—●— load case 2

—■— load case 3

(J5) $\beta=0.5$, $\gamma=16.676$ and $\tau=1$

(J6) $\beta=0.58$, $\gamma=7.5$ and $\tau=1$

(J7) $\beta=0.58$, $\gamma=9.375$ and $\tau=1$

(J8) $\beta=0.58$, $\gamma=11.538$ and $\tau=1$

—▲— load case 1

—●— load case 2

—■— load case 3

(J9) $\beta=0.58$, $\gamma=13.636$ and $\tau=1$

(J10) $\beta=0.58$, $\gamma=16.676$ and $\tau=1$

(J11) $\beta=0.66$, $\gamma=7.5$ and $\tau=1$

(J12) $\beta=0.66$, $\gamma=9.375$ and $\tau=1$

—▲— load case 1

—●— load case 2

—■— load case 3

(J13) $\beta=0.66$, $\gamma=11.538$ and $\tau=1$

(J14) $\beta=0.66$, $\gamma=13.636$ and $\tau=1$

(J15) $\beta=0.66$, $\gamma=16.667$ and $\tau=1$

(J16) $\beta=0.75$, $\gamma=7.5$ and $\tau=1$

—▲— load case 1

—●— load case 2

—■— load case 3

(J17) $\beta=0.75, \gamma=9.375$ and $\tau=1$

(J18) $\beta=0.75, \gamma=11.538$ and $\tau=1$

(J19) $\beta=0.75, \gamma=13.636$ and $\tau=1$

(J20) $\beta=0.75, \gamma=16.667$ and $\tau=1$

—▲— load case 1

—●— load case 2

—■— load case 3

(J21) $\beta=0.5$, $\gamma=7.5$ and $\tau=0.8$

(J22) $\beta=0.5$, $\gamma=9.375$ and $\tau=0.8$

(J23) $\beta=0.5$, $\gamma=11.538$ and $\tau=0.8$

(J24) $\beta=0.5$, $\gamma=13.636$ and $\tau=0.8$

—▲— load case 1

—●— load case 2

—■— load case 3

(J25) $\beta=0.5$, $\gamma=16.667$ and $\tau=0.8$

(J26) $\beta=0.58$, $\gamma=7.5$ and $\tau=0.8$

(J27) $\beta=0.58$, $\gamma=9.375$ and $\tau=0.8$

(J28) $\beta=0.58$, $\gamma=11.538$ and $\tau=0.8$

—▲— load case 1

—●— load case 2

—■— load case 3

(J29) $\beta=0.58$, $\gamma=13.636$ and $\tau=0.65$

(J30) $\beta=0.58$, $\gamma=16.676$ and $\tau=0.8$

(J31) $\beta=0.66$, $\gamma=7.8$ and $\tau=0.8$

(J32) $\beta=0.66$, $\gamma=9.375$ and $\tau=0.8$

—▲— load case 1

—●— load case 2

—■— load case 3

(J33) $\beta=0.66$, $\gamma=11.538$ and $\tau=0.8$

(J34) $\beta=0.66$, $\gamma=13.636$ and $\tau=0.8$

(J35) $\beta=0.66$, $\gamma=16.667$
 $\tau=0.8$

(J36) $\beta=0.75$, $\gamma=7.5$ $\tau=0.8$

—▲— load case 1

—●— load case 2

—■— load case 3

(J37) $\beta=0.75$, $\gamma=9.375$ and $\tau=0.8$

(J38) $\beta=0.75$, $\gamma=11.538$ and $\tau=0.8$

(J39) $\beta=0.75$, $\gamma=13.636$ and $\tau=0.8$

(J40) $\beta=0.75$, $\gamma=16.667$ and $\tau=0.8$

—▲— load case 1

—●— load case 2

—■— load case 3

(J41) $\beta=0.5$, $\gamma=7.5$ and $\tau=0.65$

(J42) $\beta=0.5$, $\gamma=9.375$ and $\tau=0.65$

(J43) $\beta=0.5$, $\gamma=11.538$ and $\tau=0.65$

(J44) $\beta=0.5$, $\gamma=11.636$ and $\tau=0.65$

—▲— load case 1

—●— load case 2

—■— load case 3

(J45) $\beta=0.5$, $\gamma=16.667$ and $\tau=0.65$

(J46) $\beta=0.58$, $\gamma=7.5$ and $\tau=0.65$

(J47) $\beta=0.58$, $\gamma=9.375$ and $\tau=0.65$

(J48) $\beta=0.58$, $\gamma=11.538$ and $\tau=0.65$

—▲— load case 1

—●— load case 2

—■— load case 3

(J49) $\beta=0.58$, $\gamma=13.636$ and $\tau=0.65$

(J50) $\beta=0.58$, $\gamma=16.667$ and $\tau=0.65$

(J51) $\beta=0.66$, $\gamma=7.5$ and $\tau=0.65$

(J52) $\beta=0.66$, $\gamma=9.375$ and $\tau=0.65$

—▲— load case 1

—●— load case 2

—■— load case 3

(J53) $\beta=0.66$, $\gamma=11.538$ and $\tau=0.65$

(J54) $\beta=0.66$, $\gamma=13.636$ and $\tau=0.65$

(J55) $\beta=0.66$, $\gamma=16.667$ and $\tau=0.65$

(J56) $\beta=0.65$, $\gamma=7.5$ and $\tau=0.65$

—▲— load case 1

—●— load case 2

—■— load case 3

(J57) $\beta=0.75$, $\gamma=9.375$ and $\tau=0.65$

(J58) $\beta=0.65$, $\gamma=11.538$ and $\tau=0.65$

(J59) $\beta=0.75$, $\gamma=13.636$ and $\tau=0.65$

(J60) $\beta=0.75$, $\gamma=16.667$ and $\tau=0.65$

—▲— load case 1

—●— load case 2

—■— load case 3

APPENDIX F LOAD-DISPLACEMENT CURVES FOR S690 GAP K-JOINTS

(J1) $\beta=0.5$, $\gamma=7.5$ and $\tau=1$

(J2) $\beta=0.5$, $\gamma=9.35$ and $\tau=1$

(J3) $\beta=0.5$, $\gamma=11.538$ and $\tau=1$

(J4) $\beta=0.5$, $\gamma=13.636$ and $\tau=1$

—▲— load case 1

—●— load case 2

—■— load case 3

(J5) $\beta=0.5$, $\gamma=16.676$ and $\tau=1$

(J6) $\beta=0.58$, $\gamma=7.5$ and $\tau=1$

(J7) $\beta=0.58$, $\gamma=9.375$ and $\tau=1$

(J8) $\beta=0.58$, $\gamma=11.538$ and $\tau=1$

—▲— load case 1

—●— load case 2

—■— load case 3

(J9) $\beta=0.58$, $\gamma=13.636$ and $\tau=1$

(J10) $\beta=0.58$, $\gamma=16.676$ and $\tau=1$

(J11) $\beta=0.66$, $\gamma=7.5$ and $\tau=1$

(J12) $\beta=0.66$, $\gamma=9.375$ and $\tau=1$

—▲— load case 1

—●— load case 2

—■— load case 3

(J13) $\beta=0.66$, $\gamma=11.538$ and $\tau=1$

(J14) $\beta=0.66$, $\gamma=13.636$ and $\tau=1$

(J15) $\beta=0.66$, $\gamma=16.667$ and $\tau=1$

(J16) $\beta=0.75$, $\gamma=7.5$ and $\tau=1$

—▲— load case 1

—●— load case 2

—■— load case 3

(J17) $\beta=0.75$, $\gamma=9.375$ and $\tau=1$

(J18) $\beta=0.75$, $\gamma=11.538$ and $\tau=1$

(J19) $\beta=0.75$, $\gamma=13.636$ and $\tau=1$

(J20) $\beta=0.75$, $\gamma=16.667$ and $\tau=1$

—▲— load case 1

—●— load case 2

—■— load case 3

(J21) $\beta=0.5$, $\gamma=7.5$ and $\tau=0.8$

(J22) $\beta=0.5$, $\gamma=9.375$ and $\tau=0.8$

(J23) $\beta=0.5$, $\gamma=11.538$ and $\tau=0.8$

(J24) $\beta=0.5$, $\gamma=13.636$ and $\tau=0.8$

—▲— load case 1

—●— load case 2

—■— load case 3

(J25) $\beta=0.5$, $\gamma=16.667$ and $\tau=0.8$

(J26) $\beta=0.58$, $\gamma=7.5$ and $\tau=0.8$

(J27) $\beta=0.58$, $\gamma=9.375$ and $\tau=0.8$

(J28) $\beta=0.58$, $\gamma=11.538$ and $\tau=0.8$

—▲— load case 1

—●— load case 2

—■— load case 3

(J29) $\beta=0.58$, $\gamma=13.636$ and $\tau=0.65$

(J30) $\beta=0.58$, $\gamma=16.676$ and $\tau=0.8$

(J31) $\beta=0.66$, $\gamma=7.8$ and $\tau=0.8$

(J32) $\beta=0.66$, $\gamma=9.375$ and $\tau=0.8$

—▲— load case 1

—●— load case 2

—■— load case 3

(J33) $\beta=0.66$, $\gamma=11.538$ and $\tau=0.8$

(J34) $\beta=0.66$, $\gamma=13.636$ and $\tau=0.8$

(J35) $\beta=0.66$, $\gamma=16.667$ and $\tau=0.8$

(J36) $\beta=0.75$, $\gamma=7.5$ and $\tau=0.8$

—▲— load case 1

—●— load case 2

—■— load case 3

(J37) $\beta=0.75$, $\gamma=9.375$ and $\tau=0.8$

(J38) $\beta=0.75$, $\gamma=11.538$ and $\tau=0.8$

(J39) $\beta=0.75$, $\gamma=13.636$ and $\tau=0.8$

(J40) $\beta=0.75$, $\gamma=16.667$ and $\tau=0.8$

—▲— load case 1

—●— load case 2

—■— load case 3

(J41) $\beta=0.5$, $\gamma=7.5$ and $\tau=0.65$

(J42) $\beta=0.5$, $\gamma=9.375$ and $\tau=0.65$

(J43) $\beta=0.5$, $\gamma=11.538$ and $\tau=0.65$

(J44) $\beta=0.5$, $\gamma=11.636$ and $\tau=0.65$

—▲— load case 1

—●— load case 2

—■— load case 3

(J45) $\beta=0.5$, $\gamma=16.667$ and $\tau=0.65$

(J46) $\beta=0.58$, $\gamma=7.5$ and $\tau=0.65$

(J47) $\beta=0.58$, $\gamma=9.375$ and $\tau=0.65$

(J48) $\beta=0.58$, $\gamma=11.538$ and $\tau=0.65$

—▲— load case 1

—●— load case 2

—■— load case 3

(J49) $\beta=0.58$, $\gamma=13.636$ and $\tau=0.65$

(J50) $\beta=0.58$, $\gamma=16.667$ and $\tau=0.65$

(J51) $\beta=0.66$, $\gamma=7.5$ and $\tau=0.65$

(J52) $\beta=0.66$, $\gamma=9.375$ and $\tau=0.65$

—▲— load case 1

—●— load case 2

—■— load case 3

(J53) $\beta=0.66$, $\gamma=11.538$ and $\tau=0.65$

(J54) $\beta=0.66$, $\gamma=13.636$ and $\tau=0.65$

(J55) $\beta=0.66$, $\gamma=16.667$ and $\tau=0.65$

(J56) $\beta=0.65$, $\gamma=7.5$ and $\tau=0.65$

—▲— load case 1

—●— load case 2

—■— load case 3

(J57) $\beta=0.75$, $\gamma=9.375$ and $\tau=0.65$

(J58) $\beta=0.65$, $\gamma=11.538$ and $\tau=0.65$

(J59) $\beta=0.75$, $\gamma=13.636$ and $\tau=0.65$

(J60) $\beta=0.75$, $\gamma=16.667$ and $\tau=0.65$

—▲— load case 1

—●— load case 2

—■— load case 3

APPENDIX G NON-DIMENSIONAL ULTIMATE LOAD VERSUS β , and τ ; AND STRENGTH RATIO VERSUS β τ γ

Load case 1

Load case 2

APPENDIX H FAILURE MODE OF GAP K-JOINTFailure Mode- Load Case 3, $\gamma=7.5$ Failure Mode- Load Case 3, $\gamma=9.375$

Failure Mode- Load Case 3, $\gamma=11.538$ Failure Mode- Load Case 3, $\gamma=13.636$

Failure Mode- Load Case 3, $\gamma=16.667$

$\tau=1$

$\beta=0.5$		non-dimensional strength		strength ratio	
joint no	γ	LC2	LC1	LC2	LC1
J1	7.5	19.62	13.85	1.20	0.94
J2	9.375	22.00	14.71	1.26	0.93
J3	11.538	21.33	13.50	1.15	0.80
J4	13.636	21.65	13.36	1.11	0.76
J5	16.667	19.83	10.61	0.95	0.57

$\beta=0.58$		non-dimensional strength		strength ratio	
joint no	γ	LC2	LC1	LC2	LC1
J6	7.5	22.09	16.43	1.14	0.92
J7	9.375	22.15	15.65	1.07	0.82
J8	11.538	24.21	15.88	1.10	0.78
J9	13.636	21.84	13.91	0.94	0.65
J10	16.667	22.47	2849257.47	0.91	0.56

$\beta=0.66$		non-dimensional strength		strength ratio	
joint no	γ	LC2	LC1	LC2	LC1
J11	7.5	22.93	18.40	1.02	0.87
J12	9.375	23.45	17.73	0.97	0.79
J13	11.538	24.16	17.01	0.94	0.71
J14	13.636	24.28	15.88	0.90	0.63
J15	16.667	22.69	13.72	0.79	0.51

$\beta=0.75$		non-dimensional strength		strength ratio	
joint no	γ	LC2	LC1	LC2	LC1
J16	7.5	24.59	20.95	0.95	0.85
J17	9.375	24.95	20.96	0.90	0.80
J18	11.538	25.76	20.28	0.88	0.73
J19	13.636	25.66	19.17	0.83	0.65
J20	16.667	24.97	17.60	0.76	0.56

$\tau=0.8$

$\beta=0.5$		non-dimensional strength		strength ratio	
joint no	γ	LC2	LC1	LC2	LC1
J21	7.5	19.30	13.91	1.18	0.94
J22	9.375	21.46	14.60	1.23	0.92
J23	11.538	20.99	13.44	1.13	0.80
J24	13.636	21.36	13.17	1.09	0.75
J25	16.667	19.72	10.42	0.95	0.55

$\beta=0.58$		non-dimensional strength		strength ratio	
joint no	γ	LC2	LC1	LC2	LC1
J26	7.5	21.43	16.10	1.10	0.90
J27	9.375	20.99	15.47	1.05	0.81
J28	11.538	21.36	15.65	1.08	0.77
J29	13.636	19.72	13.78	0.93	0.65
30	16.667	21.43	12.60	0.90	0.56

$\beta=0.66$		non-dimensional strength		strength ratio	
joint no	γ	LC2	LC1	LC2	LC1
J31	7.5	22.42	18.00	0.99	18.00
J32	9.375	23.19	17.47	0.96	17.47
J33	11.538	24.01	16.79	0.93	16.79
J34	13.636	24.14	15.67	0.89	15.67
J35	16.667	22.77	13.37	0.79	13.37

$\beta=0.75$		non-dimensional strength		strength ratio	
joint no	γ	LC2	LC1	LC2	LC1
J36	7.5	23.83	20.45	0.92	0.83
J37	9.375	24.64	20.52	0.89	0.78
J38	11.538	25.46	19.80	0.87	0.71
J39	13.636	25.43	18.64	0.82	0.63
J40	16.667	24.76	16.96	0.75	0.54

$\tau=0.65$

$\beta=0.5$		non-dimensional strength		strength ratio	
joint no	γ	LC2	LC1	LC2	LC1
J41	7.5	18.75	13.57	1.15	0.92
J42	9.375	20.68	14.30	1.18	0.91
J43	11.538	20.51	13.35	1.10	0.79
J44	13.636	20.76	13.05	1.06	0.74
J45	16.667	19.45	10.43	0.94	0.56

$\beta=0.58$		non-dimensional strength		strength ratio	
joint no	γ	LC2	LC1	LC2	LC1
J46	7.5	20.59	15.61	1.06	0.88
J47	9.375	21.20	15.21	1.02	0.80
J48	11.538	23.09	15.34	1.04	0.76
J49	13.636	21.45	13.58	0.92	0.64
J50	16.667	21.84	12.36	0.88	0.55

$\beta=0.66$		non-dimensional strength		strength ratio	
joint no	γ	LC2	LC1	LC2	LC1
J51	7.5	21.83	17.40	0.97	0.82
J52	9.375	22.68	17.10	0.94	0.76
J53	11.538	23.51	16.45	0.92	0.69
J54	13.636	23.69	15.43	0.88	0.61
J55	16.667	22.47	13.17	0.78	0.49

$\beta=0.75$		non-dimensional strength		strength ratio	
joint no	γ	LC2	LC1	LC2	LC1
J56	7.5	23.15	19.60	0.90	0.80
J57	9.375	24.31	19.90	0.88	0.76
J58	11.538	25.11	19.27	0.85	0.69
J59	13.636	25.11	17.98	0.81	0.61
J60	16.667	24.57	15.89	0.75	0.51

J1	355	LC3	DF	J2	355	LC3	DF	J3	355	LC3	CF	J4	355	LC3	CF	J5	355	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	460	LC3	DF		460	LC3	DF		460	LC3	CF		460	LC3	CF		460	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	690	LC3	DF		690	LC3	DF		690	LC3	CF		690	LC3	CF		690	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
J21	355	LC3	DF	J22	355	LC3	DF	J23	355	LC3	BF	J24	355	LC3	CF	J25	355	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	460	LC3	DF		460	LC3	DF		460	LC3	DF		460	LC3	CF		460	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	690	LC3	DF		690	LC3	DF		690	LC3	DF		690	LC3	CF		690	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
J41	355	LC3	DF	J42	355	LC3	BF	J43	355	LC3	BF	J44	355	LC3	BF	J45	355	LC3	BF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	460	LC3	DF		460	LC3	BF		460	LC3	BF		460	LC3	BF		460	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	690	LC3	DF		690	LC3	BF		690	LC3	BF		690	LC3	BF		690	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
J6	355	LC3	CF	J7	355	LC3	CF	J8	355	LC3	CF	J9	355	LC3	CF	J10	355	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	460	LC3	CF		460	LC3	CF		460	LC3	CF		460	LC3	CF		460	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	690	LC3	CF		690	LC3	CF		690	LC3	CF		690	LC3	CF		690	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
J26	355	LC3	DF	J27	355	LC3	CF	J28	355	LC3	CF	J29	355	LC3	CF	J30	355	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	460	LC3	DF		460	LC3	CF		460	LC3	CF		460	LC3	CF		460	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	690	LC3	DF		690	LC3	CF		690	LC3	CF		690	LC3	CF		690	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
J46	355	LC3	BF	J47	355	LC3	BF	J48	355	LC3	BF	J49	355	LC3	BF	J50	355	LC3	BF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	460	LC3	DF		460	LC3	BF		460	LC3	BF		460	LC3	CF		460	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	690	LC3	DF		690	LC3	BF		690	LC3	BF		690	LC3	CF		690	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
J11	355	LC3	CF	J12	355	LC3	CF	J13	355	LC3	CF	J14	355	LC3	CF	J15	355	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	460	LC3	CF		460	LC3	CF		460	LC3	CF		460	LC3	CF		460	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	690	LC3	CF		690	LC3	CF		690	LC3	CF		690	LC3	CF		690	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF

J31	355	LC3	CF	J32	355	LC3	CF	J33	355	LC3	CF	J34	355	LC3	CF	J35	355	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	460	LC3	CF		460	LC3	CF		460	LC3	CF		460	LC3	CF		460	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	690	LC3	CF		690	LC3	CF		690	LC3	CF		690	LC3	CF		690	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
J51	355	LC3	BF	J52	355	LC3	BF	J53	355	LC3	BF	J54	355	LC3	BF	J55	355	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	460	LC3	BF		460	LC3	BF		460	LC3	BF		460	LC3	BF		460	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	690	LC3	BF		690	LC3	BF		690	LC3	BF		690	LC3	BF		690	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
J16	355	LC3	CF	J17	355	LC3	CF	J18	355	LC3	CF	J19	355	LC3	CF	J20	355	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	460	LC3	CF		460	LC3	CF		460	LC3	CF		460	LC3	CF		460	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	690	LC3	CF		690	LC3	CF		690	LC3	CF		690	LC3	CF		690	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
J36	355	LC3	CF	J37	355	LC3	CF	J38	355	LC3	CF	J39	355	LC3	CF	J40	355	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	460	LC3	CF		460	LC3	CF		460	LC3	CF		460	LC3	CF		460	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	690	LC3	CF		690	LC3	CF		690	LC3	CF		690	LC3	CF		690	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
J56	355	LC3	BF	J57	355	LC3	BF	J58	355	LC3	BF	J59	355	LC3	BF	J60	355	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	460	LC3	BF		460	LC3	BF		460	LC3	BF		460	LC3	CF		460	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF
	690	LC3	BF		690	LC3	BF		690	LC3	BF		690	LC3	CF		690	LC3	CF
		LC2	CF			LC2	CF			LC2	CF			LC2	CF			LC2	CF
		LC1	CF			LC1	CF			LC1	CF			LC1	CF			LC1	CF

APPENDIX I QUICK CHECK TABLE FOR CORRECTION FACTOR

S690 chord force is 50% of the yield capacity of the chord						
β	τ	γ				
		7.5	9.375	11.538	13.636	16.667
0.5	1	0.94	0.93	0.80	0.76	0.57
	0.8	0.94	0.92	0.80	0.75	0.55
	0.65	0.92	0.91	0.79	0.74	0.56
0.58	1	0.92	0.82	0.78	0.65	0.56
	0.8	0.90	0.81	0.77	0.65	0.56
	0.65	0.88	0.80	0.76	0.64	0.55
0.66	1	0.87	0.79	0.71	0.63	0.51
	0.8	0.85	0.77	0.70	0.62	0.50
	0.65	0.82	0.76	0.69	0.61	0.49
0.75	1	0.85	0.80	0.73	0.65	0.56
	0.8	0.83	0.78	0.71	0.63	0.54
	0.65	0.80	0.76	0.69	0.61	0.51

S690 chord force is 30% of the yield capacity of the chord						
β	τ	γ				
		7.5	9.375	11.538	13.636	16.667
0.5	1	1.20	1.26	1.15	1.11	0.95
	0.8	1.18	1.23	1.13	1.09	0.95
	0.65	1.15	1.18	1.10	1.06	0.94
0.58	1	1.14	1.07	1.10	0.94	0.91
	0.8	1.10	1.05	1.08	0.93	0.90
	0.65	1.06	1.02	1.04	0.92	0.88
0.66	1	1.02	0.97	0.94	0.90	0.79
	0.8	0.99	0.96	0.93	0.89	0.79
	0.65	0.97	0.94	0.92	0.88	0.78
0.75	1	0.95	0.90	0.88	0.83	0.76
	0.8	0.92	0.89	0.87	0.82	0.75
	0.65	0.90	0.88	0.85	0.81	0.75

S690 chord is without force						
β	τ	γ				
		7.5	9.375	11.538	13.636	16.667
0.5	1	1.43	1.59	1.45	1.70	1.51
	0.8	1.17	1.44	1.40	1.63	1.46
	0.65	1.07	1.23	1.33	1.43	1.45
0.58	1	1.45	1.31	1.56	1.41	1.60
	0.8	1.31	1.27	1.47	1.41	1.52
	0.65	1.12	1.21	1.29	1.31	1.42
0.66	1	1.31	1.33	1.36	1.36	1.37
	0.8	1.23	1.25	1.29	1.30	1.29
	0.65	1.09	1.18	1.22	1.23	1.20
0.75	1	1.14	1.19	1.23	1.23	1.24
	0.8	1.10	1.14	1.17	1.17	1.16
	0.65	1.02	1.06	1.10	1.10	1.10

S460 chord force is 50% of the yield capacity of the chord						
β	τ	γ				
		7.5	9.375	11.538	13.636	16.667
0.5	1	0.94	0.92	0.84	0.79	0.66
	0.8	0.93	0.91	0.83	0.79	0.66
	0.65	0.91	0.89	0.84	0.78	0.66
0.58	1	0.90	0.84	0.80	0.71	0.64
	0.8	0.88	0.82	0.79	0.71	0.63
	0.65	0.85	0.80	0.77	0.70	0.63
0.66	1	0.87	0.82	0.76	0.70	0.59
	0.8	0.84	0.80	0.75	0.70	0.59
	0.65	0.81	0.78	0.73	0.68	0.58
0.75	1	0.86	0.85	0.78	0.72	0.63
	0.8	0.83	0.83	0.77	0.70	0.62
	0.65	0.79	0.79	0.74	0.68	0.59

S460 chord force is 30% of the yield capacity of the chord						
β	τ	γ				
		7.5	9.375	11.538	13.636	16.667
0.5	1	1.22	1.24	1.17	1.15	1.02
	0.8	1.19	1.21	1.16	1.13	1.02
	0.65	1.15	1.17	1.17	1.11	1.01
0.58	1	1.13	1.10	1.10	1.02	0.95
	0.8	1.09	1.07	1.08	1.00	0.94
	0.65	1.05	1.04	1.05	0.98	0.93
0.66	1	1.01	0.99	0.98	0.97	0.87
	0.8	0.99	0.98	0.97	0.96	0.86
	0.65	0.96	0.96	0.95	0.94	0.85
0.75	1	0.95	0.93	0.91	0.88	0.83
	0.8	0.93	0.92	0.90	0.88	0.83
	0.65	0.90	0.90	0.89	0.86	0.81

S460 chord is without force						
β	τ	γ				
		7.5	9.375	11.538	13.636	16.667
0.5	1	1.41	1.63	1.67	1.72	1.68
	0.8	1.25	1.41	1.55	1.66	1.63
	0.65	1.08	1.22	1.33	1.39	1.41
0.58	1	1.48	1.54	1.59	1.56	1.61
	0.8	1.27	1.40	1.52	1.49	1.54
	0.65	1.11	1.18	1.24	1.29	1.33
0.66	1	1.30	1.35	1.39	1.44	1.40
	0.8	1.23	1.28	1.32	1.37	1.33
	0.65	1.06	1.09	1.14	1.19	1.26
0.75	1	1.14	1.19	1.23	1.26	1.27
	0.8	1.10	1.16	1.18	1.20	1.21
	0.65	1.01	1.04	1.07	1.10	1.12

S355 chord force is 50%of the yield capacity of the chord						
β	τ	γ				
		7.5	9.375	11.538	13.636	16.667
0.5	1	0.97	0.94	0.86	0.83	0.70
	0.8	0.95	0.93	0.86	0.83	0.69
	0.65	0.93	0.92	0.85	0.82	0.69
0.58	1	0.92	0.88	0.83	0.74	0.68
	0.8	0.89	0.87	0.83	0.73	0.68
	0.65	0.87	0.85	0.81	0.73	0.67
0.66	1	0.90	0.87	0.78	0.75	0.63
	0.8	0.88	0.86	0.77	0.75	0.63
	0.65	0.84	0.83	0.76	0.73	0.62
0.75	1	0.93	0.88	0.87	0.75	0.66
	0.8	0.90	0.86	0.85	0.74	0.65
	0.65	0.86	0.83	0.81	0.73	0.64

S355 chord force is 30%of the yield capacity of the chord						
β	τ	γ				
		7.5	9.375	11.538	13.636	16.667
0.5	1	1.26	1.26	1.21	1.20	1.09
	0.8	1.22	1.24	1.19	1.20	1.08
	0.65	1.17	1.20	1.17	1.18	1.06
0.58	1	1.15	1.15	1.13	1.04	1.02
	0.8	1.12	1.13	1.12	1.03	1.02
	0.65	1.07	1.09	1.09	1.02	1.00
0.66	1	1.04	1.05	1.00	1.01	0.92
	0.8	1.02	1.04	1.00	1.00	0.91
	0.65	0.99	1.01	0.98	0.98	0.90
0.75	1	1.02	0.96	0.99	0.92	0.87
	0.8	1.00	0.95	0.97	0.91	0.87
	0.65	0.95	0.93	0.95	0.90	0.86

S355 chord is without force						
β	τ	γ				
		7.5	9.375	11.538	13.636	16.667
0.5	1	1.56	1.75	1.75	1.81	1.66
	0.8	1.34	1.53	1.61	1.75	1.62
	0.65	1.17	1.32	1.38	1.49	1.49
0.58	1	1.54	1.62	1.67	1.59	1.70
	0.8	1.37	1.53	1.58	1.53	1.62
	0.65	1.16	1.23	1.32	1.36	1.43
0.66	1	1.35	1.43	1.45	1.52	1.46
	0.8	1.28	1.36	1.38	1.45	1.39
	0.65	1.10	1.16	1.22	1.29	1.31
0.75	1	1.21	1.24	1.32	1.33	1.35
	0.8	1.17	1.20	1.28	1.26	1.27
	0.65	1.06	1.10	1.15	1.19	1.21