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STRESS AND STRAIN CONCENTRATIONS OF COMPLETELY OVERLAPPED TUBULAR JOINTS

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**SCHOOL OF CIVIL & ENVIRONMENTAL ENGINEERING
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2005

Stress and Strain Concentrations of Completely Overlapped Tubular Joints

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A thesis submitted to the Nanyang Technological University
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SUMMARY

The failure of offshore steel jackets is mainly due to fatigue at joint intersections of members. There are several methods available for fatigue design of tubular joints but the hot spot stress (HSS) approach is regarded as the most widely used method. This design method depends on the accurate prediction of stress concentration factor (SCF) for tubular joints under general load conditions. In the past, numerical and experimental works have extensively been carried out to study the SCF of simple tubular joints. Many SCF parametric equations have been developed and proposed for fatigue design of the joints. However, the recommendation for fatigue design of completely overlapped tubular joints is still insufficiently covered in the codes and guides.

In the current research, a uni-planar completely overlapped tubular joint specimen is tested under lap brace axial (AX), in-plane bending (IPB), out-of-plane bending (OPB) and combined loadings to determine the SCF at the joint intersections of the chord and through brace and the through brace and lap brace. The experimental results revealed that the curve fittings of the strain values within the extrapolation region are fairly linear. The maximum SCF occurs at the saddle of through brace near the lap brace for the joint under AX and OPB, and at the crown heel of lap brace for the joint under IPB. For the joint under combined loadings, the maximum HSS can occur between the crown and the saddle of members.

In the finite element (FE) analysis, both 8-node thick shell and 20-node solid elements are suitable for modelling the joint specimen. The stress component perpendicular to the weld toe is employed to calculate the SCF at the joint intersections. A convergence study is carried out to confirm the mesh density of both thick shell and solid FE models for analysis. The SCF obtained from the FE models agree very well with those from the test specimen. In view of the computational effort, the 8-node thick shell FE model is more suitable for the parametric study of completely overlapped tubular joints.

A total of 5184 FE models of the joint are created with wide range of geometrical parameters. The results of the parametric study revealed that for the joint under AX loading, the SCF of the joint increases with increasing β_{CT} , τ_{TL} , ξ_T , γ_C and γ_T , but decreases with increasing τ_{CT} and θ . For the joint under IPB loading, the SCF increases with increasing β_{CT} and τ_{TL} , but decreases with increasing θ . For the joint under OPB loading, the SCF increases with increasing β_{CT} , τ_{TL} , ξ_T , γ_C and γ_T , but decreases with increasing β_{TL} , τ_{CT} and θ .

A set of parametric equations is subsequently proposed for predicting the SCF of completely overlapped tubular joints under basic load cases. The equations are verified against the acceptance criteria of Fatigue Guidance Review Panel. The assessment of the proposed equations is based on the database of FE analysis and test results. The assessment confirms the reliability of the proposed equations for predicting the SCF of completely overlapped tubular joints under both basic and combined loadings.

The completely overlapped joint is commonly interpreted as two separate T/Y joints. However, the use of the existing T/Y-joint parametric equations for predicting the SCF of completely overlapped joints under AX and OPB loadings is found to be inappropriate. The T/Y-joint parametric equations only predict reasonably well the SCF of the completely overlapped tubular joint under IPB loading. For this load condition, the gap size variation does not have any significant effect on the SCF of the joint.

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LIST OF SYMBOLS

Notation

A	Area of cross section
F	Axial load
M	Bending moment
I	Moment of inertia of cross section
y	Distance from neutral axis to point considered
a, b	Finite element size
E	Young's modulus
$l_{r, \min}$	Minimum distance measured from weld toe
$l_{r, \max}$	Maximum distance measured from weld toe
K_A	Stress concentration factor under axial load
K_{Bi}	Stress concentration factor under in-plane bending load
K_{Bo}	Stress concentration factor under out-of-plane bending load
f_{ax}	Nominal stress under axial load
f_{ipb}	Nominal stress under in-plane bending load
f_{opb}	Nominal stress under out-of-plane bending load
M_i	In-plane bending moment
M_o	Out-of-plane bending moment
L	Chord length
l	Brace length
D	Chord diameter
d	Brace diameter
R	Chord radius
r	Brace radius
T	Chord wall thickness
t	Brace wall thickness
g	Gap length between braces
l_T	Through brace length
l_L	Lap brace length

d_T	Through brace diameter
d_L	Lap brace diameter
t_T	Through brace wall thickness
t_L	Lap brace wall thickness
t_w	Weld thickness
g_T	Gap length between chord and lap brace
$g_{\min}$	Minimum gap distance
$g_{\max}$	Maximum gap distance
α	Chord length parameter ($2L/D$)
β	Brace-to-chord diameter ratio (d/D)
γ	Chord radius-to-wall thickness ratio ($D/2T$)
τ	Brace-to-chord wall thickness ratio (t/T)
ξ	Gap size-to-chord diameter ratio (g/D)
α_C	Chord length parameter ($2L/D$)
α_T	Through brace length parameter ($2l_T/d_T$)
β_{CT}	Through brace-to-chord diameter ratio (d_T/D)
β_{TL}	Lap brace-to-through brace diameter ratio (d_L/d_T)
γ_C	Chord radius-to-wall thickness ratio ($D/2T$)
γ_T	Through brace radius-to-wall thickness ratio ($d_T/2t_T$)
τ_{CT}	Through brace-to-chord wall thickness ratio (t_T/T)
τ_{TL}	Lap brace-to-through brace wall thickness ratio (t_L/t_T)
ξ_T	Gap size-to-through brace diameter ratio (g_T/d_T)
θ	Angle between chord and through brace
$\sigma_{\max}$	Maximum stress
$\sigma_{\min}$	Minimum stress
$\Delta\sigma$	Stress range ($= \sigma_{\max} - \sigma_{\min}$)
σ_G	Structural stress
σ_N	Nominal stress
σ_{N-A}	Nominal stress under axial load
σ_{N-I}	Nominal stress under in-plane bending load
σ_{N-O}	Nominal stress under out-of-plane bending load

σ_{HSS}	Hot spot stress
ε_{N}	Nominal strain
ε_{HSS}	Hot spot strain
ν	Poisson's ratio
Ψ	Dihedral angle

Abbreviation

3D	Three-dimensional
2D	Two-dimensional
AX	Axial
IPB	In-plane bending
OPB	Out-of-plane bending
HSS	Hot spot stress(es)
HSSN	Hot spot strain(s)
SCF	Stress concentration factor(s)
SCF_{ax}	Maximum SCF under AX load
SCF_{ipb}	Maximum SCF under IPB load
SCF_{opb}	Maximum SCF under OPB load
SNCF	Strain concentration factor(s)
FE	Finite element
CH	Chord
TC	Through brace near chord
TL	Through brace near lap brace
LP	Lap brace

CHAPTER 1

INTRODUCTION

1.1 Background

There are various types and sizes of offshore structures installed around the world for the production and processing of oil and gas. These offshore structures are mainly designed to satisfy the functional needs in providing supports for drilling operations of oil and gas beneath the sea. Owing to the complexity of structural configuration, the expenditure of cost on materials, fabrication man-hours and facilities is enormous. The offshore structures are required to be designed to withstand all the possible loadings which may be encountered during the designed life span. In general, the loadings imposed on the structure can be classified as functional, environmental and incidental loads. The functional loads are the self weight of structures, ballast water, equipment and facilities, buoyancy and foundation reactions. The environmental loads are the loads caused by winds, waves and currents. The incidental loads are mainly from the accidental impact of vessels and seismic activities.

Fatigue is regarded as one of the major problems that cause the degradation of offshore steel structures in the long-term integrity. A significant feature of fatigue is that the applied load is not necessarily large to cause immediate failure at members and joints of structures. Instead, the failure of structural components occurs after a certain number of load fluctuations have been experienced. The Health & Safety Executive (HSE) statistic data of the North Sea steel structures revealed that the fatigue damage of offshore steel jackets was the most frequent single cause of repairs which represented about 25% of all repair works (Chang and Dover 1999a). Thus, the fatigue failure is one of the most important failure modes to be considered in the analysis for offshore steel structures.

The offshore steel jacket is a truss-work structure consisting of tubular members resting on the seabed. It supports several modules on topside with piles running

inside the main legs of structure and penetrating beneath the seabed (Fig. 1.1). This type of steel jacket is designed to resist lateral loading and to provide stability and levelling when the topside is placed. It should be noted that most of the 2500 steel jackets in the world are located in shallow waters and only about 50 are located at water depths over 100 metres (Almar 1985).

As shown in Fig. 1.1, the offshore steel jacket is mainly composed of tubular members and joints. The use of tubular members for offshore steel jackets is due to their good mechanical properties, pleasing appearance and small exposed area. Tubular connections are the joints between the main and the secondary members of steel jackets. The main member is usually larger in diameter which is known as chord, while the secondary member of smaller size tube is known as brace. A tubular joint is formed by welding one or more braces onto the surface of the chord. It should be noted that tubular joints appear in a great variety of shapes and design types. They may be classified according to the geometric configurations, transfer action of loads among braces, and types of design. For the purpose of design, Underwater Engineering Group (UEG 1985) classified the tubular joints into four (4) categories as follow.

- Simple welded joint
- Complex welded joint
- Cast steel joint
- Composite joint

Some of the different types of tubular joints are illustrated in Fig. 1.2. For fatigue analysis of tubular joints, it is more convenient to separate the applied loads on the member into three basic load cases namely axial load (AX), in-plane bending (IPB) and out-of-plane bending (OPB) (Fig. 1.3). Each load case has its particular distribution of stresses along the joint intersection of members. The geometrical parameters of typical simple welded joints are shown in Fig. 1.4.

Simple tubular joints are the most widely used connection details for the construction of offshore steel jackets in the industry (Fig. 1.5(a)). The popularity is

attributed to the available parametric equations and direct calculation methods to assess the joint capacity. However, with the progressive development of offshore exploration in deeper waters and arctic conditions, the offshore platforms are now becoming larger and more demanding. As a result, the use of simple tubular joints for larger offshore steel jackets may not be appropriate and becomes uneconomical as long thick wall cans are necessary at every connection in order to avoid the overlapping of structural members.

Partially overlapped tubular joints were first used for the construction of offshore steel jackets in the Gulf of Mexico in the early sixties (Graff 1981). K-joints with identical brace diameters are the most common types. Because part of the applied load can directly be transferred between the two braces through their common weld, the chord wall thickness can effectively be reduced, as shown in Fig. 1.5(b). However, the advantage of this joint configuration is somewhat offset by the higher fabrication costs incurred in double coping the end of the overlapping brace (Morgan and Lee 1997). Nevertheless, the main uses of the partially overlapped joints in the present industry are to minimize the joint eccentricities and thus the unfavourable moments acting in the chord.

Completely overlapped tubular joints are not commonly used for the construction of offshore steel jackets in the industry. This joint is usually adopted for secondary members to provide additional clearances to prevent clashes when other joint configurations are undesirable. For the completely overlapped tubular joint, the two joints have to be assessed together and the short segment of the through brace plays a significant role in controlling the joint behaviour (Fig. 1.5(c)). This type of joint is commonly treated as two separate T/Y-joint configurations and continued with the use of parametric equations for simple joints design as specified in the recommendations. Since the loads are predominantly transferred between the braces, the punching shear stresses on the chord wall can be reduced. As commended by Wardenier et al. (1991), the completely overlapped tubular joint configurations demonstrated merits to provide easy fabrication and better static strength than simple gap and partially overlapped joints. However, the understanding on the

behaviour of this type of joint is very limited and the existing recommendations do not adequately address the fatigue design of the joint for offshore structures. Hence, there is a need to extensively investigate the stress and strain concentrations of the joint in the current research.

1.2 Objectives of Current Research

The objectives of the current research on the stress and strain concentrations of completely overlapped tubular joints are as follow:

- (1) Investigate the stress and strain distributions at the joint intersections under basic and combined load cases experimentally and numerically.
- (2) Examine in details the influence of geometrical parameters on the stress concentration factor (SCF) of the joint under axial load, in-plane and out-of-plane bending.
- (3) Develop parametric equations to predict the SCF of the joint under axial load, in-plane and out-of-plane bending.
- (4) Identify the relationship of SCF with simple T/Y joints.

1.3 Scope of Current Research

The current research involves experimental and numerical investigation of stress and strain concentrations of completely overlapped tubular joints under both basic and combined load cases. In Chapter 1, an introduction of the use of tubular joints in the offshore construction industry is presented. The objectives as well as the originality of the current research are also given. In Chapter 2, a literature of past research findings on simple and partially overlapped tubular joints is reviewed in details. The basic understanding on the stress and strain concentrations of completely overlapped tubular joints is included.

Chapter 3 shows the experimental set up of the completely overlapped joint specimen on the test rig. The stress and the strain distributions and concentrations at the joint intersections are studied. The test data is also used for the verification and calibration of the finite element (FE) model. In Chapter 4, the FE modelling technique of the joint is described. A convergence study is conducted for optimizing the mesh density of the model for numerical analysis. In Chapter 5, a comparison of SCF of the joint under both basic and combined load cases is made between the experimental and the numerical study. The influence of various geometrical parameters on the SCF of completely overlapped joints is presented in Chapter 6.

Based on the data obtained from the FE analysis, a set of parametric equations is developed to predict the SCF of completely overlapped tubular joints under AX, IPB and OPB loading, as presented in Chapter 7. The reliability of the proposed equations is verified against the requirements of Fatigue Guidance Review Panel. A comparison of SCF between the completely overlapped joints and the simple T/Y joints is conducted and the detailed results are presented in Chapter 8. Finally, in Chapter 9, a conclusion is drawn with respect to the objectives of the current research project. The future research programmes on the behaviour of the completely overlapped tubular joint is also highlighted.

1.4 Originality of Current Research

The recent numerical study on the stress concentration of completely overlapped tubular joints by Ghossein et al. (2003) at Nanyang Technological University was based on 8-node thick-shell FE analysis of 64 models. As 20-node solid element is strongly recommended for modelling the joint in the investigation of stress concentration, there is a need to assess the accuracy of using the 8-node thick shell element for the FE model. The construction of 64 models is not sufficient to numerically examine the completely overlapped tubular joint with seven geometric parameters. Furthermore, the previous study was only based on the joint with lap brace axial compression. In the current research programme, the SCF of completely overlapped joints under both basic and combined load cases are examined in details.

It is important to realize that the completely overlapped tubular joint is commonly misinterpreted as two separate T/Y joints. Some researchers recommended the through brace of the joint to be effectively considered as a chord member. Some design engineers used the existing simple T/Y-joint parametric equations to predict the SCF of completely overlapped joints. However, as shown in the current research study, the interpretation of completely overlapped tubular joint as two simple T/Y joints may not be appropriate as the SCF predicted by the existing parametric equations always found to be too conservative.

Fig. 1.1 A typical offshore steel jacket structure

Fig. 1.2 Different types of tubular joints

Fig. 1.3 Basic load cases for tubular joints

Fig. 1.4 Geometrical parameters of tubular joints

(a) Simple gap joint

(b) Partially overlapped joint

(c) Completely overlapped joint

Fig. 1.5 Load transfer systems for simple gap, partially overlapped and completely overlapped tubular joints

CHAPTER 2

LITERATURE REVIEW

2.1 Fatigue Concepts of Tubular Joints

Fatigue can be defined as damage that results in fracture of structural elements after a sufficient number of stress cycles within the elastic limit of material. A significant feature of fatigue damage is that the load is not necessarily to be large to cause an immediate failure on the structural components. In general, the failure occurs after a certain number of load cycles that the structural elements have been experienced. In other word, it is a failure mode after an accumulated damage of the material attains at a critical load level. The process of fatigue failure actually goes through several stages. Each stage is characterized by the nature of the fatigue process from initial state of crack initiation to crack propagation and then to final fracture of materials.

The fatigue life prediction of welded components requires an appropriate stress analysis. The dominant parameter in the fatigue analysis is the stress range which can be defined as the stress difference between the maximum stress ($\sigma_{\max}$) and the minimum stress ($\sigma_{\min}$). The mean or the peak levels of loading are found to be less significant as compared to the range of stresses. In the case of constant amplitude loading, the stress range is defined as follow.

$$\Delta\sigma = \sigma_{\max} - \sigma_{\min} \quad (2-1)$$

The constant amplitude of stress histories is illustrated in Fig. 2.1(a). For welded structures, the variable amplitude loading (Fig. 2.1(b)) is more common than the constant amplitude loading.

An S-N curve for assessing the fatigue performance of tubular joints is commonly used in offshore structures. The S-N curve is a plot of the stress range versus the number of load cycles to failure. A typical S-N curve for structural hollow section

connections is shown in Fig. 2.2. The primary advantage of using these curves is that it allows the use of a single S-N curve and thickness correction for all hollow section connections. The validity of wall thickness for circular hollow section connections is limited to 50 mm. The effect of wall thickness of hollow sections can partly be explained by fracture mechanics and partly by technological and statistical factors. It can be seen from Fig. 2.2 that the thicker walled elements have less fatigue behaviour than the thinner walled elements. As a result, the thicker walled elements would fail at lower number of load cycles than the thinner walled elements in the same hot spot stress range. It is important to realize that the low fatigue strength of welded tubular joints will result in high stress concentration at the weld toe of the joint. Therefore, a proper design of welded tubular joints against fatigue failures must be based on the magnitude of SCF, which is defined as the ratio of the highest stress to the member nominal stress obtained from the global stress analysis.

2.2 Stresses Distribution in Tubular Joints

Stresses in welded tubular joints are arisen from three main conditions. They are the basic structural response of the joint to the applied load (nominal stress), the need to maintain compatibility between the members (geometric stress) and the highly localized deformations at the joint intersection between the brace and the chord (local stress) (DEn 1984a). A typical stresses distribution of a tubular joint is shown in Fig. 2.3.

(a) Nominal stress

The nominal stress (σ_N) is calculated using the simple beam theory and the superposition method without taking accounts the geometric discontinuity and other localizing effects. The equation to determine the nominal stress is as follow.

$$\sigma_N = \frac{F}{A} + \frac{M}{Z} \quad (2-2)$$

where,

F : applied axial load

A : cross-sectional area

M : applied bending moment

Z : modulus of cross section

If fatigue at the welded attachment is to be considered, the nominal stress would be determined in the region including the effect of weld detail but excluding the influence of the attachment on the stress distribution (IIW 1995). In the current research on the stress and strain concentrations of completely overlapped joints, the load is applied at the end of the lap brace. The nominal stress of the lap brace is therefore used to determine the SCF of the joint.

(b) Geometric stress

The geometric stress (σ_G) is the structural stress resulted from the difference in deformation between the brace and the chord when the joint is subjected to loading. It is also known as the Hot Spot Stress (HSS) (IIW 1999). The difference in deformation causes the tube wall to bend elastically so that the brace and the chord can remain in contact at the joint. This will also cause a distribution of nominal membrane stresses around the brace circumference. The geometric stress is the most commonly adopted stress in the research of stress concentrations for welded tubular joints. In the current research, the SCF of completely overlapped joints under basic load cases is defined as the ratio of the HSS at the weld toe to the nominal stress of the lap brace.

(c) Local stress

The local stress arises owing to the effect of weld quality such as the local notch of the weld toe, the undercut and the lack of fusion. As the weld quality is dependent on the workmanship and the use of welding methods, it is very difficult to incorporate a correction factor in the calculation to account for these effects. Hence, the weldment is considered acceptable if the minimum requirements in the specification such as AWS (2000) are satisfied. Despite the

fact that the local stress is not propagated far through the wall thickness, a local region of three-dimensional stress can occur. It should be noted that the sharp corner at the weld toe and the great angle of the weld profile can cause the local stress increases (DEn 1984a). For the stress concentration of completely overlapped joints, only the HSS is considered and the local stress is excluded.

2.3 Hot Spot Stress Method

There are several methods available to determine the fatigue resistance of welded connections (Zhao et al. 2001). The commonly used methods are the classification, the hot spot stress (HSS), the local notch stress and the fracture mechanics. The classification method is based purely on the nominal stresses. The hot spot and the local notch stress methods are based on the hot spot stresses at weld toe and the local peak notch stresses at weld root respectively. However, the HSS method is regarded to be the most practical approach as it relates different structural geometry of the joints to the same S-N curve by introducing SCF for fatigue calculation (Marshall 1987). Hence, the HSS method is adopted in the current study to determine the stress concentrations of completely overlapped tubular joints.

It should be noted that the points of higher localized stresses at the joint intersection of members are known as “hot-spots” and the associated stresses are known as HSS. Although HSS method is used in many design guidelines, the definition of HSS in tubular joints has been subject to attention. Based on a large amount of data on stress analysis of tubular joints obtained by UKOSRP programme, Irvine (1981) suggested that the HSS should be defined as “*the linear stress distribution outside the notch region on a tubular joint extrapolated to the weld toe to obtain experimental values of tubular joint hot spot stress*”. Additionally, rosette gauges were recommended to be used to obtain the maximum principal stresses so that the stresses could be conservatively extrapolated to obtain the HSS.

On the other hand, DEn (1984a) recommended that “*...stress is used to describe the fatigue performance of a tubular joint. It should incorporate the effects of overall*

tube geometry (i.e. the relative sizes of the brace and chord) but omit the concentrating influence of the weld geometry which changes around the periphery of any brace/chord intersection and, although weld profiling is specified by codes of practice such as AWS D1.1, it will in practice vary from joint to joint". As stated, the greatest value of the maximum principle stress extrapolated to the weld toe through the local stress region around the brace and the chord periphery conservatively determines the HSS. Thus, the general definition of HSS can be defined as the peak value of geometric stress at the weld toe.

However, van Wingerde et al. (1996) proposed a more precise approach based on the HSS method to replace the previous nominal stress and HSS approaches for the fatigue analysis of steel connections. The following guideline was proposed for the fatigue design of hollow section connections.

(a) Type of stress

Only stresses perpendicular to the weld toe were considered.

(b) Extrapolation approach

A quadratic extrapolation was recommended to exclude local stress concentrations. This extrapolation approach accurately described a nonlinear stress increase near the weld toe as more data was obtained. However, for most simple tubular joints except overlapped K-joints, the stress increase within the extrapolation region was linear. Hence, a linear extrapolation was sufficient for simple T/Y joints to determine the HSS at the weld toe.

(c) Position of HSS at weld toe

The exact position of SCF at weld toe had to be established to determine the total HSS caused by axial forces and in-plane bending moments of members. For tubular joints, these positions were located at the crown and saddle of the chord and the braces.

It should be noted that the HSS is the extrapolated stress at the weld toe. For simple welded joints, the SCF is defined as the HSS divided by the nominal stress of the loaded brace that causes the HSS. Therefore, the total HSS at the weld toe is a function of all the nominal stresses in the members of the connection multiplied by their corresponding SCF.

The International Standards Organization (ISO 1998) considered HSS as the highest stress at a joint. However, it should be noticed that tubular joints did not normally have a single isolated 'hot spot'. For multi-brace joints with low SCF, the 'hot spot' could be extended over a considerable length of welds on the brace and the chord. Thus, Geometric Stress Range (GSR) was introduced in the code to replace the HSS. The basis of GSR concept was to capture stresses in the proximity of weld toe to determine the fatigue life of the joint excluding the local microscopic effects such as sharp notch, undercut and crack-like defects at the weld toe. This concept was based on the different structural geometry on a common basis which allowed the use of a single S-N curve (Baerheim et al. 1996). The GSR was defined as follow:

$$\text{GSR} = \text{SCF} \times \text{Nominal Brace Stress Range} \quad (2-3)$$

In the latest IIW fatigue design guide (IIW 1999), the use of the HSS range has a similar concept as the HSS method proposed by van Wingerde et al. (1996) with procedure described below.

1. The HSS range at a specific location of a joint under a load case was the product of the nominal stress range and the corresponding SCF.
2. The HSS ranges at the same location of a joint under combined load cases could be superimposed.
3. If the position of the maximum HSS in a member under a relevant loading could not be determined, the maximum SCF must be applied for all the points around the periphery of the member at a joint.
4. The HSS ranges must be calculated for both the chord and the brace.

From the above, it could be seen that the principal stress and the stress perpendicular to the weld toe were the two commonly used stresses to determine the HSS at the weld toe. For simple welded joints, owing to the stiffening effect of the weld and the member wall thickness, the principal stress tended to divert to a perpendicular direction as it moved toward the weld toe. In another words, the ratio of the principal stress to the stress perpendicular to the weld toe decreased with the distance to the weld (Romeijn et al. 1992, Smedley and Fisher 1991). It was important to note that the direction of the maximum principal stress at the crown toe and crown heel positions was always perpendicular to the weld toe. However, in certain location of tubular joints, the geometric stress perpendicular to the weld toe may not be the maximum principal stress (DEn 1984a). In this case, one of the above methods should be chosen to calculate the HSS.

Van Wingerde et al. (1996) also summarized the advantages of using the stress perpendicular to the weld toe to determine the HSS.

1. The stresses perpendicular to the weld toe could easily be measured using simple strain gauges.
2. All the stress components were still required to be separately considered, even when the principal stresses were determined
3. The hot spot principal stresses caused by various load cases could not be superimposed.
4. The stress component perpendicular to the weld toe was enlarged by the presence of global weld shape and notch. This view was supported by the direction of crack growth.

Based on the advantages described above, the stress perpendicular to the weld toe is adopted in the current research to determine the HSS of completely overlapped tubular joints. The definition of HSS at the joint intersection of the chord and the brace is given in Fig. 2.4. The SCF is defined as the ratio of the hot spot stress (σ_{HSS}) to the nominal stress (σ_N), while the SNCF is defined as the ratio of the hot spot strain (ϵ_{HSS}) to the nominal strain (ϵ_N) as shown below.

$$SCF = \frac{\sigma_{HSS}}{\sigma_N} \quad (2-4)$$

$$SNCF = \frac{\varepsilon_{HSS}}{\varepsilon_N} \quad (2-5)$$

2.4 Extrapolation Methods

Owing to the effect of localized weld shape and notch stresses, HSS cannot be directly obtained by using the strain gauges at the vicinity of the weld toe. Thus, the extrapolation of stresses within the specific region is adopted to determine the HSS. Generally, the extrapolation region is defined by specified minimum and maximum distance measured from the weld toe of the joint. The region is defined in such a way that the effect of the geometry of the weld and the condition at the weld toe are not included in the HSS (Romeijn and Wardenier 1994).

It was recommended by DEn (1984a) that “*the maximum extent of local notch region is defined as $0.2(rt)^{1/2}$ (and not less than 4 mm), where r and t are the brace outside radius and thickness respectively*”. The dependence of $(rt)^{1/2}$ was derived from the study of bending stresses in tubes (Clayton and Irvine 1978). This parameter was modified according to the analysis of large-scale tests on tubular joints in ECSC and UKOSRP projects. Based on DEn guidance, the requirements for the extrapolation region of the chord and the brace can be seen in Fig. 2.5.

An alternative approach to determine the HSS was to specify a minimum strain gauge distance of $0.4t$ from the weld toe as highlighted by Gurney (1979). Gurney’s recommended distance was actually derived from the finite element analysis of simple fillet weld joints in plates. The region of the notch stress was a function of plate thickness. Swensson et al. (1986) and Wardenier (1982) commented that for joints with pronounced 3-dimensional effects, Gurney’s recommendation described the notch region better than DEn (Smedley and Fisher 1991). ECSC Working Group

III eventually adopts the requirement of 0.4t minimum distance as the extrapolation region with details summarized in Table 2.1 (Romeijn and Wardenier 1994). The requirements for the extrapolation region to determine the HSS near the weld toe of the joint are also included in IIW (1999) and CIDECT (Zhao et al. 2001).

The commonly used extrapolation approaches to determine the HSS at the weld toe of tubular joints are the linear, quadratic and combined extrapolation methods. The use of the linear and the quadratic extrapolation methods is illustrated in Fig. 2.6. For the combined extrapolation method, a parabolic equation is first determined for the stresses in and around the extrapolation region. The stresses derived from this equation are subsequently analyzed at points from which a linear extrapolation to the weld toe is drawn. It should be noted that the quadratic and the combined methods require more data to be plotted in order to accurately determine the non-linear stress increase near the weld toe of the joint.

It is interesting to note that DEn (1984a) recommended a linear extrapolation method to determine the HSS at the weld toe for simple T- and X-joints and suggested a non-linear geometric stress distribution for Y- and K-joints. Romeijn et al. (1993) suggested that for non-linear stress gradients, a combined extrapolation method should be used to determine the SCF at locations of a joint between the crown and the saddle of members.

2.5 Stress Analysis Methods for Tubular Joints

In offshore tubular structures, one of the most influential factors affecting the fatigue life is the magnitude of stresses acting at the joint. A full stress analysis of a tubular joint is usually carried out in association with the measurement of stress distributions at the joint intersection of the chord and braces. The hot spot locations are subsequently determined to calculate the SCF at the weld toe of the joint. In the past, the commonly used techniques for the stress analysis of tubular joints are the static strain gauge test on large-scale specimens; photo-elastic study of weld profiles

as featured on the steel model tubular joints; static strain gauge test on acrylic models and finite element analysis of tubular joints.

(a) Large-scale test

Experimental study of large-scale specimens was an important approach for stress analysis of tubular joints. This method involved the fabrication of steel joint specimens with geometrical properties within the range of practical limits. The experimental study based on large-scale tests was not commonly seen as the cost to fabricate a full-scale specimen and a rig with large capacity could be expensive. In the past, small-scale steel models were the most popular test specimens conducted in the laboratory. API RP2A (1993) used the results obtained from the small-scale tests to derive S-N curves for the design of tubular joints under fatigue loading (Dimitrakis et al. 1995). However, it should be noted that the small-scale steel model was subjected to size effects which prevented the results from being directly applied for practical sizes of joint design. Furthermore, a scaled down test specimen would have a large weld size which caused stiffening effects in the region around the joint intersection (Chiew et al. 1996).

For the steel model tests, the strain gauges were commonly used to measure the strain distributions at the joint intersections under various loadings. Two or more strain gauges were bonded in the region of stress linearity so that the strain values could be extrapolated to determine the hot spot strain (HSSN) at the weld toe. The extrapolation method required the innermost strain gauge to be placed as close to the weld toe as possible but outside the notch region to reduce extrapolation errors. The outermost strain gauge was placed in the region where the decay of geometric stress was still linear (Irvine 1981). In general, the experimental results were used for the verification and calibration of analytical methods and proposed empirical parametric equations. Additionally, the experimental results could also provide background of the theoretical analysis for better understanding on the stress and strain distribution of tubular joints.

(b) Photo-elastic test

A three-dimensional photo-elastic test was regarded as the most efficient experimental approach for the analysis of complex joints with peak local stresses at weld toes. The test method was particularly suitable for systematic studies in relation to weld profiles, grind repairs and other specialized items for design (Gibstein 1987). The test models were made of epoxy resin materials. The stress freezing technique was utilized to determine the stress distribution at the joint intersection. Since the stresses could be obtained at any location in the region of the joint including the weld, the photo-elastic test was commented no problem with the stress extrapolation to determine the hot spot stress at the weld toe.

(c) Acrylic model test

The use of acrylic model to determine the stress distribution at the joint intersection showed several advantages.

1. The acrylic material had low Young's modulus which means that a small load was sufficient to produce a given strain.
2. The manufacture cost of the acrylic model was less expensive and the process of producing the model was rapid. The brace end could easily be machined by a single point cutter and bonded onto the chord surface.
3. The welds could be added by gluing the acrylic 'welds' with required shape.
4. The strain gauges could be fitted at locations which were inaccessible before the acrylic members were assembled to form a joint.

However, the main disadvantage of using the acrylic materials was that it crept under load and thus the strain values must be recorded as soon as the load was applied. The acrylic model of the joint usually had no weld and the hot spot strains were extrapolated using two strain gauges to the weld toe. The use of the acrylic model was commented to be reliable, cheap and flexible (Irvine 1981).

(d) Finite element analysis

The use of finite element (FE) model to simulate the joint was considered an expensive approach in the past owing to the complexity of the joint intersections

which required a large amount of work to create the meshes. Greste and Clough (1967) first developed the FE program for the stress analysis of tubular connections. In the early eighties, the FE analysis of tubular joints underwent a spectacular and rapid development, and today it is the most commonly used technique to investigate the stress concentrations of tubular joints. There are numerous general purpose and specialized FE packages available in the market. These FE packages are suitable for the stress analysis of tubular joints such as MARC, ABAQUS, NASTRAN, PAFEC, SAP, ANSYS, DIANA, I-DEAS and PATRAN.

The FE program could only effectively and reliably be used for stress analysis of tubular joints with a good background in terms of geometry of members, type of finite elements and density of meshes. Additionally, other important aspects such as boundary conditions, use of integration schemes and modelling technique of weld zones should carefully be studied (IIW 1995). In the early research, the high computational cost hindered the use of FE method to determine the stress distribution of tubular joints based on three-dimensional (3D) analysis. Much attention was directly towards the use of thin shell elements in the model (Clayton and Irvine 1978). Generally speaking, the shell elements were particularly suitable for solving elastic structural stresses based on shell theory. For modelling the tubular joints, it was easier to generate two-dimensional (2D) shell than 3D solid models. However, it should be noted that the shear deformation through the thickness with the use of thin shell elements could be omitted for thin walled structural analysis (Chang and Dover 1999a).

The modelling technique with the use of shell element was that the tubular joint was modelled as intersecting cylindrical tubes at mid-surfaces of the walls with the mid-plane stress equivalent to the membrane stress. The top and the bottom surface stresses were the superimposed membrane and shell bending stresses. Apparently, the shortcoming of thin shell elements for modelling was that the weld toe of the tubular joint could not be modelled. As a result, the stress obtained at the joint intersection of the brace and the chord was subjected to large errors. Furthermore, the wall thicknesses of the brace and the chord at the joint intersection could be

overlapped as the meshes of the shell element were based on the mid-surfaces of each member. It was recommended that a more accurate FE analysis of tubular joints should be carried out with the use of thick shell elements (Hu and Long 1986). Unlike the thin shell element, the thick shell element considered the transverse shear deformation in the direction of wall thickness in the FE analysis. The thick shell element was commented to perform better than the thin shell element as the distance between the adjacent intersections of members was small and the significant shear stresses near the weld toe were measured (IIW 1995).

Apart from the use of shell elements, solid elements were highly recommended for modelling the tubular joints with three dimensional stress and deformation fields. The curved iso-parametric 20-noded element was the most popular solid element used in the FE model. This element was able to accurately model the profile of the weld toe as a sharp notch at the joint intersection. The solid FE model provided more accurate and detailed stress behaviour near the joint intersection than the simple 2D shell model. For applications which required the detailed information in the weld vicinity and through wall thickness of the members such as the fracture mechanism of the small defects in tubular joints, the solid element was essentially needed for modelling the structural component for analysis (Chang and Dover 1999a). However, it should be noted that the generation of the mesh with the use of solid element at the joint intersection could be more laborious and the cost of running a full 3D FE stress analysis could be very high.

Alternatively, a tubular joint could be modelled with the use of both shell and solid elements (Chen 1987, 1988, Romeijn et al. 1992). In this modelling technique, the solid element was used for the meshes at the brace and chord intersection, while the shell elements were employed outside the intersection region. This method provided a compromise between the accuracy of analysis and the cost of computer programme. In order to ensure compatibility, the modelling of tubular joints at the transition region from the solid to the shell element was obviously significant. Since the shell and the solid elements were commonly used for the FE analysis of tubular joints, it was necessary to select the most proper and efficient element type. The

choice of element type for the tubular joint analysis depended on the geometry of the joint and the purpose for which the results of the analysis were required. Thus, it was a compromise between the accuracy of representation of the elements and the efficiency of the computational time (Chang and Dover 1999b).

2.6 Stress Concentration of Simple Tubular Joints

Simple tubular joints are the most widely used connection details in offshore construction industry. For the past three decades, many sets of SCF parametric equations have been established by researchers to determine the hot spot stress of simple tubular joints. Kuang et al. (1977) derived SCF parametric equations for T/Y-, K- and KT-joints based on a modified thin shell FE program. In their analysis, the joints were modelled without taking account the weld and the stresses were measured at the mid-surface of the wall thickness of members. The equations were derived based on a mean fit of the database without considering the exact location of the hot spot stress. As the equations covered only a few joint configurations, the SCF obtained were commented to be less realistic. However, the Kuang et al. equations pioneered the numerical analysis and set a benchmark for the investigation of stress concentrations for tubular joints based on the FE method (Robert and Radenkovic 1978).

On the other hand, Wordsworth and Smedley (1978) and Wordsworth (1981) derived parametric equations based on test results of acrylic models of tubular joints without the fillet weld. The test models covered a wide geometrical range of tubular joint configurations such as T/Y-, X-, K-, KT- and V-joints. For SCF on the chord, the equations were commented to yield results comparable with database. On the brace, the SCF was determined based on a factor applied on the chord SCF. As a result, the SCF on the brace was found to be conservatively predicted in comparison to that measured in the test. It was noted that for the joint under axial and out-of-plane loading, the equations under predicted the SCF at the saddle of tubular joints with large β and γ due to significant degree of weld cut-back.

UEG (1985) proposed a set of SCF parametric equations based on Wordsworth and Smedley equations (1978) and Wordsworth (1981). A minor modification with factors was incorporated in the equations to accurately predict the SCF of tubular joints with high β (> 0.6) and γ (> 20). These modification factors were derived based on the comparison of the predicted and the measured results of both static and fatigue studies. It was found that the UEG equations yielded more conservative SCF than the Wordsworth and Smedley equations.

In the same year, Efthymiou and Durkin (1985) also derived a series of SCF equations which covered T/Y- and K-joint configurations. Over 150 tubular joints were analyzed using the PMBSHELL FE program which was based on the 3D shell elements to better describe the effect of weld elements at the joint intersections. The hot spot SCF were determined based on the maximum principal stresses linearly extrapolated to the weld toe of the joint. The short chord effects and the fixity of boundary conditions were also considered. In 1988, Efthymiou (1988) published a comprehensive set of parametric equations to predict SCF of T/Y-, X-, K- and KT-joints. These SCF equations were developed based on the influential functions as well as the carry-over effects from additional loaded braces of K- and KT-joints. It should be noted that Efthymiou equations were independent of the chord end boundary conditions and thus the equations yielded maximum SCF at the weld toe of the chord and the brace.

In the nineties, Hellier et al. (1990) developed SCF equations with objective to improve the accuracy of estimating the life span of tubular joints based on fracture mechanics. The equations only covered T/Y-joint configurations. A comprehensive FE study was conducted using thin shell elements subjected to axial, in-plane and out-of-plane loading. The derived parametric equations estimated the SCF at the saddle and crown locations as well as the maximum SCF at the joint intersection. However, it was noted that the SCF of the joint models with large β were found to be less accurate with the use of thin shell element. The SCF equations proposed by Hellier et al. (1990) were only applicable for joints with $\beta < 0.8$.

Lloyds Register developed equations (Smedley and Fisher 1991) based on database of test results of 69 steel and acrylic models. The joints with $\beta=1.0$ were considered with the cut-back of weld at the saddle. The equations were based on a mean fit of data, which used a design factor of one as a standard deviation from the mean value. As a result, the predicted SCF was found to be 20% to 30% higher than the mean value. These equations calculated only the SCF at the saddle and the crown of the chord and the brace. The maximum SCF between the saddle and the crown at the joint intersection was not accounted for. The short chord effects were considered in the equations which referenced to those proposed by Efthymiou (1988).

Recently, Morgan and Lee (1997, 1998a and 1998b) derived a series of parametric equations for tubular joints under axial, in-plane and out-of-plane loading. The equations covered a comprehensive range of geometrical parameters for K-joints. A thin shell FE program was used for modelling without taking account weld fillets. The stresses were measured at the mid-surface of the wall thickness of members. The comparison of SCF showed that the equations proposed by Morgan and Lee (1997, 1998a and 1998b) performed better than the equations derived by Efthymiou (1988) and Lloyds Register (Smedley and Fisher 1991). For the joint under bending moment loadings, the database of the FE results was used to develop the parametric equations to determine the SCF at the key locations of the joint on both the outer and the inner surfaces of the chord. With reference to fatigue calculation based on fracture mechanics, the proposed equations by Morgan and Lee (1997, 1998a and 1998b) were commented to provide accurate and safe fatigue life estimates.

The equations proposed by Chang and Dover (1999a, 1999b) were able to predict the SCF distribution along the perimeter of the joint intersection. A thin shell FE analysis was conducted on 330 models of T/Y-, X- and DT-joints subjected to six different modes of loading. Based on 2000 FE analysis results, the parametric equations were derived using the 2D regression methodology. The criteria of the Fatigue Guidance Review Panel (MATSU 1996) for acceptance were used to assess the reliability of the proposed SCF equations. The assessment indicated that the SCF predicted by the proposed equations were found to be conservative.

Karamanos et al. (2000a, 2000b) carried out a comprehensive study on the stress concentrations of gap K-joints. Extensive FE analysis based on 20-node solid elements was conducted to obtain the SCF at the joint intersection of the chord and the braces. The weld profile was simulated accordingly to the requirement specified in AWS provisions. The results covered a wide range of geometrical parameters and load conditions with emphasis on SCF location and carry-over effect. Based on the FE results, a set of design equations and graphs was established with reference to IIW recommendation (1995) to determine the SCF of gap K-joints. A methodology was also proposed for hot spot stress fatigue design of gap K-joints.

Van Wingerde et al. (2001) derived a set of simplified design equations and graphs to predict the SCF of K- and KK-joint configurations. These design equations and graphs were developed based on the rational hot spot stress approach for hollow section connections presented by van Wingerde et al. (1995, 1997). Despite the simplified equations yielded conservative SCF, the design process with these equations was found to be straightforward. The graphs were included in their research to allow for accurate and easy prediction of SCF. Additionally, the S-N lines with thickness correction were also derived for the design of welded hollow section connections.

2.7 Stress Concentration of Partially Overlapped Tubular Joints

In the offshore industry, overlapped joints are generally referred as the joints with two braces partially overlapped. These joints are widely perceived of having higher properties than simple joints owing to a more efficient load transfer system of axial load components between the braces. However, the use of partially overlapped joints in the offshore tubular structures presents less cost savings over simple gap joints because of the double coping at the lap brace end before joining the through brace and the chord.

To derive parametric equations for estimating the SCF of overlapped K-joints, Veritas carried out a systematic research between 1982 and 1984 to verify the

validity of hot spot definitions and the applicability of S-N curves for overlapping joints (Almar 1985). It was commented that,

1. The overlapping K-joints with $\beta < 0.85$ could be designed to provide improved fatigue properties compared to simple gap joints.
2. The stress level of the concealed part of the overlapped joint was found to be moderate and did not represent hazard to the safety of the connection.
3. The maximum SCF of the overlapping K-joints occurred at the brace as the crack was detected to be developed.
4. The failure pattern of the overlapping joint was the brace failure.

Efthymiou and Durkin (1985) carried out extensively the stress analysis of 100 K-joints using PMBSHELL FE program. Apart from the investigation of simple gap K-joints, partially overlapped K-joints were also considered. The SCF parametric equations of the partially overlapped K-joints were developed under both balanced and unbalanced load cases. For the overlapped joints with identical inclination of braces, the highest stresses were found to occur on or adjacent to the through brace under balance axial load condition. This was found to be similar to the overlapped N-joints with large inclination of the brace with respect to the chord. The SCF on the chord side was considerably reduced with the overlapping of braces. However, the SCF on the brace side could be reduced or increased depending on the degree of overlapping between the two braces. It was noted that in some overlapped joints, the highest stresses occurred at the weld toes of the “hidden” weld.

Gibstein (1987) studied the stress concentrations of 19 K-joints with $\beta = 1$ under five (5) different load cases. A set of parametric equations was derived to estimate the SCF of gap K-joints as well as overlapping K-joints with and without stiffeners. However, the investigation did not cover the full range of geometric parameters of the joints. From the study, it was concluded that,

1. The improvement of SCF could not simply be achieved by overlapping the braces if stiffeners were provided.
2. The overlapping of braces with or without stiffeners was not recommended as the SCF obtained could be higher. Furthermore, the hot spot location on

the chord side could be in the concealed part of the joint.

3. The overlapping of braces was generally justified for the joint designed for particular conditions such as the conductor frames of an offshore steel jacket which the out-of-plane bending was critical.

Moe (1987) performed the stress analysis and the fatigue tests of two overlapped K-joints subjected to balanced axial loads. The experimental results revealed that the peak stresses occurred somewhere in between the crown heel and the saddle of the through brace, as well as in between the crown (unhidden weld) and the saddle of the lap brace. It was noted that the K(N)-joint specimen yielded slightly higher SCF than the K-joint specimen with the maximum SCF on the brace side. It was important to realize that the crack initiation and development on the brace side could lead to a more critical failure mode than that on the chord member. Furthermore, the brace failures of the overlapped joints would lead to shorter fatigue life.

Lalani and Forsyth (1987) also investigated a series of elastic and fatigue tests on overlapping K(N)-joints. A total of ten (10) elastic and six (6) fatigue tests were undertaken. The hot spot stress approach was used to determine the SCF of the joints. For the joint under balanced axial load case, the maximum SCF occurred at the crown heel of the 45 degree diagonal brace. Similarly, for the brace perpendicular to the chord, the maximum SCF occurred at the crown position. However, it was noted that the peak stress of the joint did not necessarily occur at the crown or the saddle position of members. It was further commented that the use of the current design approaches for overlapping joints provided accurate SCF but conservative estimate of fatigue life.

2.8 Stress Concentration of Completely Overlapped Tubular Joints

The use of completely overlapped joints at connections of offshore steel jackets is not common in practice. This type of joint configuration is usually given less priority than simple gap and partially overlapped joints. For a completely

overlapped tubular joint, the two braces are completely overlapped before joining the chord. A gap size is maintained on the through brace surface between the outer surfaces of the chord and the lap brace to facilitate welding and non-destructive testing. Owing to the load distribution among members at the joint, the stress interaction between the chord and through brace as well as the through brace and lap brace has to be assessed together with the short segment of the through brace. For the past decades, the understanding on the fatigue behaviour of completely overlapped joints is limited to the following.

DEn (1984b)

When braces are overlapped, the amount of overlap should not be less than 20%. If overlap is larger or complete, the overlapped brace is effectively a chord member and must be considered on such in the analysis of the joint.

API RP2A (2000)

Connections in which load transfer is accomplished by overlap; a minimum stress concentration factor of 6.0 should be used in the brace member, in lieu of additional analysis.

Gho et al. (2003) only investigated the SCF of the joint at the crown and the saddle locations of members under lap brace axial loading. No information is currently available to assess the stress distribution of completely overlapped joints under in-plane and out-of-plane bending as well as combined loadings. The existing recommendations do not adequately address the fatigue design of completely overlapped tubular joints for offshore steel jackets. The previous recommendation by DEn (1984b) suggested that the through brace of the joint could be taken as a chord member in the analysis. However, this has been proven to be inappropriate in the study on the stress and strain concentrations of completely overlapped joints by Gho et al. (2003). Their analytical results revealed that by assuming the through brace as a chord member, the maximum SCF of the joint could be too conservative for design. On the other hand, API RP2A (2000) recommended a minimum SCF of six (6) for brace members in the fatigue design of overlapping joints. It is important

to realize that the SCF of six (6) was recommended owing to the lack of test data for fatigue analysis of the completely overlapped tubular joint.

Presently, there are no parametric equations available for fatigue design of completely overlapped tubular joints. An extensive research is therefore essentially needed in this area before the joint configuration could confidently be considered in practice. In the current research, the determination of the stress and the strain concentrations of the completely overlapped joint is the primary focus. Apart from the experimental investigation, a set of parametric equations based on over 5000 FE models is derived to predict the SCF of completely overlapped tubular joint configurations under axial, in-plane and out-of-plane loadings.

Table 2.1 Extrapolation region recommended by IIW (1999) and CIDECT (2001)

CHS chord member		CHS brace member
Crown	Saddle	Crown and saddle
$l_{r, \min} = 0.4T$ $l_{r, \min} \geq 4 \text{ mm}$		$l_{r, \min} = 0.4t$ $l_{r, \min} \geq 4 \text{ mm}$
$l_{r, \max} = 0.4(rtRT)^{1/4}$	$l_{r, \max} = 5^\circ$	$l_{r, \max} = 0.65(rt)^{1/2}$
$l_{r, \min}$ ($l_{r, \max}$): minimum (maximum) distance measured from the weld toe location in a direction perpendicular to the weld toe (for chord member location) or/and a direction parallel to axis of the brace member (for brace member location)

Fig. 2.1 Stress (σ) – Time history

Fig. 2.2 Typical S-N curves for fatigue design of structural hollow section connections (IIW 1999, Zhao et al. 2001)

Fig. 2.3 Stress distributions at joint intersection of chord and brace

Fig. 2.4 Hot spot stress definition for tubular joints (IIW 1999)

Minimum distance

$$a = 0.2(r_1 t_1)^{1/2}, a \geq 4 \text{ mm}$$

Maximum distance

Chord member

Saddle 5°

$$\text{Crown } x_c = 0.4(r_1 t_1 r_0 t_0)^{1/4}$$

Brace member

$$\text{Saddle and crown } x_b = 0.65(r_1 t_1)^{1/2}$$

Fig. 2.5 Extrapolation region defined by DEN (1984a)

Fig. 2.6 Linear and quadratic extrapolation procedures

CHAPTER 3

EXPERIMENTAL STUDY

3.1 Introduction

The experimental investigation on the stress and strain concentrations of completely overlapped tubular joints is very limited. The experiment of a large-scale completely overlapped tubular K(N)-joint conducted by Gho et al. (2003) in the Heavy Structures Laboratory, Nanyang Technological University, only measured the hot spot strains at the crown toe, saddle and crown heel of the chord, through brace and lap brace. The load condition was unbalanced and the joint specimen was subjected to lap brace axial compression. In the current experimental programme, the configuration of the joint specimen is similar to that conducted by Gho et al. (2003) except that the members are different in size and the through brace is inclined 30 degree with respect to the chord. The joint specimen is subjected to loads at the end of lap brace under both basic (AX, IPB and OPB) and combined loadings. These loadings are independently or concurrently applied and are within the elastic limit of material. The main objective of the test is to determine the hot spot strains at the crown heel, saddle and crown toe as well as those in-between the crown heel and saddle and the saddle and crown toe so that the stress concentration factors (SCF) of the completely overlapped tubular joint at these locations can be determined for investigation.

3.2 Experimental Investigation

3.2.1 Description of test rig

A simple beam-column test rig which is housed in the Heavy Structures Laboratory, Nanyang Technological University, is used for testing the completely overlapped tubular joint specimen under both basic and combined loadings. Apart from the experimental investigation, the strain values of the joint specimen obtained in the test are also used for the verification and calibration of numerical FE model.

As shown in Fig. 3.1, the main rig is made up of two steel columns and a steel plate girder. An independent steel column was installed next to the main rig to apply out-of-plane loading on the test specimen. All the steel columns were firmly supported on the 1.3-metre-thick high strength reinforced concrete cellular floor slab with the use of 25 mm diameter holding down bolts. For the main rig, both ends of the plate girder were directly bolted onto the columns. All the steel columns were of structural H-section and had identical geometrical and dimensional properties. A series of bolt holes on the flanges of the columns allowed the height of the plate girder to be adjusted. The spacing of the bolt holes in the longitudinal and transverse directions was 150 mm and 140 mm respectively. In the current experimental set up, the main rig was used for testing the joint under AX and IPB loadings, while the independent column was to support the actuator to exert OPB loading on the joint specimen.

3.2.2 Double-acting hydraulic cylinder

The double-acting hydraulic cylinders were mounted on the test rig to apply loads in three different directions. Two (2) of the hydraulic cylinders were fixed on the main rig to exert AX and IPB loadings and one was on the independent column to apply OPB load on the joint specimen. These cylinders were hydraulic controlled and were capable of generating a maximum static compression and tension of 1000 kN and 440 kN respectively with a maximum stroke of 333.5 mm. The two-speed hydraulic pump with maximum operating pressure of 68.9 N/mm² was utilized to power the hydraulic cylinder. Two (2) of the pumps were manually-operated with 9465 cm³ reservoir capacity. These pumps were incorporated with the double-acting hydraulic cylinders to exert IPB and OPB loadings on the joint specimen. One (1) electric pump with two-speed design was used to power the hydraulic cylinder to exert AX load at the end of lap brace. As the two-speed feature of the pumps provided high oil volume for fast cylinder piston, the number of strokes of the cylinder to achieve the required level of loading could easily be handled and monitored. The hydraulic cylinders on the joint specimen and the detail of the pumps can be seen in Fig. 3.1 and Fig 3.2 respectively.

In the test, the high pressure hydraulic hoses and couplers were used to transport the hydraulic fluid between the hydraulic cylinder and the pump. The shut-off valves were employed to regulate and to cut off the flow of hydraulic fluid in case of emergency. A load cell was attached to every hydraulic cylinder to measure the applied load. Two (2) of the load cells with capacity of 50 kN and coefficient of 0.0163 kN/us were for IPB and OPB loadings, while the 1000 kN capacity load cell with coefficient of 0.5 kN/us was used for AX loading. The detailed configuration of the load cells can be seen in Fig. 3.3. An adapter is provided to firmly connect the hydraulic cylinder with the load cell as shown in Fig. 3.4.

3.2.3 Set up of joint specimen

The definition of the geometrical parameters of the completely overlapped joint is presented in Fig. 3.5. The configuration of the joint specimen on the test rig is shown in Fig. 3.6. The joint specimen comprises a horizontal chord, a 30° diagonal through brace and a vertical lap brace. The geometrical properties and the dimensionless parameters of the joint specimen are summarized in Table 3.1. The joint specimen was designed and fabricated according to the requirements specified by AWS (2000). A full penetration groove weld with standard flat profile was provided at the joint intersections between the tube members. All the members were fabricated from the standard API 5L (1991) Grade B structural steel pipes. From the mill's certificates, the chemical and the mechanical properties of members satisfied the requirements stated in API 5L (1991).

As shown in Fig. 3.6, both ends of the chord and the end of the through brace are welded on the flat plates and directly bolted onto the columns of the test rig. Three (3) pieces of flat plates were welded at the end of lap brace so that the load could be applied in the axial, in-plane and out-of-plane direction respectively. A gap size of 143 mm was allowed on the through brace surface between the outer surfaces of the chord and the lap brace to avoid overlapping of welds between the two joints. The self weight of the joint specimen was fully supported by the rig and transferred down to the floor through the columns. The joint specimen on the test rig was

placed in such a way that the installation, the fabrication and the strain-gauging work could easily be accomplished.

3.2.4 Tensile coupon test

Six (6) strip coupons were flamed cut in the longitudinal direction of the members prior to the test (two coupons for each member). These coupons had dimensions slightly larger than the requirement and were machined cut to the specific size in order to avoid the effect of heat. All the coupons were fabricated in accordance to the requirement specified by BS EN10002-1 (1990). The gauge length of the coupon at the reduced section was 80 mm. An extensometer with a standard gauge length of 50 mm was attached to record the elongation of the coupon during the test. It was removed after 10% yield strain of the coupon was attained to avoid damage. The surface of the coupon was marked to determine the amount of elongation.

The coupon test was carried out in the Protective Engineering Laboratory. The INSTRON 4486 testing machine which utilized a closed loop command with feedback control of rate was used to fracture the coupon. As shown in Fig. 3.7, both ends of the coupon are mechanically flattened without heating so that a firm support is assured. In the test, the bottom device of the testing machine was fixed, while the cross-head was moved upwards with the use of the electrical-mechanical system at a constant speed of 1.5 mm/min. This speed was maintained until the coupon broke into two parts. A displacement control mode was set throughout the test to avoid a sudden acceleration of the cross-head upon yielding of the coupon. The loads and the strains were read via the 300 kN load cell and the extensometer respectively.

Two (2) pieces of single element strain gauges (type FLA-5-11-5L) were bonded on each side of the coupon to calculate the Young's modulus. The stress and the strain relationship of the chord, the through brace and the lap brace of the joint specimen is plotted as shown in Fig. 3.8. The details of the coupon test results for all the members are summarized in Table 3.2.

3.2.5 Strain gauges and accessories

Two (2) specific types of standard foil strain gauges were used to measure the strains on the outer surface of the joint specimen. The strain gauge type FLA-5-11-5L is a general single element of 5 mm length, while FXV-1-11-002LE comprises of five (5) single elements on a common carrier backing, which is used specifically for stress concentration measurement.

Strain gauge type FLA-5-11-5L

A total of 32 strain gauges (FLA-5-11-5L) are placed on the outer surface of the joint specimen as illustrated in Fig. 3.9. Eight (8) pieces of these strain gauges were bonded along the longitudinal axis of the lap brace to measure the nominal stresses and to determine the possible eccentricities. Another 24 pieces were placed near the end plates of the chord and the through brace to determine the end movement.

Two (2) sets of strain gauges (type FLA-5-11-5L) are bonded in the longitudinal direction of the lap brace as depicted in Fig. 3.9. In each set, four (4) strain gauges were positioned at 90° intervals around the perimeter of the lap brace to determine the in-plane and out-of-plane eccentricity. The first and the second sets of the strain gauges were located at 100 mm and 300 mm respectively measured from the end of the lap brace. For the chord and the through brace, the arrangement of the strain gauges was similar to that on the lap brace. For the chord, the four (4) sets of strain gauges were located at 100 mm, 700 mm, 2240 mm, and 2540 mm measured from the end plate. For the through brace, they were located at 100 mm and 650 mm. In order to avoid the raise of stresses due to the discontinuity of members at the joint intersection, the distance between the strain gauge (FLA-5-11-5L) and the weld toe was kept at least three (3) times the member diameter (CIDECT, 2001).

For ease of reference, the strain gauges on the members of the joint specimen were indicated as follow.

- On the lap brace
 - L-a-1, L-a-2, L-a-3 and L-a-4 (100 mm from the end plate)
 - L-b-1, L-b-2, L-b-3 and L-b-4 (300 mm from the end plate)
- On the through brace
 - T-a-1, T-a-2, T-a-3 and T-a-4 (100 mm from the end plate)
 - T-b-1, T-b-2, T-b-3 and T-b-4 (650 mm from the end plate)
- On the chord
 - C-a-1, C-a-2, C-a-3 and C-a-4 (100 mm from the end plate)
 - C-b-1, C-b-2, C-b-3 and C-b-4 (700 mm from the end plate)
 - C-c-1, C-c-2, C-c-3 and C-c-4 (2240 mm from the end plate)
 - C-d-1, C-d-2, C-d-3 and C-d-4 (2540 mm from the end plate)

L, T and C denoted the lap brace, the through brace and the chord respectively. a, b, c and d were the locations of the set of strain gauges on the members. 1, 3 and 2, 4 indicated the strain gauges on the members of the joint in the in-plane and out-of-plane position respectively.

Strain gauge type FXV-1-11-002LE

The close-up view of strain gauges at the intersections of the completely overlapped joint specimen is shown in Fig. 3.10. The strain gauge (FXV-1-11-002LE) used for the stress concentration measurement consists of five (5) active single element gauges configured in a common backing in the same direction to measure the strain values on the outer surface of members. The positions of these strain gauges to determine the hot spot strains of the joint were according to the recommendation specified by CIDECT (2001). At the joint intersection of the through brace and lap brace, the strain gauges were placed perpendicular to the weld toe around the joint perimeter at every 45° interval. However, at the joint intersection of the chord and through brace, the strain gauges were bonded only half the perimeter of the joint. The main reason was that the inclination of the through brace with respect to the chord was too small to carry out a proper bonding of strain gauges at the crown heel. Furthermore, the experimental investigation by Gho et al. (2003) showed that the

hot spot strains at the weld toe of the joint intersection of the chord and through brace were less significant. This was also verified in the FE analysis of the joint prior to the test. It should be noted that the strain values obtained in the test yielded sufficient results for analysis in consideration of joint symmetrical properties under AX and IPB load conditions. The layout of the strain gauges at the intersections of the chord and through brace and the through brace and lap brace of the joint specimen is shown in Fig. 3.11.

For ease of reference, the strain gauge bonded at the joint intersections was denoted as a form of XX-YY-Z. XX represented the position of the strain gauge on the chord (CH), the through brace near the chord (TC), the through brace near the lap brace (TL) and the lap brace (LP). YY indicated the angular orientation of the strain gauge on the member of the joint measured from the crown heel. Z showed the position of a gauge point on the strain gauge with the first one nearest to the weld toe. An example of TC-135-2 denoted the second gauge point of the strain gauge (FXV-1-11-002LE) at 135 degree orientation measured from the crown heel on the through brace near the chord.

In the preparation of strain gauging, the soldering was kept at a temperature of 280 to 290°C to connect effectively the strain gauge and the extension lead wire onto the terminal. The extension lead wires were 4 to 5 m long. The gauge factors of the strain gauges were reduced accordingly to account for the effect of length of lead wires. No temperature compensation was made to eliminate the apparent strain as the lead wire was of three-wire system. The connecting terminal TF-2SS was used to provide a junction point to connect the strain gauge and the extension lead wire. The rapid adhesive HBM Z70 was adopted to bond the strain gauge and the terminal on the member surface. The coating material, DOW CORNING 3140 silicone rubber, was used to protect the strain gauges and the terminals from dust and corrosion.

3.2.6 Measuring equipment and computer facilities

Three (3) TML ASW-50C switch boxes with 50 channels each were utilized. All the extension lead wires from the load cells and the strain gauges were connected to the switch boxes. A portable data logger TML TDS-302 was used to print all the forces and the strain values. The force was expressed in kN, while the strain was in $\times 10^{-6}$. Both the insulation and the stability of the strain gauges were checked prior to the testing of the joint specimen. For the insulation, the electrical resistance (in M-Ohms) was kept as large as possible to an unlimited value. For the stability, the strain value was set within 0 to 2. The data acquisition was done using “Lab Windows” software on a personal computer which was connected to the data logger through an IEEE-488 General Purpose Interface Bus communication cable. The test control program enabled the strain values obtained from the strain gauges to be directly recorded in a text file and subsequently transferred into a Microsoft Excel file for analysis. The set-up of the data acquisition system can be seen in Fig. 3.12.

3.2.7 Applied load cases

A total of six (6) load cases with both basic (AX, IPB and OPB) and combined loadings acting at the end of the lap brace are considered in the experimental investigation of the completely overlapped joint specimen as shown in Fig. 3.13. As shown in Table 3.3, load cases 1, 2 and 3 are the basic loadings for the joint under lap brace AX, IPB and OPB respectively, while load cases 4, 5 and 6 are the combined loadings for the joint under different combination of basic load cases.

3.3 Experimental Results and Observation

3.3.1 Basic load cases

It was noted that several strain gauges for stress concentration measurement showed errors prior to the test. This was only limited to some gauge points on the strain gauges with small insulation of less than 50 M-Ohms or large instability of more

than two. Those damaged gauge points were listed as follow: CH-45-4, CH-45-5, CH-90-1, CH-135-4, CH-135-5, CH-180-2, TC-135-1, TC-180-5, TL-0-5, LP-0-5, LP-180-5, LP-225-4, LP-225-5, LP-270-5, LP-270-5, LP-315-4 and LP-315-5. However, in consideration of the possibility of causing damage to the adjacent gauge points, repairing or replacing of these strain gauges in a common carrier backing were not carried out. It should be noted that there were five gauge points in one strain gauge. A minimum of three data points was sufficient to determine the hot spot strain for the calculation of SNCF and to identify the linear or quadratic behaviour of the strain distribution near the weld toe of the joint.

The hot spot strains obtained from the strain gauges at the intersections of the chord and through brace and the through brace and lap brace under basic loadings are shown in Fig. 3.14. It could be seen from the figure that the curve fittings of strain values within the extrapolation region on the outer surfaces of members were fairly linear. A linear extrapolation method was adopted to determine the SNCF at the weld toe of members. The SNCF for the test specimen under lap brace AX, IPB and OPB is summarized in Table 3.4. The results showed a slightly asymmetric SNCF distribution at the intersection of the through brace and lap brace, which indicated that the members of the specimen were misaligned. The adjustment was not made as the misalignment of the centerlines of members was found to be small.

Basic AX loading (Load case 1)

For the joint under lap brace AX loading, the maximum SNCF of 5.79 occurred at the saddle of through brace near the lap brace. It was noticed that the maximum SNCF on the chord, the through brace and the lap brace were located at the saddle and the minimum SNCF were at the crown heel.

Basic IPB loading (Load case 2)

For the joint under lap brace IPB, the maximum SNCF of 1.73 occurred at the crown heel of lap brace. The SNCF of the joint increased from the saddle to the

crown of members. At the through brace near the lap brace, the SNCF at the angular orientation of 45° , 180° , and 315° were almost identical. However, the SNCF at the joint intersection of the chord and through brace were found to be very small with maximum value of only 0.35.

Basic OPB loading (Load case 3)

For the joint under lap brace OPB, the maximum SNCF of 4.34 occurred at the saddle of through brace near the lap brace. The SNCF at the crown of members were very small with maximum value of only 0.26. Similar to the case for the joint under lap brace IPB, the SNCF at the joint intersection of the chord and through brace were so small that could be neglected.

3.3.2 Combined load cases

The HSS distributions at the intersection of the through brace and lap brace for the joint under combined load cases 4, 5 and 6 are illustrated in Figs. 3.15, 3.16 and 3.17 respectively. However, the HSS distributions at the intersection of the chord and through brace were not considered as they were found to be very small. The detail of the respective combined load cases is listed in Table 3.3.

Combined AX and IPB loading (Load case 4)

For the joint under combined AX and IPB loading, the maximum HSS occurred at 45° orientation on the through brace near the lap brace. The influence of IPB on the HSS of the joint is apparent as shown in Fig. 3.15. For LC 4.2, the stresses at 45° and 90° orientation on the through brace near the lap brace were nearly identical. However, for LC 4.5, the stress at 45° orientation increased with increasing IPB and reached the peak stress of 76.3 MPa. On the other hand, the stress at 90° orientation was not affected with increasing IPB and it was found to be no more than the value at 45° orientation. On the lap brace, the HSS distribution was similar with that on the through brace near the lap brace except that the maximum HSS at 0° orientation.

Combined IPB and OPB loading (Load case 5)

For the joint under combined IPB and OPB loading, the influence of IPB on the HSS distribution is significant as shown in Fig. 3.16. The maximum HSS occurred at 315° orientation on the through brace near the lap brace. It revealed that for the joint under small IPB, the combined loading caused the peak HSS to shift to the position between 270° and 315° orientation. It was noted that the increment of IPB had no effect on the HSS at the saddle of the joint. The stresses at 90° and 270° orientation on the through brace and the lap brace were found to remain constant.

Combined AX, IPB and OPB loading (Load case 6)

For the joint under combined AX, IPB and OPB loading, the maximum HSS occurred at 270° orientation on the through brace near the lap brace. It is noted that the HSS remains constant with increasing IPB at the saddle of the joint as shown in Fig. 3.17. On the lap brace, the maximum HSS occurred at 315° orientation. However, the distribution of HSS under small IPB indicated that the combined loading caused the peak HSS to shift to the position between 270° and 315° orientation.

3.4 Comparison of Test Results with Existing Equations

In this section, the comparison of the test results with the existing equations was carried out for the completely overlapped tubular joint under combined loadings. Practically, the actual load condition of a tubular joint could be any combination of the three (3) basic load cases. For the case of combined loadings, Gulati et al. (1982) proposed an equation (referred as EQ (1)) to determine the stress on the member of a tubular joint as follow.

$$\sigma(\phi) = K_A(\phi)f_{ax} + K_{Bi}(\phi)f_{ipb} + K_{Bo}(\phi)f_{opb} \quad (3-1)$$

where $K_A(\phi)$, $K_{Bi}(\phi)$ and $K_{Bo}(\phi)$ were the SCF at the intersection of members for a joint under AX, IPB and OPB respectively. f_{ax} , f_{ipb} and f_{opb} were the corresponding nominal stresses for these three (3) basic load cases.

On the other hand, the offshore design recommendation API RP2A (2000) recommended the following equation (referred as EQ (2)) to determine the HSS of a tubular joint for fatigue design,

$$\sigma_{HSS} = |SCF_{ax} f_{ax}| + \left[(SCF_{ipb} f_{ipb})^2 + (SCF_{opb} f_{opb})^2 \right]^{1/2} \quad (3-2)$$

where SCF_{ax} , SCF_{ipb} and SCF_{opb} were the maximum SCF and f_{ax} , f_{ipb} and f_{opb} were the nominal stresses on the braces under AX, IPB and OPB load cases respectively.

For EQ (1), the HSS was obtained by superposition of stress distribution for each load case. As a result, the magnitude and the location of the HSS were determined along the intersection of a tubular joint. On the contrary, EQ (2) used the maximum SCF of basic load cases to determine the HSS at a joint. This approach did not consider the exact location of the HSS. It should be noted that most of the parametric equations proposed by researchers were only applicable for predicting maximum SCF of the joint under basic load cases. The main reason was that the stress distribution at the joint intersection was too complicated for analysis particularly for the joint subjected to different combination of loadings. The use of EQ (2) was found to be more straightforward than EQ (1) to determine the HSS of the joint under combined loadings.

3.4.1 Comparison of test results with EQ (1)

In the current research, the test results obtained from the strain gauges of the joint specimen under combined load cases were compared with the values calculated by Gulati et al. (1982) equation. In EQ (1), K factors were determined based on the SCF of the joint under independent load cases of AX, IPB and OPB. The

comparison of HSS between the test results and the values calculated from EQ (1) is shown in Fig. 3.18.

In general, the comparison of stresses between the test and EQ (1) showed good agreement. As shown in Fig. 3.18(a), the stress distribution calculated from EQ (1) compares very well with the test results. The respective mean and standard deviation of EQ (1) to test data were found to be 1.03 and 0.14. The mean value greater than unity indicated that EQ (1) was more conservative. However, to avoid the scatter of results due to very small stresses obtained in the test, only those stresses greater than 2 MPa were considered in the statistical analysis.

The detailed assessment of the test results and the values calculated from EQ (1) is summarized in Table 3.5. In the table, S and C represented the stress obtained from the equation and the test respectively. Overall, EQ (1) fitted very well the test results. The respective mean and standard deviation of S/C ratio in the statistic analysis were found to be 1.03 and 0.19.

3.4.2 Comparison of test results with EQ (2)

In this section, the significant impact on the HSS at the intersection of the through brace and lap brace for the joint under combined load cases was considered. The peak HSS obtained from the test and the equation proposed by design recommendation API RP2A (2000) are listed in Table 3.6.

From the comparison of HSS on the through brace near the lap brace as shown in Table 3.6(a), EQ (2) over predicts the peak HSS for the joint under all combined load cases with average difference of 22.4 MPa and 25.6% in terms of numeric and percentage respectively. In the table, AS and C represented the HSS determined from EQ (2) and the test respectively for the joint under combined loadings. It was noticed that the maximum difference of HSS occurred at Load case 4 (combined AX and IPB loading) with difference of 51.5%.

The comparison of peak HSS on the lap brace as shown in Table 3.6(b) revealed that the HSS obtained from EQ (2) is more conservative than that from the test. The average difference in terms of numeric and percentage was found to be 8.7 MPa and 15.5% respectively. Similar to the case on the through brace near the lap brace, EQ (2) excessively over predicted the HSS as indicated in Load case 4.

3.5 Concluding Remarks

A uni-planar completely overlapped tubular joint specimen is tested under basic (AX, IPB and OPB) and combined loadings for stress concentration study. The experimental results showed that the curve fittings of strain values within the extrapolation region on the outer surfaces of members are linear. For the joint under lap brace AX loading, the maximum SNCF of 5.79 occurs at the saddle of through brace near the lap brace. For the joint under lap brace IPB and OPB, the maximum SNCF of 1.73 and 4.34 occur at the crown heel of lap brace and the saddle of through brace near the lap brace respectively. The SNCF at the joint intersection of the chord and through brace is found to be negligible under both IPB and OPB.

For the joint under combined loadings, the peak HSS can shift to the position between the crown and the saddle of members. The comparison of HSS showed that the test results agree reasonably well with the values calculated from the equation proposed by Gulati et al. (1982). However, the values determined by the design recommendation, API RP2A (2000), over predict the test results. It is commented from the current study that the equation based on linear superposition approach for simple joints is suitable for predicting the HSS of completely overlapped tubular joints under combined loadings.

Table 3.1 Geometric parameters of completely overlapped tubular joint specimen

Geometric parameters	Non-dimensional parameters
	Chord and through brace
$\theta = 30.0^\circ$	$\alpha_C = 2L/D = 24.4$
$L = 2670.0\text{mm}$	$\gamma_C = D/2T = 13.9$
$L_T = 1888.0\text{mm}$	$\beta_{CT} = d_T/D = 0.77$
$L_L = 623.0\text{mm}$	$\tau_{CT} = t_T/T = 0.89$
$D = 219.1\text{mm}$	Through brace and lap brace
$d_T = 168.3\text{mm}$	$\alpha_T = 2l_T/d_T = 22.4$
$d_L = 88.9\text{mm}$	$\gamma_T = d_T/2t_T = 12.0$
$T = 7.9\text{mm}$	$\beta_{TL} = d_L/d_T = 0.53$
$t_T = 7.0\text{mm}$	$\tau_{TL} = t_L/t_T = 0.78$
$t_L = 5.5\text{mm}$	Gap parameter
$g_T = 143.0\text{mm}$	$\xi_T = g_T/d_T = 0.85$

Table 3.2 Summary of coupon test results

Member	Young's modulus (GPa)	Yield stress (MPa)	Tensile stress (MPa)	Elongation (%)
Chord	197	353	458	32
Through brace	205	377	486	36
Lap brace	193	375	467	28

Table 3.3 Applied load cases for completely overlapped joint specimen

Load case 1					Load case 2				
LC	Nominal		Nominal		LC	Nominal		Nominal	
	AX stress (MPa)	IPB stress (MPa)	OPB stress (MPa)	Nominal OPB stress (MPa)		AX stress (MPa)	IPB stress (MPa)	OPB stress (MPa)	Nominal OPB stress (MPa)
1.1	5	0	0	0	2.1	0	15	0	0
1.2	10	0	0	0	2.2	0	20	0	0
1.3	15	0	0	0	2.3	0	25	0	0
1.4	20	0	0	0	2.4	0	30	0	0
1.5	25	0	0	0	2.5	0	35	0	0

Load case 3					Load case 4				
LC	Nominal		Nominal		LC	Nominal		Nominal	
	AX stress (MPa)	IPB stress (MPa)	OPB stress (MPa)	Nominal OPB stress (MPa)		AX stress (MPa)	IPB stress (MPa)	OPB stress (MPa)	Nominal OPB stress (MPa)
3.1	0	0	0	15	4.1	10	15	0	0
3.2	0	0	0	20	4.2	10	20	0	0
3.3	0	0	0	25	4.3	10	25	0	0
3.4	0	0	0	30	4.4	10	30	0	0
3.5	0	0	0	35	4.5	10	35	0	0

Load case 5					Load case 6				
LC	Nominal		Nominal		LC	Nominal		Nominal	
	AX stress (MPa)	IPB stress (MPa)	OPB stress (MPa)	Nominal OPB stress (MPa)		AX stress (MPa)	IPB stress (MPa)	OPB stress (MPa)	Nominal OPB stress (MPa)
5.1	0	30	22	22	6.1	10	25	20	20
5.2	0	35	22	22	6.2	10	30	20	20
5.3	0	40	22	22	6.3	10	35	20	20
5.4	0	45	22	22	6.4	10	40	20	20
5.5	0	50	22	22	6.5	10	45	20	20

Table 3.4 SNCF of completely overlapped tubular joint specimen

* Location	Experimental Result		
	AX	IPB	OPB
CH-045	-0.56	-0.18	0.40
CH-090	-1.51	-0.08	0.59
CH-135	-0.88	0.20	-0.17
CH-180	0.52	0.16	0.01
TC-045	-0.68	-0.10	0.23
TC-090	-2.59	-0.15	0.62
TC-135	-0.93	0.35	-0.31
TC-180	1.36	0.04	-0.04
TL-000	-1.56	-1.21	0.16
TL-045	-2.41	-1.49	1.90
TL-090	-5.56	-0.02	4.16
TL-135	-4.33	1.25	2.11
TL-180	-3.28	1.57	-0.10
TL-225	-4.51	1.29	-2.05
TL-270	-5.79 (Max)	0.01	-4.34 (Max)
TL-315	-2.61	-1.56	-1.99
LP-000	-0.94	-1.73 (Max)	0.26
LP-045	-1.26	-1.55	1.03
LP-090	-3.15	-0.52	1.95
LP-135	-2.05	0.77	1.15
LP-180	-1.57	1.27	0.04
LP-225	-2.00	0.84	-1.11
LP-270	-3.26	-0.42	-1.92
LP-315	-1.33	-1.50	-0.99

Note: CH – Chord;
 TC – Through brace in contact with chord;
 TL – Through brace in contact with lap brace;
 LP – Lap brace.

* Angular orientation ($= 0^\circ$) is measured from crown heel position.

Table 3.5 Comparison of HSS between test results and EQ (1)

Load case	Description	Mean	StDev	Stress (MPa)	
		S/C	S/C	Min	Max
4	AX+IPB	1.03	0.14	-76.3	29.9
5	IPB+OPB	1.06	0.22	-114.2	107.8
6	AX+IPB+OPB	1.01	0.21	-140.2	46.8
Average		1.03	0.19		

Note S: Equation (Gulati et al. 1982)
 C: Test results under combined loading

Table 3.6 Comparison of peak HSS between test results and EQ (2)

(a) Through brace near lap brace					
Load case	Description	Test results (MPa)	EQ (2) (MPa)	AS-C	(AS-C)/C
4.1	AX+IPB	-55.5	-81.5	-26.0	46.8%
4.2	AX+IPB	-60.7	-89.3	-28.6	47.1%
4.3	AX+IPB	-67.2	-97.2	-30.0	44.6%
4.4	AX+IPB	-69.3	-105.0	-35.7	51.5%
4.5	AX+IPB	-76.3	-112.9	-36.6	47.9%
5.1	IPB+OPB	-95.9	-108.4	-12.5	13.1%
5.2	IPB+OPB	-96.1	-112.0	-15.9	16.6%
5.3	IPB+OPB	-100.9	-116.1	-15.2	15.1%
5.4	IPB+OPB	-107.1	-120.5	-13.4	12.5%
5.5	IPB+OPB	-114.2	-125.3	-11.1	9.7%
6.1	AX+IPB+OPB	-138.2	-153.4	-15.2	11.0%
6.2	AX+IPB+OPB	-138.9	-156.9	-18.0	12.9%
6.3	AX+IPB+OPB	-138.4	-160.8	-22.4	16.2%
6.4	AX+IPB+OPB	-139.8	-165.2	-25.4	18.2%
6.5	AX+IPB+OPB	-140.2	-170.0	-29.8	21.3%
			Average	-22.4	25.6%

(b) Lap brace					
Load case	Description	Test results (MPa)	EQ (2) (MPa)	AS-C	(AS-C)/C
4.1	AX+IPB	-42.3	-58.6	-16.3	38.4%
4.2	AX+IPB	-45.0	-67.2	-22.2	49.3%
4.3	AX+IPB	-47.8	-75.9	-28.1	58.7%
4.4	AX+IPB	-61.6	-84.5	-22.9	37.2%
4.5	AX+IPB	-70.3	-93.2	-22.9	32.5%
5.1	IPB+OPB	-74.2	-68.0	6.2	-8.4%
5.2	IPB+OPB	-82.1	-74.8	7.3	-8.9%
5.3	IPB+OPB	-89.2	-81.9	7.3	-8.1%
5.4	IPB+OPB	-95.8	-89.4	6.4	-6.7%
5.5	IPB+OPB	-102.9	-97.0	5.9	-5.7%
6.1	AX+IPB+OPB	-84.8	-91.0	-6.2	7.3%
6.2	AX+IPB+OPB	-87.8	-97.6	-9.8	11.2%
6.3	AX+IPB+OPB	-93.8	-104.7	-10.9	11.7%
6.4	AX+IPB+OPB	-100.6	-112.1	-11.5	11.5%
6.5	AX+IPB+OPB	-106.7	-119.8	-13.1	12.3%
			Average	-8.7	15.5%

Note AS: Equation (API RP2A 2000)
C: Test results under combined loading

Fig. 3.1 Completely overlapped tubular joint specimen

(a) Manually-operated pump

(b) Electric pump

Fig. 3.2 Two-speed hydraulic pumps used in the test

Fig. 3.3 Load cell used in the test

Fig. 3.4 Design of adapter to connect hydraulic cylinder and load cell

Fig. 3.5 Definition of geometric parameters of completely overlapped tubular joint

Fig. 3.6 Geometrical properties of completely overlapped tubular joint specimen

Fig. 3.7 Failure of coupon under tension

Fig. 3.8 Stress and strain curves of members from coupon test

Fig. 3.9 Distribution of single-element strain gauges

Fig. 3.10 Distribution of strain gauges at joint intersections

(a) Joint intersection of through brace and lap brace

(b) Joint intersection of chord and through brace

Fig. 3.11 Layout of strain gauges at joint intersections

Fig. 3.12 Set-up of data acquisition system

Fig. 3.13 Basic and combined load cases

Fig. 3.14(a) SNCF at joint intersection of chord and through brace

Fig. 3.14(b) SNCF at joint intersection of through brace and lap brace

Fig. 3.15 Stress distribution at joint intersection of through brace and lap brace under AX and IPB load case

Fig. 3.16 Stress distribution at joint intersection of through brace and lap brace under IPB and OPB load case

Fig. 3.17 Stress distribution at joint intersection of through brace and lap brace under AX, IPB and OPB load case

Fig. 3.18 Comparison of HSS between test results and EQ (1)

CHAPTER 4

NUMERICAL ANALYSIS

4.1 Introduction

This chapter describes in detail the numerical modelling technique of the completely overlapped tubular joint specimen tested in the Heavy Structures Laboratory, Nanyang Technological University. The main objective is to establish a reliable and efficient finite element (FE) method for the parametric stress analysis of the joint. A commercial FE package MARC (2001) with pre- and post-processing programme MENTAT is adopted in the current study to intensively investigate the stress and strain concentrations of completely overlapped tubular joints. MARC is a well recognized FE program, which has been used for many years to examine both linear and non-linear stress analyses of tubular joints. Both MARC and MENTAT programmes used in the present work are run on the SUN SPARC workstation.

4.2 Finite Element Analysis

4.2.1 Elastic test of joint specimen

A uni-planar completely overlapped tubular joint specimen was tested under basic and combined loadings for the investigation of stress and strain concentrations. The load condition was unbalanced and the load was applied at the end of lap brace. During the test, the load level for all the load cases was controlled within the elastic limit of steel material (Table 3.3). The definition of parameters and the geometrical properties of the completely overlapped tubular joint test specimen are depicted in Figs. 3.5 and 3.6 respectively. The detail of the geometrical parameters of the joint is given in Table 3.1.

4.2.2 Types of finite elements

In the FE analysis, two types of elements were found suitable for modelling the joint specimen namely 8-node thick shell (MARC element type 22) and 20-node solid (MARC element type 57) elements. However, it was well noted that the suitability of the element for modelling the joint specimen was dependent upon the joint configuration, the applied load and the area of investigation.

The 8-node thick shell element was a higher order element with reduced integration. It was a doubly curved element, which used a second order interpolation for the coordinates, displacements and rotations. Each node had six degrees of freedom with three translational and three rotational. The stiffness of the element was determined based on four integration points in the element. Seven integration points through the thickness of the element were considered to account for the transverse shear effect in the analysis.

The 20-node solid element was an isoparametric element with arbitrary hexahedral reduced integration. This element used triquadratic interpolation functions to represent the coordinates and displacements. The strain values were linearly varied, which allowed accurate representation of the strain fields in the elastic analysis. The stiffness of the element was determined based on eight-point Gaussian integration which was a reduced integration element exhibited in an hourglass mode. A more detailed description on the properties of the above two elements could be found in MARC (2001).

4.2.3 Mesh refinement and integration scheme

For the FE model of completely overlapped tubular joint, the attention was particularly focus on the mesh refinement at the joint intersections of the chord and through brace and the through brace and lap brace. A total of 64 and 36 divisions of elements along the weld perimeters at these two joint intersections were created. The number of subdivisions of elements at the joint intersections satisfied the

minimum requirement of 24 stated in ARSEM (1987). Furthermore, the subdivisions of elements were more than 16 and 32 divisions of solid elements provided for T- and gap K-joints by Romeijn and Wardenier (1994) and Karamanos et al. (2000b) respectively. Along the direction perpendicular to the weld toe, the width of the first two rows of elements was within two times the minimum extrapolation distance as recommended by CIDECT (2001) (Table 2.1). Element sizes outside the joint intersections were gradually increased with relatively large elements near the ends of members. Transition elements were included in the FE models to reduce the number of elements for time saving in the analysis.

The 8-node thick shell and the 20-node solid element models of the completely overlapped tubular joint are shown in Figs. 4.1 and 4.2 respectively. Fig. 4.2 shows the one half joint model with close-up view of elements along the thickness of members. A total of 5118 and 4366 of the 8-node thick shell and 20-node solid elements respectively were used for the meshes in the joint models. For the verification, the geometrical and the dimensional properties of the joint model were identical to those of the test specimen.

For the integration scheme of the finite elements, the reduced-integration-scheme was adopted for both the 8-node thick shell (2×2) and the 20-node solid ($2 \times 2 \times 2$) elements to calculate the stresses and strains of the completely overlapped tubular joint. This approach was also recommended by Romeijn et al. (1993).

4.2.4 Modelling technique of weld elements

The weld element at the joint intersection of members could significantly affect the stress distribution. In the current research, the weld element was sized according to the specification and included in both the 8-node thick shell and the 20-node solid FE models for an accurate stress analysis of the joint. The dihedral angle (Ψ) was an important parameter for the design of welded tubular joints. AWS (2000) defined the dihedral angle as *“the angle, measured in a plane perpendicular to the line of the weld, between tangents to the outside surfaces of the tubes being joined at the*

weld. The exterior dihedral angle, where one looks at a localized section of the connection, such that the intersecting surfaces may be treated as plane". The thickness of the weld profile was determined based on the dihedral angle along the joint perimeter specified by AWS (2000). For the 8-node thick shell and the 20-node solid FE models, the techniques for modelling the weld at the joint intersections were referenced to the work of van der Vegte (1995) and Lie et al. (2001) respectively. The range of the dihedral angle considered in the FE models is within 30° to 180° as shown in Fig. 4.3.

4.2.5 Nominal stress

For a tubular joint under AX loading, the nominal stress can be defined as the total applied axial load divided by the cross-sectional area of the brace as shown below.

$$\sigma_{N-A} = \frac{4F}{\pi[d^2 - (d - 2t)^2]} \quad (4-1)$$

where

F : brace axial load

d : brace diameter

t : brace thickness

For a joint under IPB and OPB, the nominal stresses are calculated based on the simple beam theory as shown in EQs (4-2) and (4-3) respectively.

$$\sigma_{N-I} = \frac{32dM_i}{\pi[d^4 - (d - 2t)^4]} \quad (4-2)$$

$$\sigma_{N-O} = \frac{32dM_o}{\pi[d^4 - (d - 2t)^4]} \quad (4-3)$$

where

M_i : brace IPB moment

M_o : brace OPB moment

For a joint under combined loadings of the three basic load cases, the stress at any point P (as shown in Fig. 4.4) on the outer surface of brace can be determined based on a superposition method as shown in EQ (4-4).

$$\sigma = \frac{4F}{\pi[d^2 - (d - 2t)^2]} + \frac{32dM_i}{\pi[d^4 - (d - 2t)^4]} \sin \theta + \frac{32dM_o}{\pi[d^4 - (d - 2t)^4]} \cos \theta \quad (4-4)$$

where θ is the angular orientation on cross-sectional plane of brace measured from saddle as shown in Fig. 4.4.

The nominal stress of a tubular joint under combined loadings is defined as the maximum stress obtained from EQ (4-4).

$$\sigma_N = \frac{4F}{\pi[d^2 - (d - 2t)^2]} + \sqrt{\left(\frac{32dM_i}{\pi[d^4 - (d - 2t)^4]}\right)^2 + \left(\frac{32dM_o}{\pi[d^4 - (d - 2t)^4]}\right)^2} \quad (4-5)$$

EQ (4-5) is applicable for tubular joints subjected to both combined and basic load cases. The position of the nominal stress can be obtained based on the angular orientation, θ , as follow:

$$\theta = \frac{\pi}{2} - \arctg \frac{M_o}{M_i} \quad (4-6)$$

4.2.6 Extrapolation procedure

In the experimental investigation of the joint specimen, a specific type of strain gauge was used for stress concentration measurement. This strain gauge comprises five (5) single gauges of 1 mm long each bonded on a common backing to capture the nonlinear distribution of stresses. At the intersection of the through brace and lap brace, the strain gauges were placed perpendicular to the weld toe around the joint perimeter at every 45° interval. However, at the intersection of the chord and through brace, the strain gauges were only bonded half the perimeter of the joint. From the experimental results, the curve fittings of strain values on each member

were fairly linear. Hence, a linear extrapolation method was adopted in the current study to obtain the data in and around the extrapolation region. The extrapolation procedure to determine the HSS at the weld toe is referenced to Fig. 2.6.

The stress and the strain output files were generated by MENTAT after the stress and strain analysis. In order to facilitate the calculation of SCF and SNCF, the nominal stress of each load case was assigned as unit value. The stresses and the strains in the output file with the nodes within the extrapolation region could directly be used as the SCF and SNCF for each node point. To obtain the extrapolated SCF and SNCF at the weld toe, two computer programs were developed using Visual C language for the thick shell and the solid FE models respectively. The difference of the computer programs between these two models was that the thick shell element model used local coordinate, while the solid element model used Cartesian coordinate. Both programs were very efficient in manipulating the huge volumes of the output files generated from FE model analysis. The explanation of the usage of the two programs is given in Appendix A.

4.3 Convergence Study

Three different mesh refinements of the 8-node thick shell FE models were created for convergence study based on the criteria recommended by Romeijn and Wardenier (1994). As shown in Fig. 4.1, the FE model with 15150 nodes and 5118 elements is first generated using MARC. Based on the mesh density of this model, two refined meshes were subsequently created by doubling and tripling the element density of the joint. Fig. 4.5 shows the close-up view at the joint intersection region for the FE models with single, double and triple meshes.

Similarly, a convergence study was also conducted for 20-node solid FE models based on three mesh refinements. A FE model with an initial mesh is first created as shown in Fig. 4.2. There were three layers of elements along the wall thickness near the joint intersections of the chord and through brace and the through brace and lap brace. Transition elements were used outside the intersection region to reduce the

number of solid elements in the model. A linear elastic analysis was employed for all the three FE models with different meshes to determine the SNCF at the weld toe. These data points were perpendicular to the weld toe and obtained from the node points of the elements near the joint intersections of the FE model.

The comparison of SNCF for the three 8-node thick shell FE models under lap brace AX loading is presented in Figs. 4.6 and 4.7. The results indicated that the maximum SNCF occurred at the saddle of members. It was also found that the SNCF obtained from the three models were very close with maximum discrepancy of not more than 0.2. The results of the convergence study of the three 20-node solid FE models were very similar to those of the 8-node thick shell FE models. In consideration of the accuracy and the computational effort (Table 4.1), it was commented that both the 8-node thick shell and the 20-node solid FE models with single meshes were sufficient to simulate the completely overlapped tubular joint.

4.4 Relationship between SNCF and SCF

Since only strains could directly be measured using strain gauges in the experiment, it was a usual practice that SNCF was determined prior to SCF. In many cases, an assumption was necessary to convert the experimentally measured SNCF into SCF with the use of a conversion factor of 1.1 (UEG 1985) or 1.2 (van Delft et al. 1987 and Frater 1991). However, according to the numerical investigation of tubular joints by Romeijn and Wardenier (1994), the use of factor 1.2 was commented to be too high for simple T- and Y-joints. Furthermore, some joint parameters could have influential effects on the factor as well.

In the current FE study, both SNCF and SCF were obtained at the joint intersections of the chord and through brace and the through brace and lap brace from the FE models under basic load cases. The relationship between SNCF and SCF for the joint under AX, IPB and OPB loads is shown in Figs. 4.8, 4.9 and 4.10 respectively. The range of SCF to SNCF ratio (referred as S/SN) and the average value of the ratio for the joint under basic load cases are presented in Table 4.2.

For the completely overlapped tubular joint under AX loading (Fig. 4.8), the range of S/SN ratios was between 0.92 and 1.24. The mean and CoV (coefficient of variation) values were 1.15 and 0.06 respectively. The SCF always showed a larger value than SNCF. However, the SCF was equivalent to SNCF at the crown heel of the chord and through brace. At the joint intersection of the through brace and lap brace, the S/SN ratios were in the range of 1.14 to 1.24, which indicated that SCF was larger than SNCF at this intersection under AX load case.

For the joint under IPB (Fig. 4.9), the SCF was larger than SNCF with minimum and maximum S/SN ratios of 1.01 and 1.28 respectively. The respective mean and CoV values were 1.14 and 0.05. At the saddle, it was noted that both SCF and SNCF were negligible.

The S/SN ratios for the joint under OPB (Fig. 4.10) were very similar to those for the joint under IPB. The range of S/SN ratios was between 1.03 and 1.30. The mean and CoV values were 1.13 and 0.05 respectively. As expected, both SCF and SNCF at the crown heel and crown toe of the joint were found to be negligible.

4.5 Discussion and Concluding Remarks

In the modelling of completely overlapped tubular joints, the weld elements are included in both 8-node thick shell and 20-node solid FE models. For the 8-node thick shell FE model, two-dimensional weld element is modelled based on the mid-layer of wall thickness of members. For the 20-node solid FE model, three-dimensional weld element is considered to actually simulate the shape and the size of the weld. It should be noted that the techniques for modelling the weld elements described in the current study are commonly adopted for the investigation of stress concentration of tubular joints. Based on the geometrical parameters of the test specimen given in Chapter 3, the SNCF at the weld toe is found larger than that at the weld root, as shown in Fig. 4.11.

In the current study, the stress and the strain components perpendicular to the weld toe are adopted for the calculation of SCF and SNCF respectively. The locations for stress and strain concentration measurement are identical to those of the test specimen. Furthermore, this is also to ensure that a more accurate prediction of SCF and SNCF can be obtained for the joint under combined loadings. In the current FE study, the nodal stress is used to obtain the hot spot stress at the joint. The stress at a node point is calculated by averaging the stresses at the integration points of the finite elements. However, the nodal stress at the weld toe cannot directly be used for the HSS as it includes the stress due to the effect of weld. Thus, in order to obtain accurately the SCF of the joint based on the FE analysis, the nodal stresses are extrapolated within the extrapolation region specified by CIDECT (2001).

For the completely overlapped tubular joint, the SCF is larger than SNCF except at the crown heel of the chord and through brace under AX load. The maximum and minimum S/SN ratios are 1.30 and 0.92 and the average values are 1.15, 1.14 and 1.13 for the joint under lap brace AX, IPB and OPB load cases respectively. From the results, it can be commented that the use of $S/SN = 1.1$ underestimates the SCF. However, the use of $S/SN = 1.2$ is slightly higher for the joint under basic load cases. Since S/SN ratio varies with geometry and location of the joint, it is very difficult to obtain exactly the relationship between SCF and SNCF. In this aspect, the use of $S/SN = 1.2$ for converting SNCF to SCF is considered to be acceptable and reasonable as it yields a slightly conservative SCF in stress analysis of completely overlapped tubular joints.

Table 4.1 CPU times of different FE meshes

Element type	Description	Elements	CPU times (s)
8-node	Single	5118	130
thick shell	Double	20472	565
elememt	Triple	46062	1380
20-node	Single	4366	660
solid	Double	34928	5924
elememt	Triple	117882	21993

Table 4.2 Relationship between SCF and SNCF

Load case	Location	Range S/SN	Average S/SN
AX	CH	$0.92 < S/SN < 1.21$	1.08
	TC	$0.96 < S/SN < 1.19$	1.14
	TL	$1.14 < S/SN < 1.22$	1.18
	LP	$1.14 < S/SN < 1.24$	1.17
IPB	CH	$1.01 < S/SN < 1.18$	1.11
	TC	$1.03 < S/SN < 1.23$	1.16
	TL	$1.02 < S/SN < 1.28$	1.17
	LP	$1.05 < S/SN < 1.22$	1.14
OPB	CH	$1.03 < S/SN < 1.24$	1.12
	TC	$1.05 < S/SN < 1.18$	1.12
	TL	$1.07 < S/SN < 1.22$	1.14
	LP	$1.08 < S/SN < 1.30$	1.15

Fig. 4.1 8-node thick shell FE model

Fig. 4.2 Sectional view of 20-node solid FE model

Note (Ψ) dihedral angle, (a, b) FE sizes, (t_w) weld thickness

Fig. 4.3 Sizes of weld elements

Fig. 4.4 Cross-sectional view of brace

(a) Single mesh

(b) Double mesh

(c) Triple mesh

Fig. 4.5 Sectional view for single, double and triple meshes of FE model

Fig. 4.6 Convergence study of FE models – chord and through brace

Fig. 4.7 Convergence study of FE models – through brace and lap brace

Fig. 4.8 Relationship between SNCF and SCF under AX load case

Fig. 4.9 Relationship between SNCF and SCF under IPB load case

Fig. 4.10 Relationship between SNCF and SCF under OPB load case

Fig. 4.11 Comparison of SNCF at weld toe and weld root

CHAPTER 5

COMPARISON OF EXPERIMENTAL AND FE ANALYSIS RESULTS

5.1 Introduction

A uni-planar completely overlapped tubular joint specimen is tested under basic (AX, IPB and OPB) and combined loadings to determine the stress concentration for the verification and calibration of FE models. In this chapter, the experimental SNCF of the joint specimen is compared with the SNCF of the FE model at the hot spot locations of the chord, through brace and lap brace under basic loadings. For the case of combined loadings, the comparison is based on the HSS of each member. In the test, all the strain values obtained from the strain gauges are within the elastic limit of steel material. The nominal strain is calculated based on the actual Young's modulus and cross sectional area of the lap brace. For the numerical analysis, the 8-node thick shell (MARC element type 22) and the 20-node solid elements (MARC element type 57) are found suitable for modelling the test specimen. In both FE models, the weld element is included and modelled according to the requirement specified by AWS (2000).

5.2 Comparison of SNCF and SCF under Basic Loadings

The SNCF of the test specimen and the FE models under AX, IPB and OPB load cases are summarized in Tables 5.1, 5.2 and 5.3 respectively. It was noted that the SNCF in some locations was very small, but the difference in terms of percentage could be misinterpreted to be significant. An example of SNCF at the chord saddle under IPB load case given in Table 5.2 showed that the difference is only 0.09 in terms of numeric but 112.5% in terms of percentage. In this circumstance, the difference of 112.5% was considered to be too significant from percentage view point. However, the difference in terms of numeric was negligible. This discrepancy was attributed to the very small value of SNCF obtained from the test. In previous

study, several researchers recommended that the SCF of tubular joints should not be less than 1.5 (Smedley and Fisher 1991, Chang and Dover 1999a, 1999b). Furthermore, the SCF was taken as 1.2 times the SNCF recommended by van Delft et al. (1987) and Frater (1991). Thus, if the SNCF was found to be less than 1.25, the analysis results expressed in terms of percentage would not accurately reflect the actual difference. In the current comparison, if the value of SNCF in the test was so small that could be neglected, the difference in terms of percentage between the test specimen and the FE models would not be presented.

5.2.1 Comparison of SNCF and SCF under AX load case

Test specimen and 8-node thick shell FE model

The comparison of SNCF between the test specimen and the 8-node thick shell FE model under AX load case can be seen in Table 5.1. It was found that the maximum difference of SNCF of 0.49 occurred at the saddle of through brace near the lap brace. The maximum SNCF of the joint also occurred at this location for both the test specimen and the 8-node thick shell FE model with the values of 5.79 and 6.05 respectively. Although the maximum difference in terms of percentage at 45° orientation on the chord measured from crown heel was 21.4%, the difference in terms of numeric was only 0.12. The average difference was 7.9% which was less than the limit of 10% specified by Gibstein (1978). Thus, in view of the small difference, the SNCF of the 8-node thick shell FE model under AX load case was concluded to be in good agreement with the test values.

Test specimen and 20-node solid FE model

The comparison of SNCF between the test specimen and the 20-node solid FE model showed that the maximum value occurred at the saddle of through brace near the lap brace (Table 5.1). The maximum difference of SNCF at this location was 0.71. However, the difference in terms of percentage was 12.8% which was larger than 8.9% obtained from the comparison of the test specimen with the 8-node thick

shell FE model presented in the previous section. It should be noted from the comparison of SNCF that the maximum difference at the crown toe of chord was 21.2%. However, the difference in terms of numeric at this location was only 0.11. As the average difference was 8.8% which was less than the limit of 10% specified by Gibstein (1978), the SNCF of the 20-node solid FE model was commented to compare reasonably well with that of the test specimen.

8-node thick shell and 20-node solid FE model

The distribution of SCF at the joint intersections of the chord and through brace and the through brace and lap brace of the 8-node thick shell and the 20-node solid FE models under AX load case is presented in Fig. 5.1. In the figure, ϕ represented the angle orientation measured from the crown heel to the crown toe and then to the crown heel. It was noted that the maximum SCF occurred at the saddle for every member. However, the maximum SCF for the joint was found to be located at the saddle of through brace near the lap brace. At this location, the SNCF of the 8-node thick shell and the 20-node solid FE models were 6.05 and 6.27 respectively and the difference was 0.22 (Table 5.1). As shown in the previous two sections, the SNCF of the two FE models were higher than the experimental results. The SCF of the 8-node thick shell and the 20-node solid FE models were 6.92 and 7.19 respectively and the difference was only 0.27 (Fig. 5.1). From the comparison of SCF, both the 8-node thick shell and the 20-node solid elements were suitable for modelling the completely overlapped tubular joint under AX load case.

5.2.2 Comparison of SNCF and SCF under IPB load case

Test specimen and 8-node thick shell FE model

The comparison of SNCF between the test specimen and the 8-node thick shell FE model under IPB load case is presented in Table 5.2. The maximum difference of SNCF of 0.27 occurred at the saddle of lap brace. However, the maximum SNCF of the joint occurred at the crown heel of lap brace. At this location, the FE model

yielded a lower SNCF than the test specimen with a difference of 0.06. The average difference of SNCF was 10.6% which was slightly higher than the limit of 10% recommended by Gibstein (1978). However, it was noted that the SNCF for the joint under IPB load case were small with maximum value of 1.73. Furthermore, some SNCF on the members were not presented in terms of percentage as the test results were approximately equal to zero. In view of the small difference of only 0.27, the SNCF obtained from the 8-node thick shell FE model under IPB load case was considered in reasonably good agreement with the test values. The difference of 0.27 was also less than the limit of 2 specified by ARSEM (1987).

Test specimen and 20-node solid FE model

The comparison of SNCF between the test specimen and the 20-node solid FE model showed that the maximum value occurred at the crown heel of lap brace and the crown toe of through brace near the lap brace respectively (Table 5.2). The SNCF at these two locations were nearly identical and the discrepancy between the test and the FE analysis was found to be negligible. The maximum difference of SNCF of 0.29 occurred at the saddle of lap brace. The maximum difference in terms of percentage at 135° orientation on the through brace near the lap brace was 18.9%. However, the difference in terms of numeric at this location was only 0.23. The average difference of SNCF was 10.7% which was slightly higher than the limit of 10% recommended by Gibstein (1978). It should be noted that the difference of 0.29 was less than the limit of 2 specified by ARSEM (1987). Similar to the comparison of SNCF between the test specimen and the 8-node thick shell FE model, it was commented that the comparison of SNCF between the test specimen and the 20-node solid FE model was reasonably well.

8-node thick shell and 20-node solid FE model

The SCF distribution at the joint intersection of the through brace and lap brace of the 8-node thick shell and the 20-node solid FE models under IPB load case is presented in Fig. 5.2. The SCF distribution at the joint intersection of the chord and

through brace was not considered as the maximum SCF was less than 0.4. In Fig. 5.2, ϕ is the angle orientation measured from the crown heel to the crown toe and then to the crown heel. The maximum SCF occurred at the crown heel of lap brace. At this location, the SNCF of the 8-node thick shell and the 20-node solid FE models were 1.66 and 1.62 respectively (Table 5.2). Both SNCF from the FE models were lower than the experimental values. The SCF for the 8-node thick shell and the 20-node solid FE models were 1.96 and 1.90 respectively and the difference was only 0.06. Hence, it could be concluded from the comparison of SCF that both the 8-node thick shell and the 20-node solid elements were suitable for modelling the completely overlapped tubular joint under IPB load case.

5.2.3 Comparison of SNCF and SCF under OPB load case

Test specimen and 8-node thick shell FE model

The comparison of SNCF between the test specimen and the 8-node thick shell FE model under OPB load case is shown in Table 5.3. The maximum difference of SNCF of 0.29 occurred at the saddle of through brace near the lap brace. The maximum SNCF for both the test specimen and the 8-node thick shell FE model also occurred at this location with values of 4.16 and 4.46 respectively. The maximum difference of SNCF in terms of percentage at the saddle of lap brace was 9.9%. But the difference in terms of numeric at this location was only 0.19. The average difference of SNCF was 5.8% which was less than the limit of 10% recommended by Gibstein (1978). Thus, in view of the small difference, the SNCF obtained from the 8-node thick shell FE model under OPB load case was considered in good agreement with the test values.

Test specimen and 20-node solid FE model

The comparison of SNCF between the test specimen and the 20-node solid FE model showed that the maximum value occurred at the saddle of through brace near the lap brace (Table 5.3). The maximum difference of SNCF at this location was

0.48. The difference of SNCF in terms of percentage was 11.5% which was larger than the value of 7.1% obtained from the comparison of SNCF between the test specimen and the 8-node thick shell FE model described in the above section. However, the maximum difference of SNCF at 135° orientation on the lap brace measured from the crown heel was 15.9%. The difference in terms of numeric at this location was 0.18. The average difference was 10.6% which was slightly higher than the limit of 10% recommended by Gibstein (1978). As the maximum difference in terms of numeric was 0.48 which was less than the limit of 2 specified by ARSEM (1987), the SNCF obtained from the 20-node solid FE model under OPB load case was considered in reasonably good agreement with the test values.

8-node thick shell and 20-node solid FE model

The SCF distribution at the joint intersection of the through brace and lap brace of the 8-node thick shell and the 20-node solid FE models under OPB load case is presented in Fig. 5.3. Similar to the joint under IPB load case described in the previous section, the SCF distribution at the joint intersection of the chord and through brace was very small with maximum SCF less than 0.8 and thus neglected in the current study. In Fig. 5.3, ϕ is the angle orientation measured from the crown heel to the crown toe and then to the crown heel. The maximum SCF occurred at the saddle for every member. The maximum SCF of the joint was located at the saddle of through brace near the lap brace. At this location, the SNCF for the 8-node thick shell and the 20-node solid FE models were 4.46 and 4.64 respectively and the difference was 0.18 (Table 5.3). Both the maximum SNCF obtained from the FE models were greater than the experimental value. The SCF for the 8-node thick shell and the 20-node solid FE models were 5.16 and 5.37 respectively with a difference of only 0.21 (Fig. 5.3). Hence, it could be concluded that both the 8-node thick shell and the 20-node solid elements were suitable for modelling the completely overlapped tubular joint under OPB load case.

5.3 Comparison of HSS under Combined Loadings

The HSS obtained from the test specimen and the FE model under load cases 4, 5 and 6 (refer to Table 3.3) is summarized in Fig. 5.4. Since the SNCF and SCF of both 8-node thick shell and 20-node solid elements were in good agreement with the test values under basic loadings, the comparison of HSS in the current study was focus on the 8-node thick shell FE model and the test specimen.

5.3.1 Combined AX and IPB loading (Load case 4)

The comparison of HSS between the test specimen and the FE model under combined AX and IPB loading is shown in Fig. 5.4. As depicted in the figure, the maximum HSS of 76.3 and 72.8 MPa for the test specimen and the FE model respectively occurred at 45° orientation measured from the crown heel on the through brace near the lap brace. The HSS ratio of the FE model to the test specimen ranged from 0.77 to 1.49. As shown in Fig. 5.5(a), the stress distribution obtained from the FE model compares very well with the test results. The respective mean and standard deviation of the FE model to the test specimen ratio were found to be 1.02 and 0.13. The mean value of greater than unity indicated that the FE model yielded more conservative HSS. However, to avoid the scatter of experimental results due to very small stresses, the HSS of less than 2 MPa was not considered in the statistical analysis.

5.3.2 Combined IPB and OPB loading (Load case 5)

For the joint under combined IPB and OPB loading (Fig. 5.4), the maximum HSS of the test specimen and the FE model of 114.2 and 106.7 MPa respectively occurred at 315° orientation measured from the crown heel on the through brace near the lap brace. The HSS ratio of the FE model to the test specimen ranged from 0.76 to 1.40. The HSS of the FE model agreed reasonably well with that of the test specimen with the mean ratio and standard deviation of 1.04 and 0.14 respectively (Fig. 5.5(b)). Similar to the case for the joint under AX and IPB loading presented

in the previous section, the HSS of less than 2 MPa was not considered in the statistical analysis.

5.3.3 Combined AX, IPB and OPB loading (Load case 6)

The comparison of HSS for the joint under combined AX, IPB and OPB between the test specimen and the FE model is shown in Fig. 5.4. The maximum HSS of the test specimen and the FE model of 140.2 and 144.3 MPa respectively occurred at 270^0 orientation measured from the crown heel on the through brace near the lap brace. The HSS ratio of the FE model to the test specimen ranged from 0.83 to 1.34. The HSS of the FE model compared very well with that of the test specimen with the mean ratio and standard deviation of 1.03 and 0.13 respectively (Fig. 5.5(c)). The FE model yielded more conservative HSS than the test specimen.

5.4 Discussion and Concluding Remarks

The principal discrepancies between the experiment and the FE analysis can be identified as follow.

(1) Experimental errors

The accuracy of the experimental results can significantly be affected by the dimensional properties of test specimen, the weld profiles at joint intersections, the boundary conditions at member ends and the positions of stain gauges.

(2) Idealization of FE model

The accuracy of the FE results is greatly dependent on the use of element types, the degree of mesh refinements, the integration schemes, the inclusion of weld elements and the boundary conditions.

The comparison of SCF and SNCF between the test specimen and the FE models is generally considered satisfactorily if the individual and the average differences are not more than 20% and 10% respectively (Gibstein 1978). It should be noted that the comparison of SNCF between the 8-node thick shell FE model and the test

specimen in the current study showed that the maximum and average differences are (21.4%, 7.9%), (16.5%, 10.6%) and (9.9%, 5.8%) for the joint under AX, IPB and OPB load cases respectively. For the comparison of SNCF between the 20-node solid FE model and the test specimen, the respective differences are (21.2%, 8.8%), (18.9%, 10.7%) and (15.9%, 10.6%).

The above results showed that both the 8-node thick shell and the 20-node solid FE model compare reasonably well with the test specimen based on the limits specified by Gibstein (1978). Some SNCF are slightly higher than the limits. The main reason is attributed to the very small SNCF obtained from the experiment. However, the maximum difference of SNCF between the experiment and the FE analysis in terms of numeric is only 0.71. Hence, a judgment is necessary to determine if the difference of SNCF and SCF should be expressed in terms of percentage or numeric. ARSEM (1987) recommended from a comparative study that the difference of SCF between the test specimen and the FE models should be 2 and 4 for the tubular joints within and outside the validity ranges of geometrical parameters respectively. From this view point, it could be commented that both the 8-node thick shell and the 20-node solid FE models are well suitable for modelling the completely overlapped tubular joint configuration.

For the joint under combined loadings, the comparison of HSS between the 8-node thick shell FE model and the test specimen showed that the minimum and maximum HSS ratios are (0.77, 1.49), (0.76, 1.40) and (0.83, 1.34) under AX+IPB, IPB+OPB and AX+IPB+OPB load cases respectively. The difference of HSS for the joint under combined loadings is larger than that under basic loadings. This is attributed to the error of superposition approach to determine the stresses based on individual basic load case. Since the mean ratio and standard deviation are (1.02, 0.13), (1.04, 0.14) and (1.03, 0.13) under respective combined load case, the FE model is considered in good agreement with the test specimen.

From the comparison, the SNCF obtained from the 8-node thick shell and the 20-node solid FE models is close to that from the test specimen. Both the 8-node thick

shell and the 20-node solid FE models are suitable for modelling the joint. The comparison of SNCF with the test specimen showed that the discrepancy is less than 10% recommended by Gibstein (1978). However, it should be noted that the type of finite elements used in the analysis could significantly affect the accuracy of results as well as the efficiency of mesh generation. In the current study, the CPU time of using the 8-node thick shell and the 20-node solid elements to determine the stress and strain of the completely overlapped tubular joint specimen is 130 and 660 seconds respectively (Table 4.1). The CPU time to run the solid FE model is 5 times higher than the thick shell FE model. Furthermore, it is much easier to generate the FE mesh using the thick shell element than the solid element. In view of the accuracy of results and the efficiency of modelling, the 8-node thick shell FE model is adopted in the parametric study presented in the next chapter.

Table 5.1 Comparison of SNCF between test specimen and FE models under AX load case

Member	Location	Test specimen (1)	FE model				% difference	
			Thick shell (2)	Solid (3)	(4)=(1)-(2)	(5)=(1)-(3)		
Chord	CH-045	-0.56	-0.44	-0.62	-0.12	0.06	21.4%	10.7%
	CH-090	-1.51	-1.61	-1.68	0.10	0.17	6.6%	11.3%
	CH-135	-0.88	-0.82	-0.91	-0.06	0.03	6.8%	3.4%
	CH-180	0.52	0.55	0.63	-0.03	-0.11	5.8%	21.2%
Through brace (near chord)	TC-045	-0.68	-0.69	-0.54	0.01	-0.14	1.5%	20.6%
	TC-090	-2.59	-2.75	-2.30	0.16	-0.29	6.2%	11.2%
	TC-135	-0.93	-0.96	-0.83	0.03	-0.10	3.2%	10.8%
	TC-180	1.36	1.25	1.20	0.11	0.16	8.1%	11.8%
Through brace (near lap brace)	TL-000	-1.56	-1.72	-1.84	0.16	0.28	10.4%	18.3%
	TL-045	-2.41	-2.73	-2.83	0.32	0.42	13.1%	17.2%
	TL-090	-5.56	-6.05	-6.27	0.49	0.71	8.9%	12.8%
	TL-135	-4.33	-4.15	-4.46	-0.18	0.13	4.1%	3.1%
	TL-180	-3.28	-3.16	-3.22	-0.12	-0.06	3.6%	1.7%
	TL-225	-4.51	-4.15	-4.46	-0.36	-0.05	8.1%	1.2%
	TL-270	-5.79	-6.05	-6.27	0.26	0.48	4.5%	8.3%
	TL-315	-2.61	-2.73	-2.83	0.12	0.22	4.7%	8.6%
Lap brace	LP-000	-0.94	-1.10	-0.95	0.16	0.01	16.9%	1.2%
	LP-045	-1.26	-1.46	-1.25	0.20	-0.01	15.8%	1.0%
	LP-090	-3.15	-3.43	-3.23	0.28	0.08	9.0%	2.6%
	LP-135	-2.05	-1.95	-1.81	-0.10	-0.24	4.8%	11.7%
	LP-180	-1.57	-1.65	-1.46	0.08	-0.11	4.8%	7.2%
	LP-225	-2.00	-1.90	-1.81	-0.10	-0.19	4.9%	9.4%
	LP-270	-3.26	-3.43	-3.23	0.17	-0.03	5.3%	0.8%
	LP-315	-1.33	-1.46	-1.25	0.14	-0.08	10.3%	5.7%
Average % difference							7.9%	8.8%

Table 5.2 Comparison of SNCF between test specimen and FE models under IPB load case

Member	Location	Test specimen (1)	FE model			% difference (5)/(1)
			Thick shell (2)	Solid (3)	(4)=(1)-(2) (5)=(1)-(3)	
Chord	CH-045	-0.18	-0.19	-0.23	0.05	-
	CH-090	-0.08	-0.17	-0.20	0.12	-
	CH-135	0.20	0.24	0.25	-0.05	-
	CH-180	0.16	0.11	0.14	0.02	-
Through brace (near chord)	TC-045	-0.10	-0.12	-0.09	-0.01	-
	TC-090	-0.15	-0.08	-0.13	-0.02	-
	TC-135	0.35	0.36	0.32	0.03	-
	TC-180	0.04	0.07	0.05	-0.01	-
Through brace (near lap brace)	TL-000	-1.21	-1.25	-1.33	0.12	3.6%
	TL-045	-1.49	-1.30	-1.41	-0.08	12.7%
	TL-090	-0.02	0.12	0.15	-0.17	-
	TL-135	1.25	1.43	1.48	-0.23	14.9%
	TL-180	1.57	1.63	1.71	-0.14	4.0%
	TL-225	1.29	1.43	1.48	-0.19	10.7%
	TL-270	0.01	0.12	0.15	-0.14	-
	TL-315	-1.56	-1.30	-1.41	-0.15	16.5%
Lap brace	LP-000	-1.73	-1.66	-1.62	-0.11	3.6%
	LP-045	-1.55	-1.34	-1.27	-0.28	13.6%
	LP-090	-0.52	-0.25	-0.23	-0.29	-
	LP-135	0.77	0.89	0.73	0.04	15.7%
	LP-180	1.27	1.47	1.32	-0.05	15.7%
	LP-225	0.84	0.89	0.73	0.11	5.5%
	LP-270	-0.42	-0.25	-0.23	-0.19	-
	LP-315	-1.50	-1.34	-1.27	-0.23	10.9%
Average % difference					10.6%	10.7%

Table 5.3 Comparison of SNCF between test specimen and FE models under OPB load case

Member	Location	Test specimen (1)	FE model			% difference	
			Thick shell (2)	Solid (3)	(4)=(1)-(2)	(5)=(1)-(3)	(4)/(1) (5)/(1)
Chord	CH-045	0.40	0.35	0.42	0.05	-0.02	-
	CH-090	0.59	0.63	0.69	-0.04	-0.10	-
	CH-135	-0.17	-0.07	-0.12	-0.10	-0.05	-
	CH-180	0.01	0.00	0.00	0.01	0.01	-
Through brace (near chord)	TC-045	0.23	0.22	0.18	0.01	0.05	-
	TC-090	0.62	0.68	0.62	-0.06	0.00	-
	TC-135	-0.31	-0.19	-0.15	-0.12	-0.16	-
	TC-180	-0.04	0.00	0.00	-0.04	-0.04	-
Through brace (near lap brace)	TL-000	0.16	0.00	0.00	0.16	0.16	-
	TL-045	1.90	1.85	2.05	0.05	-0.15	2.5% 7.8%
	TL-090	4.16	4.46	4.64	-0.29	-0.48	7.1% 11.5%
	TL-135	2.11	2.00	2.27	0.12	-0.16	5.5% 7.6%
	TL-180	-0.10	0.00	0.00	-0.10	-0.10	-
	TL-225	-2.05	-2.00	-2.35	-0.06	0.30	2.7% 14.6%
	TL-270	-4.34	-4.46	-4.64	0.12	0.30	2.7% 6.9%
	TL-315	-1.99	-1.85	-2.27	-0.14	0.28	6.9% 14.1%
Lap brace	LP-000	0.26	0.00	0.00	0.26	0.26	-
	LP-045	1.03	0.94	0.90	0.09	0.13	9.0% 12.7%
	LP-090	1.95	2.11	1.80	-0.16	0.15	8.1% 7.8%
	LP-135	1.15	1.19	0.97	-0.03	0.18	2.9% 15.9%
	LP-180	0.04	0.00	0.00	0.04	0.04	-
	LP-225	-1.11	-1.19	-0.97	0.08	-0.14	6.9% 12.6%
	LP-270	-1.92	-2.11	-1.80	0.19	-0.12	9.9% 6.2%
	LP-315	-0.99	-0.94	-0.90	-0.05	-0.09	5.3% 9.1%
Average % difference						5.8%	10.6%

**Fig. 5.1 (a) SCF distributions at joint intersection under AX load case
- chord and through brace**

Fig. 5.1 (b) SCF distributions at joint intersection under AX load case - through brace and lap brace

**Fig. 5.2 SCF distributions at joint intersection under IPB load case
- through brace and lap brace**

**Fig. 5.3 SCF distributions at joint intersection under OPB load case
- through brace and lap brace**

Fig. 5.4 Comparison of HSS between test specimen and FE model under combined load cases

Fig. 5.5 Comparison of HSS between test results and FE analyses

CHAPTER 6

PARAMETRIC STUDY

6.1 Introduction

The stress distribution at the chord and the brace intersection of a tubular joint is complex and non-uniform. The analytical solution to determine the stress distribution at the joint intersection is almost impossible. The commonly used techniques to determine the stress distribution are the experimental investigation and the numerical method. Generally speaking, the most appropriate method to determine the stress concentration of a tubular joint is by testing a full-scale strain gauged specimen with practical size of weld. However, the high cost of fabricating a large capacity test rig and facilities prevents the comprehensive study of the joints with various geometrical parameters and load conditions. As a result, the FE method becomes the most widely used technique for modelling the joint to determine the stress distribution. In the current study, the test of the joint specimen is carried out for the purpose of verifying the joint model for detailed analysis.

In this chapter, the influence of geometrical parameters on the SCF of completely overlapped tubular joints is investigated. The load condition is unbalanced and the joint is subjected to lap brace AX, IPB and OPB loadings. Throughout the analysis, the joint under axial load case is subjected to lap brace axial compression. It should be noted in the current study that the positive and negative SCF indicated that the stresses at the weld toe of the joint are in tension and compression respectively. All the FE models are generated and analyzed using the commercial FE package MARC (2001) with pre- and post-processing programs MENTAT. The 8-node thick shell element (MARC element type 22) is adopted in the current parametric study for creating the meshes of all the joint models. The Young's modulus (E) and the Poisson's ratio (ν) of steel material are taken as 200 kN/mm^2 and 0.3 respectively.

6.2 Effect of Member Length Parameters

6.2.1 Chord length parameter, α_C

The effect on the SCF of completely overlapped tubular joints is studied by varying the parameters α_C (4, 8, 12, 16, 20, 24, 28 and 32) and γ_C (8, 16, 24 and 32). Three basic load cases (AX, IPB and OPB) are considered and the loads are applied at the end of lap brace. The SCF at the joint intersection of the through brace and lap brace is not included in view that the chord length parameter mainly affects the SCF at the joint intersection of the chord and through brace, as depicted in Fig. 6.1. Only the SCF at the crown heel, saddle and crown toe of members are examined and the results are summarized as follow.

AX load case

- SCF at saddle of CH and TC decreases with increasing α_C .
- SCF at saddle of CH and TC remains constant at $\alpha_C > 12$.

IPB load case

- SCF at crown heel of CH and TC remains constant at $\alpha_C > 12$.

OPB load case

- SCF at saddle of CH and TC decreases with increasing α_C .
- Small variation of SCF at saddle of CH and TC at $\alpha_C > 12$.

The chord length effect on the SCF of the joint under three basic load cases at $\alpha_C > 12$ is negligible. Hence, the use of chord length parameter of $\alpha_C = 12$ to avoid the short chord effect in the current parametric study is considered to be acceptable.

6.2.2 Through brace length parameter, α_T

The effect on the SCF of completely overlapped tubular joints is studied by varying the parameters α_T (4, 8, 12, 16, 20, 24, 28 and 32) and γ_T (8, 16, 24 and 32). The SCF at the joint intersection of the chord and through brace is not considered as large SCF occurs at the joint intersection of the through brace and lap brace, as

depicted in Fig. 6.2. Similar to the case of α_C presented in the previous section, the SCF at the crown heel, saddle and crown toe of members are considered in the current study.

AX load case

- SCF at saddle of TL and LP increases with increasing α_T .
- SCF at saddle of TL and LP remains constant at $\alpha_T > 8$.

IPB load case

- SCF at crown heel of TL and LP decreases with increasing α_T .
- SCF at crown heel of TL and LP remains constant at $\alpha_T > 12$.

OPB load case

- SCF at saddle of TL and LP increases with increasing α_T .
- SCF at saddle of TL and LP remains constant at $\alpha_T > 8$.

The through brace length parameter has no effect on the SCF of the joint under AX and OPB at $\alpha_T > 8$ and under IPB load case at $\alpha_T > 12$. Hence, the use of through brace length parameter of $\alpha_T = 12$ to avoid the short through brace length effect in the current parametric study is considered to be acceptable.

6.2.3 Boundary conditions

Two support conditions (fixed and pinned) at the ends of members are examined. The lengths of the chord and the through brace are varied to study the effect. From the results, it is found that the SCF of members are identical to those presented in Figs. 6.1 and 6.2 in the previous sections. It can therefore be concluded that the SCF of completely overlapped tubular joints is not affected by the fixed or pinned boundary conditions at the ends of the chord and the through brace. In the current parametric study, the boundary conditions of the chord and the through brace are assumed to be fixed.

6.3 Effect of Through Brace-to-Chord Diameter Ratio, β_{CT}

6.3.1 Chord radius-to-wall thickness ratio, γ_C

In this section, the effect on the SCF of completely overlapped tubular joints is studied by varying the parameters β_{CT} (0.4, 0.6 and 0.8) and γ_C (8, 16, 24 and 32). The distribution of maximum SCF for the joint under basic load cases is summarized in Table 6.1. The SCF at the hot spot locations of the joint are shown in Fig. 6.3. The following results from Table 6.1 and Fig. 6.3 are specifically noted.

AX load case

- Maximum SCF at small and medium γ_C occurs at crown toe of LP.
- Maximum SCF at medium and large γ_C occurs at saddle of LP.
- SCF at saddle of LP increases with increasing γ_C .
- SCF increases with increasing β_{CT} .

IPB load case

- Maximum SCF shifts from crown heel of LP to TL as γ_C increases.
- SCF at crown heel of TL increases with increasing β_{CT} .
- SCF at crown heel of TL decreases with decreasing γ_C .
- SCF at crown heel of LP decreases with increasing γ_C .

OPB load case

- Maximum SCF occurs at saddle of LP.
- SCF increases with increasing β_{CT} and γ_C .

6.3.2 Through brace-to-chord wall thickness ratio, τ_{CT}

In this section, the effect on the SCF of completely overlapped tubular joints is studied by varying the parameters β_{CT} (0.4, 0.6 and 0.8) and τ_{CT} (0.4, 0.6, 0.8 and 1.0). The distribution of maximum SCF for the joint under basic load cases is summarized in Table 6.2. The SCF at the hot spot locations of the joint are shown in Fig. 6.4. The following results from Table 6.2 and Fig. 6.4 are specifically noted.

AX load case

- Maximum SCF at small τ_{CT} occurs at saddle of LP.
- Maximum SCF at medium and large τ_{CT} occurs at crown toe of LP.
- SCF at saddle of LP decreases with increasing τ_{CT} .

IPB load case

- Maximum SCF shifts from crown heel of TL to LP as τ_{CT} increases.
- SCF at crown heel of TL increases with increasing β_{CT} .
- SCF at crown heel of TL decreases with increasing τ_{CT} .
- SCF at crown heel of LP decreases with decreasing τ_{CT} .

OPB load case

- Maximum SCF occurs at saddle of LP.
- SCF decreases with decreasing β_{CT} .
- SCF decreases with increasing τ_{CT} .

6.4 Effect of Lap Brace-to-Through Brace Diameter Ratio, β_{TL} **6.4.1 Through brace radius-to-wall thickness ratio, γ_T**

In this section, the effect on the SCF of completely overlapped tubular joints is studied by varying the parameters β_{TL} (0.4, 0.6 and 0.8) and γ_T (8, 16, 24 and 32). The distribution of maximum SCF for the joint under basic load cases is summarized in Table 6.3. The SCF at the hot spot locations of the joint are shown in Fig. 6.5. The following results from Table 6.3 and Fig. 6.5 are specifically noted.

AX load case

- Maximum SCF shifts from saddle of LP to TL as γ_T increases.
- SCF increases with decreasing β_{TL} .
- SCF increases with increasing γ_T .

IPB load case

- Maximum SCF shifts from crown heel of LP to TL as γ_T increases.
- SCF at crown heel of TL increases with increasing γ_T .

- SCF at crown heel of LP increases with decreasing γ_T .

OPB load case

- Maximum SCF shifts from saddle of LP to TL as γ_T increases.
- SCF at saddle of TL increases with decreasing β_{TL} .
- SCF increases with increasing γ_T .

6.4.2 Lap brace-to-through brace wall thickness ratio, τ_{TL}

In this section, the effect on the SCF of completely overlapped tubular joints is studied by varying the parameters β_{TL} (0.4, 0.6 and 0.8) and τ_{TL} (0.4 0.6 0.8 and 1.0). The distribution of maximum SCF for the joint under basic load cases is summarized in Table 6.4. The SCF at the hot spot locations of the joint are shown in Fig. 6.6. The following results from Table 6.4 and Fig. 6.6 are specifically noted.

AX load case

- Maximum SCF shifts from saddle of TL to TC as β_{TL} increases.
- SCF at saddle of TC increases with increasing β_{TL} .
- SCF at saddle of TL increases with decreasing β_{TL} .
- SCF increases with increasing τ_{TL} .

IPB load case

- Maximum SCF at small and medium τ_{TL} occurs at crown heel of TL.
- Maximum SCF at medium and large τ_{TL} shifts from crown heel to crown toe of TL as β_{TL} increases.
- SCF increases with increasing τ_{TL} .

OPB load case

- Maximum SCF shifts from saddle of TL to LP as β_{TL} increases.
- SCF at saddle of TL increases with decreasing β_{TL} .
- SCF at saddle of LP increases with increasing β_{TL} .
- SCF increases with increasing τ_{TL} .

6.5 Effect of Through Brace-to-Chord Wall Thickness Ratio, τ_{CT}

6.5.1 Chord radius-to-wall thickness ratio, γ_C

In this section, the effect on the SCF of completely overlapped tubular joints is studied by varying the parameters τ_{CT} (0.4, 0.6, 0.8 and 1.0) and γ_C (8, 16, 24 and 32). The distribution of maximum SCF for the joint under basic load cases is summarized in Table 6.5. The SCF at the hot spot locations of the joint are shown in Fig. 6.7. The following results from Table 6.5 and Fig. 6.7 are specifically noted.

AX load case

- Maximum SCF at small γ_C occurs at crown toe of LP.
- Maximum SCF at medium and large γ_C occurs at crown toe of TL.
- SCF at crown toe of TL increases with decreasing τ_{CT} .
- SCF increases with increasing γ_C .

IPB load case

- Maximum SCF shifts from crown heel of LP to TL as γ_C increases.
- SCF at crown heel of TL decreases with increasing τ_{CT} .
- SCF at crown heel of LP decreases with decreasing τ_{CT} .
- SCF at crown heel of TL decreases with decreasing γ_C .
- SCF at crown heel of LP decreases with increasing γ_C .

OPB load case

- Maximum SCF always occurs at saddle of LP.
- SCF increases with decreasing τ_{CT} .
- SCF increases with increasing γ_C .

6.5.2 Lap brace-to-through brace wall thickness ratio, τ_{TL}

In this section, the effect on the SCF of completely overlapped tubular joints is studied by varying the parameters τ_{CT} (0.4, 0.6, 0.8 and 1.0) and τ_{TL} (0.4, 0.6, 0.8 and 1.0). The distribution of maximum SCF for the joint under basic load cases is

summarized in Table 6.6. The SCF at the hot spot locations are shown in Fig. 6.8. The following results from Table 6.6 and Fig. 6.8 are specifically noted.

AX load case

- Maximum SCF at small and medium τ_{TL} occurs at crown toe of LP.
- Maximum SCF at medium and large τ_{TL} occurs at crown toe of TL.
- SCF at crown toe of TL decreases with increasing τ_{CT} .
- Large SCF at crown toe of LP occurs at $\tau_{CT}=0.7-0.8$.
- SCF at crown toe of TL decreases with decreasing τ_{TL} .

IPB load case

- Maximum SCF shifts from crown heel of LP to TL as τ_{TL} increases.
- SCF at crown heel of LP decreases with decreasing τ_{CT} .
- SCF at crown heel of TL decreases with increasing τ_{CT} (0.4-0.7), and begins to saturate at $\tau_{CT}=0.7$.
- SCF at crown heel of TL decreases with decreasing τ_{TL} .
- SCF at crown heel of LP decreases with increasing τ_{TL} .

OPB load case

- Maximum SCF at small and medium τ_{TL} occurs at saddle of LP.
- Maximum SCF at large τ_{TL} occurs at saddle of TL.
- SCF increases with decreasing τ_{CT} .
- SCF increases with increasing τ_{TL} .

6.6 Effect of Lap Brace-to-Through Brace Wall Thickness Ratio, τ_{TL}

6.6.1 Through brace radius-to-wall thickness ratio, γ_T

In this section, the effect on the SCF of completely overlapped tubular joints is studied by varying the parameters τ_{TL} (0.4, 0.6, 0.8 and 1.0) and γ_T (8, 16, 24 and 32). The distribution of maximum SCF for the joint under basic load cases is summarized in Table 6.7. The SCF at the hot spot locations of the joint are shown in Fig. 6.9. The following results from Table 6.7 and Fig. 6.9 are specifically noted.

AX load case

- Maximum SCF shifts from crown toe of LP to saddle of TL as τ_{TL} increases.
- SCF at saddle of TL increases with increasing τ_{TL} and γ_T .
- Large SCF at crown toe of LP occurs at $\tau_{TL}=0.6-0.7$.

IPB load case

- Maximum SCF at small and medium τ_{TL} occurs at crown heel of LP.
- Maximum SCF at medium and large τ_{TL} occurs at crown heel of TL.
- SCF at crown heel of TL decreases with decreasing τ_{TL} .
- Large SCF at crown heel of LP occurs in between $\tau_{TL}=0.6-0.7$.
- SCF at crown heel of TL decreases with decreasing γ_T .
- SCF at crown heel of LP decreases with increasing γ_T .

OPB load case

- Maximum SCF at small and medium τ_{TL} occurs at saddle of LP.
- Maximum SCF at medium and large τ_{TL} occurs at saddle of TL.
- SCF at saddle of TL increases with increasing τ_{TL} .
- SCF at saddle of LP increases with increasing τ_{TL} (0.4-0.7), and begins to saturate at $\tau_{TL}=0.7$.
- SCF decreases with decreasing γ_T .

6.7 Effect of Gap Size-to-Through Brace Diameter Ratio, ξ_T

The gap size (g_T) of the completely overlapped joint on the through brace surface between the outer surfaces of the chord and the lap brace is an important parameter. The minimum requirements of the gap size for the gap joints specified in the codes are reviewed in the current section. Several codes are selected for comparison as shown in Table 6.8. It should be noted that in the current FE analysis of the joint model, the minimum gap distance (g_{min}) is set at 51 mm. The gap size of 51 mm is commonly provided to allow for proper welding for simple gap joints. The maximum gap distance (g_{max}) however is equivalent to the clear distance between the outer surface of the lap brace to the other end of the through brace support. The definition of the minimum and the maximum gap distances for the completely

overlapped tubular joint can be seen in Fig. 6.10. In the current study, a non-dimensional parameter $\xi_T (=g_T/d_T)$ is introduced to examine the gap size effect on the SCF of the joint.

6.7.1 Chord radius-to-wall thickness ratio, γ_C

In this section, the effect on the SCF of completely overlapped tubular joints is studied by varying the parameters ξ_T (0.25, 0.50, 0.75, 1.00, 1.25 and 1.50) and γ_C (8, 16, 24 and 32). The distribution of maximum SCF for the joint under basic load cases is summarized in Table 6.9. The SCF at the hot spot locations of the joint are shown in Fig. 6.11. The following results from Table 6.9 and Fig. 6.11 are specifically noted.

AX load case

- Maximum SCF at small ξ_T occurs at saddle of TC.
- Maximum SCF shifts from crown toe of LP to crown toe of TL, and to saddle of TL as γ_C increases.
- SCF decreases with decreasing ξ_T .
- SCF increases with increasing γ_C .

IPB load case

- Maximum SCF at small γ_C occurs at crown heel of LP.
- Maximum SCF at medium and large γ_C occurs at crown heel of TL.
- SCF increases with increasing ξ_T (0.25-0.5) and remains constant at $\xi_T=0.5$.
- SCF at crown heel of TL decreases with decreasing γ_C .
- SCF at crown heel of LP decreases with increasing γ_C .

OPB load case

- Maximum SCF occurs at saddle of TL.
- SCF increases with increasing ξ_T .
- SCF increases with increasing γ_C .

6.7.2 Lap brace-to-through brace wall thickness ratio, τ_{TL}

In this section, the effect on the SCF of completely overlapped tubular joints is studied by varying the parameters ξ_T (0.25, 0.50, 0.75, 1.00, 1.25 and 1.50) and τ_{TL} (0.4, 0.6, 0.8 and 1.0). The distribution of maximum SCF for the joint under basic load cases is summarized in Table 6.10. The SCF at the hot spot locations of the joint are shown in Fig. 6.12. The following results from Table 6.10 and Fig. 6.12 are specifically noted.

AX load case

- Maximum SCF at small and medium τ_{TL} occurs at crown toe of LP.
- Maximum SCF at medium and large τ_{TL} occurs at saddle of TL.
- SCF decreases with decreasing ξ_T .
- SCF at saddle of TL increases with increasing τ_{TL} .

IPB load case

- Maximum SCF at small and medium τ_{TL} occurs at crown heel of LP.
- Maximum SCF at medium and large τ_{TL} occurs at crown heel of TL.
- SCF increases with increasing ξ_T (0.25-0.5) and remains constant at $\xi_T=0.5$.
- SCF at crown heel of TL decreases with decreasing τ_{TL} .
- SCF at crown heel of LP decreases with increasing τ_{TL} .

OPB load case

- Maximum SCF at small and medium τ_{TL} occurs at saddle of LP.
- Maximum SCF at medium and large τ_{TL} occurs at saddle of TL.
- SCF increases with increasing ξ_T and τ_{TL} .

6.7.3 Through brace-to-chord wall thickness ratio, τ_{CT}

In this section, the effect on the SCF of completely overlapped tubular joints is investigated by varying the parameters ξ_T (0.25, 0.50, 0.75, 1.00, 1.25 and 1.50) and τ_{CT} (0.4, 0.6, 0.8 and 1.0). The distribution of maximum SCF for the joint under basic load cases is summarized in Table 6.11. The SCF at the hot spot locations of

the joint are shown in Fig. 6.13. The following results from Table 6.11 and Fig. 6.13 are specifically noted.

AX load case

- Maximum SCF at small ξ_T occurs at saddle of TC.
- Maximum SCF at medium and large ξ_T occurs at saddle of TL.
- SCF at saddle of TL increases with increasing ξ_T .
- SCF decreases with increasing τ_{CT} .

IPB load case

- Maximum SCF occurs at crown heel of TL.
- SCF increases with increasing ξ_T (0.25-0.5) and remains constant at $\xi_T=0.5$.
- SCF at crown heel of TL decreases with increasing τ_{CT} .
- SCF at crown heel of LP decreases with decreasing τ_{CT} .

OPB load case

- Maximum SCF occurs at saddle of TL.
- SCF increases with increasing ξ_T .
- SCF increases with decreasing τ_{CT} .

6.8 Effect of Angle between Chord and Through Brace, θ

6.8.1 Chord radius-to-wall thickness ratio, γ_C

In this section, the effect on the SCF of completely overlapped joints is studied by varying the parameters θ (30° , 45° and 60°) and γ_C (8, 16, 24 and 32). The distribution of maximum SCF for the joint under basic load cases is summarized in Table 6.12. The SCF at the hot spot locations of the joint are shown in Fig. 6.14. The following results from Table 6.12 and Fig. 6.14 are specifically noted.

AX load case

- Maximum SCF shifts from saddle of LP to crown toe of LP as θ increases.
- SCF at saddle of LP increases with decreasing θ .

- Large SCF at crown toe of LP occurs at $\theta=40^\circ$ - 45° .
- SCF increases with increasing γ_C .

IPB load case

- Maximum SCF occurs at crown heel of TL or LP.
- SCF at crown heel of TL decreases with increasing θ .
- SCF at crown heel of TL decreases with decreasing γ_C .
- SCF at crown heel of LP decreases with increasing γ_C .

OPB load case

- Maximum SCF occurs at saddle of LP.
- SCF increases with decreasing θ .
- SCF increases with increasing γ_C .

6.8.2 Through brace-to-chord wall thickness ratio, τ_{CT}

In this section, the effect on the SCF of completely overlapped joints is studied by varying the parameters θ (30° , 45° and 60°) and τ_{CT} (0.4, 0.6, 0.8 and 1.0). The distribution of maximum SCF for the joint under basic load cases is summarized in Table 6.13. The SCF at the hot spot locations of the joint are shown in Fig. 6.15. The following results from Table 6.13 and Fig. 6.15 are specifically noted.

AX load case

- SCF increases with decreasing θ .
- SCF increases with decreasing τ_{CT} .

IPB load case

- Maximum SCF occurs at crown heel of TL.
- SCF decreases with increasing θ .
- SCF at crown heel of TL decreases with increasing τ_{CT} .
- SCF at crown heel of LP decreases with decreasing τ_{CT} .

OPB load case

- Maximum SCF always occurs at saddle of LP.
- SCF increases with decreasing θ and τ_{CT} .

6.9 Discussions

Chord and through brace length parameters

Efthymiou and Durkin (1985) commented from their research study that simple T/Y joints with short chord ($\alpha < 12$) exhibited a significant reduction of SCF at the saddle. The SCF of a simple T-joint with a short chord ($\alpha = 5$) and large γ could have half of that for a joint with a long chord ($\alpha > 12$). For the simple T/Y joint with $\alpha > 12$, the SCF was not significantly affected by the chord length parameter.

In the current study, the SCF of the completely overlapped joint decreases with increasing α_C when $\alpha_C < 12$ (see Fig. 6.1). The reason for this behaviour is attributed to the load distribution among members at the joint. For the completely overlapped tubular joint configuration with lap brace loaded, the chord length parameter significantly affects the load transfer mechanism from the lap brace to the through brace. Generally speaking, the joint with short chord contributes smaller load transfer from the lap brace to the through brace as the load is mainly supported by the end supports of the chord. The current numerical results showed that 20%, 38% and 55% of the applied load are transferred from the lap brace to the through brace at $\alpha_C = 4, 8$ and 12 respectively. On the other hand, for the joint with long chord ($\alpha_C > 12$), the chord length parameter has less impact on the load transfer mechanism among members at the joint. Similar to the study for simple T/Y joints, the SCF of the completely overlapped tubular joint is not significantly affected with long chord length parameter ($\alpha_C > 12$).

For the case of bending moment, the chord length parameter has minimum impact on the SCF of the completely overlapped tubular joint. The maximum SCF obtained in the analysis at the intersection of the chord and through brace is very small, less than 1.2. It is important to realize that the chord length parameter showed no effect on the SCF at the intersection of the through brace and lap brace for the joint under basic load cases.

For the effect of through brace length parameter, the trend of SCF at the saddle of through brace and lap brace for the joint under AX loading is similar to that of simple T/Y joints with the through brace acting as a chord. The completely overlapped joint with short through brace length parameter ($\alpha_T < 8$) showed a reduction of SCF at the saddle due to the restriction of through brace ovalization by end supports. However, the reduction of SCF is found to be smaller than that of simple T/Y joints. The SCF of the completely overlapped joint with short through brace length of $\alpha_T = 4$ and large γ_T ratio is 82% of that with long through brace length of $\alpha_T > 12$. It is noted that the boundary condition of through brace on the surface of chord is determined by the shear and bending rigidity of the chord wall.

Maximum SCF distribution

In the FE analysis, the SCF of 5184 FE models are determined based on 12 hot spot locations for a joint. These hot spot locations include the crown heel, saddle and crown toe at the joint intersections of the chord and through brace and the through brace and lap brace. The hot spot locations of completely overlapped tubular joints are selected according to those of uni-planar and multi-planar tubular joints. The load condition is unbalanced with the joint subjected to basic loads at the end of lap brace. The boundary conditions of the chord and the through brace are fixed. The distribution of maximum SCF for the joint under AX, IPB and OPB load cases is presented in Fig. 6.16.

Based on the statistical analysis, the results of the maximum SCF distribution of 5184 FE models subjected to lap brace AX loading as shown in Fig. 6.16(a) are summarized as follow.

- Frequency of occurrences of maximum SCF at saddle and crown toe of TL, saddle and crown toe of LP is 22.4%, 15.7%, 16.9% and 36.7% respectively.
- Frequency of occurrences of maximum SCF at saddle of chord, saddle and crown toe of TC is 1.2%, 4.0% and 2.4% respectively.

- Frequency of occurrences of maximum SCF at crown heel of TC and LP is minimal and only 0.2% and 0.5% respectively.
- Maximum SCF do not occur at crown heel and crown toe of chord, and crown heel of TL.
- Maximum SCF range from 1.54 to 29.9.

The results of the maximum SCF distribution for the joint subjected to lap brace IPB loading as shown in Fig. 6.16(b) are summarized as follow.

- Frequency of occurrences of maximum SCF at crown heel of TL and LP is 51.7% and 43.2% respectively.
- Frequency of occurrences of maximum SCF at crown toe of TL and LP is 2.2% and 2.9% respectively.
- Maximum SCF do not occur at CH, TC and saddle of TL and LP.
- Maximum SCF range from 1.38 to 8.19.

The results of the maximum SCF distribution for the joint subjected to lap brace OPB loading as shown in Fig. 6.16(c) revealed that the frequency of occurrences of maximum SCF at saddle of TL and LP is 43.9% and 56.1% respectively. Maximum SCF range from 1.26 to 26.8.

Gap size parameters

For a simple gap K-joint, the gap region is between the two braces on the chord surface. For a completely overlapped tubular joint, the gap region is on the through brace surface between the outer surfaces of the chord and the lap brace. In the current parametric study, a non-dimensional gap size parameter (ξ_T) is defined as $\xi_T = g_T/d_T$, which is similar to that of g/D defined in the gap K-joint.

For the completely overlapped tubular joint under lap brace AX and OPB loadings, the SCF at the saddle of through brace and lap brace increases with increasing ξ_T . At small gap size, the through brace is restraint from ovalization due to stiffening effect of weld and chord wall thickness. As gap size increases, the ovalization effect

decreases and results in the increase of SCF at the saddle of through brace and lap brace. The SCF at the saddle of through brace near the lap brace at small $\tau_{CT}=0.4$ increases from 4.31 to 9.95 with increasing ξ_T from 0.25 to 1.50.

For the joint under IPB moment, the non-dimensional gap size parameter (ξ_T) does not have any impact on the SCF of completely overlapped tubular joints when $\xi_T > 0.5$. At small gap size ($0.25 < \xi_T < 0.5$), the SCF at the crown toe and crown heel of through brace and lap brace increases with increasing ξ_T . This is attributed to the localized effect of shell deformation of through brace. As gap size of the completely overlapped joint increases, the effect of local shell deformation of through brace becomes less significant. As a result, the SCF at the crown toe and crown heel of the joint is smaller in comparison to that of the joint with large gap size.

Geometrical parameters of joint

There are several ways to minimize SCF of tubular joints. Although the use of cast steel nodes or seamless nodes enables the SCF to be reduced, the cost of fabrication is too expensive. Alternatively, overlapping the braces, increasing the joint diameter ratio, or the combination of these methods could also reduce the SCF. For the completely overlapped tubular joint, the SCF is found to be considerably lower in comparison to that of simple T/Y joints. Furthermore, the joint could have a similar fabrication as simple gap joints. The maximum SCF always occurs at the joint intersection of the through brace and lap brace, which allows the use of a thinner chord wall. Thus, the economic design of offshore steel jackets with the use of completely overlapped tubular joint configuration has great application potential.

In the current parametric study, eight (8) different geometric parameters are considered to examine the effects on the SCF of the joint. These parameters include,

- through brace-to-chord diameter ratio (β_{CT})
 - lap brace-to-through brace diameter ratio (β_{TL})
 - angle between chord and through brace (θ)
 - gap size-to-through brace diameter ratio (ξ_T)
-

- through brace-to-chord wall thickness ratio (τ_{CT})
- lap brace-to-through brace wall thickness ratio (τ_{TL})
- chord radius-to-wall thickness ratio (γ_C)
- through brace radius-to-wall thickness ratio (γ_T)

The main objective of the study is to better understand the relationship between these geometric parameters and the SCF so that tubular joints with complete overlap of braces can effectively be designed to resist fatigue loading.

The trend of the eight (8) geometric parameters on the SCF under basic load cases is summarized in Table 6.14. For the joint under lap brace AX loading, the SCF increases with increasing β_{CT} , τ_{TL} , ξ_T , γ_C and γ_T , but decreases with increasing τ_{CT} and θ . In other words, the SCF at the hot spot locations for the joint under AX loading can be reduced by,

- decreasing lap brace wall thickness
- increasing through brace wall thickness
- decreasing gap size between chord and lap brace
- increasing angle between chord and through brace

It is also observed that the SCF at the saddle of TC increases with increasing β_{TL} but the SCF at the saddle and crown toe of TL, and the saddle of LP increases with decreasing β_{TL} . For this case, it is recommended to use medium geometric parameters for joint design to avoid sudden increase of SCF due to smaller or larger geometric parameters.

For the completely overlapped joint under lap brace IPB moment, the SCF at the crown heel of TL and LP as shown in Fig. 6.16(b) are investigated. From Table 6.14, the SCF increases with increasing β_{CT} and τ_{TL} , but decreases with increasing θ . It is commented that the SCF of the joint under IPB bending can be reduced by,

- increasing chord diameter
- decreasing through brace diameter
- increasing through brace wall thickness

- decreasing lap brace wall thickness
- increasing angle between chord and through brace

It is also observed from geometrical parameters τ_{CT} , γ_C and γ_T that the trends of SCF at the crown heel of TL and LP do not coincide. Hence, it is suggested that medium geometrical parameters should be adopted to avoid sudden increase of SCF at the hot spot location of the joint. However, it should be noted that ξ_T and β_{TL} show no effects on the SCF of the joint.

For the completely overlapped joint under lap brace OPB moment as shown in Fig. 6.16(c), the SCF at the saddle of TL and LP are investigated. As shown in Table 6.14, the trend of SCF obtained for the joint under OPB loading is very similar to that under AX loading. The SCF increases with increasing β_{CT} , τ_{TL} , ξ_T , γ_C and γ_T , but decreases with increasing β_{TL} , τ_{CT} and θ . It is commented that the SCF of the joint under OPB loading can be reduced by,

- increasing lap brace diameter
- decreasing lap brace wall thickness
- increasing through brace wall thickness
- decreasing gap size between chord and lap brace
- increasing angle between chord and through brace

6.10 Concluding Remarks

A numerical study is extensively carried out to investigate the geometric parameters effects on the SCF of completely overlapped joints under basic load cases. A total of 5184 FE models are created with various geometric parameters for investigation. The boundary condition at the ends of the chord and the through brace is considered fixed. The length parameters for the chord (α_c) and the through brace (α_T) are set at 16 and 12 respectively. It is confirmed that the fixed or pinned boundary condition and a length parameter of greater than 12 show no significant effects on the SCF of completely overlapped tubular joints. The Young's modulus and the Poisson's ratio of steel material in the FE models are taken as 200 kN/mm² and 0.3 respectively.

For the parametric study, eight (8) geometric parameters are considered to study the effects on the SCF of completely overlapped tubular joints. These parameters include β_{CT} , β_{TL} , θ , ξ_T , τ_{CT} , τ_{TL} , γ_C and γ_T . It is concluded that for the joint under AX load, the maximum SCF always occurs at the saddle and crown toe of TL and LP. The SCF is found to increase with increasing β_{CT} , τ_{TL} , ξ_T , γ_C and γ_T , but decrease with increasing τ_{CT} and θ . On the other hand, for the joint under IPB moment, the maximum SCF occurs at the crown heel of TL and LP. The SCF increases with increasing β_{CT} and τ_{TL} , but decreases with increasing θ . For the joint under OPB moment, the maximum SCF occurs at the saddle of TL and LP. The SCF increases with increasing β_{CT} , τ_{TL} , ξ_T , γ_C and γ_T , but decreases with increasing β_{TL} , τ_{CT} and θ .

Table 6.1 Maximum SCF distribution - effect of β_{CT} and γ_C

Location	Crown heel of TL			Crown heel of LP		
γ/β_{CT}	0.4	0.6	0.8	0.4	0.6	0.8
8				○	○	○
16				○	○	○
24		○	○	○		
32	○	○	○			

Location	Saddle of LP			Crown toe of LP		
γ/β_{CT}	0.4	0.6	0.8	0.4	0.6	0.8
8	△	△	△	□	□	□
16	△	△	△	□	□	□
24	□△	□△	□△			
32	□△	□△	□△			

Note: □ Maximum SCF under AX load case
 ○ Maximum SCF under IPB load case
 △ Maximum SCF under OPB load case

Table 6.2 Maximum SCF distribution - effect of β_{CT} and τ_{CT}

Location	Crown heel of TL			Crown heel of LP		
τ_{CT}/β_{CT}	0.4	0.6	0.8	0.4	0.6	0.8
0.4		○	○	○		
0.6				○	○	○
0.8				○	○	○
1.0				○	○	○

Location	Saddle of LP			Crown toe of LP		
τ_{CT}/β_{CT}	0.4	0.6	0.8	0.4	0.6	0.8
0.4	□△	□△	□△			
0.6	△	△	△	□	□	□
0.8	△	△	△	□	□	□
1.0	△	△	△	□	□	□

Note: □ Maximum SCF under AX load case
 ○ Maximum SCF under IPB load case
 △ Maximum SCF under OPB load case

Table 6.3 Maximum SCF distribution - effect of β_{TL} and γ_T

Location	Crown heel of TL			Crwon heel of LP		
γ/β_{TL}	0.4	0.6	0.8	0.4	0.6	0.8
8				○	○	
16			○	○	○	○
24	○	○	○			
32	○	○	○			

Location	Saddle of TL			Saddle of LP		
γ/β_{TL}	0.4	0.6	0.8	0.4	0.6	0.8
8				□△	□△	□△
16				□△	□△	□△
24	□△				□△	□△
32	□△	△			□	□△

Note: □ Maximum SCF under AX load case
 ○ Maximum SCF under IPB load case
 △ Maximum SCF under OPB load case

Table 6.4 Maximum SCF distribution - effect of β_{TL} and τ_{TL}

Location	Crown heel of TL			Crown toe of TL		
τ_{TL}/β_{TL}	0.4	0.6	0.8	0.4	0.6	0.8
0.4	○	○	○			
0.6	○	○	○			
0.8	○				○	○
1.0	○				○	○
Location	Saddle of TC			Saddle of TL		
τ_{TL}/β_{TL}	0.4	0.6	0.8	0.4	0.6	0.8
0.4			□	□△	△	
0.6			□	□△	□△	
0.8			□	□△	□△	△
1.0			□	□△	□△	△
Location	Saddle of LP					
τ_{TL}/β_{TL}	0.4	0.6	0.8			
0.4		□	△			
0.6			△			
0.8						
1.0						

Note: □ Maximum SCF under AX load case
 ○ Maximum SCF under IPB load case
 △ Maximum SCF under OPB load case

Table 6.5 Maximum SCF distribution - effect of τ_{CT} and γ_C

Location	Crown heel of TL				Crown heel of LP			
γ_C/τ_{CT}	0.4	0.6	0.8	1.0	0.4	0.6	0.8	1.0
8	○					○	○	○
16	○	○	○	○				
24	○	○	○	○				
32	○	○	○	○				
Location	Saddle of TL				Saddle of LP			
γ_C/τ_{CT}	0.4	0.6	0.8	1.0	0.4	0.6	0.8	1.0
8					△	△	△	△
16					△	△	△	△
24					△	△	△	△
32	△				△	△	△	△
Location	Crown toe of TL				Crown toe of LP			
γ_C/τ_{CT}	0.4	0.6	0.8	1.0	0.4	0.6	0.8	1.0
8					□	□	□	□
16	□	□	□	□				
24	□	□	□	□				
32	□	□	□	□				

Note: □ Maximum SCF under AX load case
 ○ Maximum SCF under IPB load case
 △ Maximum SCF under OPB load case

Table 6.6 Maximum SCF distribution - effect of τ_{CT} and τ_{TL}

Location	Crown heel of TL				Crown heel of LP			
τ_{TL}/τ_{CT}	0.4	0.6	0.8	1.0	0.4	0.6	0.8	1.0
0.4					○	○		○
0.6	○	○					○	○
0.8	○	○	○	○				
1.0	○	○	○	○				
Location	Saddle of TL				Saddle of LP			
τ_{TL}/τ_{CT}	0.4	0.6	0.8	1.0	0.4	0.6	0.8	1.0
0.4					△	△	△	△
0.6					△	△	△	△
0.8					△	△	△	△
1.0	△	△	△	△				
Location	Crown toe of TL				Crown toe of LP			
τ_{TL}/τ_{CT}	0.4	0.6	0.8	1.0	0.4	0.6	0.8	1.0
0.4					□	□	□	□
0.6					□	□	□	□
0.8	□	□	□	□				
1.0	□	□	□	□				

Note: □ Maximum SCF under AX load case
○ Maximum SCF under IPB load case
△ Maximum SCF under OPB load case

Table 6.7 Maximum SCF distribution - effect of τ_{TL} and γ_r

Location	Crown heel of TL				Crown heel of LP			
γ_r/τ_{TL}	0.4	0.6	0.8	1.0	0.4	0.6	0.8	1.0
8			○	○	○	○		
16			○	○	○	○		
24			○	○	○	○		
32			○	○	○	○		
Location	Saddle of TL				Crown toe of LP			
γ_r/τ_{TL}	0.4	0.6	0.8	1.0	0.4	0.6	0.8	1.0
8			△	□△	□	□	□	
16			□△	□△	□	□		
24		□	□△	□△	□			
32		□	□△	□△	□			
Location	Saddle of LP							
γ_r/τ_{TL}	0.4	0.6	0.8	1.0				
8	△	△						
16	△	△						
24	△	△						
32	△	△						

Note: □ Maximum SCF under AX load case
○ Maximum SCF under IPB load case
△ Maximum SCF under OPB load case

Table 6.8 Minimum gap requirements for gap joints

Design codes	Minimum gap requirements
	$g \geq 2t_1$ if $t_1 \geq t_2$
DEn (1984)	where t_1 and t_2 are the wall thickness of braces
API RP2A (2000)	$g \geq 51 \text{ mm}$
AWS (2000)	Not clear defined
	$g \geq t_1 + t_2$
CIDECT (2001)	where t_1 and t_2 are the wall thickness of braces

Table 6.9 Maximum SCF distribution - effect of ξ_T and γ_C

Location	Crown heel of TL				Crown heel of LP			
ξ_T/γ_C	8	16	24	32	8	16	24	32
0.25		○	○	○	○			
0.50		○	○	○	○			
0.75		○	○	○	○			
1.00		○	○	○	○			
1.25		○	○	○	○			
1.50		○	○	○	○			
Location	Saddle of TC				Saddle of TL			
ξ_T/γ_C	8	16	24	32	8	16	24	32
0.25		□	□	□	△	△	△	△
0.50					△	△	□△	□△
0.75					△	△	□△	□△
1.00					△	△	□△	□△
1.25					△	△	□△	□△
1.50					△	△	□△	□△
Location	Crown toe of TL				Crown toe of LP			
ξ_T/γ_C	8	16	24	32	8	16	24	32
0.25					□			
0.50					□	□		
0.75		□			□			
1.00		□			□			
1.25		□			□			
1.50		□			□			

Note: □ Maximum SCF under AX load case
 ○ Maximum SCF under IPB load case
 △ Maximum SCF under OPB load case

Table 6.10 Maximum SCF distribution - effect of ξ_T and τ_{TL}

Location	Crown heel of TL				Crown heel of LP			
ξ_T/τ_{TL}	0.4	0.6	0.8	1.0	0.4	0.6	0.8	1.0
0.25			○	○	○	○		
0.50			○	○	○	○		
0.75			○	○	○	○		
1.00			○	○	○	○		
1.25			○	○	○	○		
1.50			○	○	○	○		
Location	Saddle of LP				Crown heel of LP			
ξ_T/τ_{TL}	0.4	0.6	0.8	1.0	0.4	0.6	0.8	1.0
0.25	△	△			□	□		
0.50	△	△			□	□		
0.75	△	△			□	□		
1.00	△	△			□	□		
1.25	△	△			□	□		
1.50	△	△			□	□		
Location	Saddle of TL							
ξ_T/τ_{TL}	0.4	0.6	0.8	1.0				
0.25			□△	□△				
0.50			□△	□△				
0.75			□△	□△				
1.00			□△	□△				
1.25			□△	□△				
1.50			□△	□△				

Note: □ Maximum SCF under AX load case
○ Maximum SCF under IPB load case
△ Maximum SCF under OPB load case

Table 6.11 Maximum SCF distribution - effect of ξ_T and τ_{CT}

Location	Saddle of TC				Saddle of TL			
ξ_T/τ_{CT}	0.4	0.6	0.8	1.0	0.4	0.6	0.8	1.0
0.25	□	□	□	□	△	△	△	△
0.50					□△	□△	□△	□△
0.75					□△	□△	□△	□△
1.00					□△	□△	□△	□△
1.25					□△	□△	□△	□△
1.50					□△	□△	□△	□△
Location	Crown heel of TL							
ξ_T/τ_{CT}	0.4	0.6	0.8	1.0				
0.25	○	○	○	○				
0.50	○	○	○	○				
0.75	○	○	○	○				
1.00	○	○	○	○				
1.25	○	○	○	○				
1.50	○	○	○	○				

Note: □ Maximum SCF under AX load case
○ Maximum SCF under IPB load case
△ Maximum SCF under OPB load case

Table 6.12 Maximum SCF distribution - effect of θ and γ_c

Location	Crown heel of TL			Crown heel of LP		
γ_c/θ	30°	45°	60°	30°	45°	60°
8				○	○	○
16	○				○	○
24	○	○				○
32	○	○	○			

Location	Saddle of LP			Crown toe of LP		
γ_c/θ	30°	45°	60°	30°	45°	60°
8	△	△	△	□	□	□
16	□△	△	△		□	□
24	□△	△	△		□	□
32	□△	△	△		□	□

Note: □ Maximum SCF under AX load case
 ○ Maximum SCF under IPB load case
 △ Maximum SCF under OPB load case

Table 6.13 Maximum SCF distribution - effect of θ and τ_{CT}

Location	Saddle of TC			Crown heel of TL		
τ_{CT}/θ	30°	45°	60°	30°	45°	60°
0.4		□		○	○	○
0.6				○	○	○
0.8				○	○	○
1.0				○	○	○

Location	Saddle of TL			Crown toe of TL		
τ_{CT}/θ	30°	45°	60°	30°	45°	60°
0.4	△			□		□
0.6					□	
0.8					□	
1.0						

Location	Saddel of LP			Crown toe of LP		
τ_{CT}/θ	30°	45°	60°	30°	45°	60°
0.4		△	△			
0.6	□△	△	△			□
0.8	□△	△	△			□
1.0	□△	△	△		□	□

Note: □ Maximum SCF under AX load case
 ○ Maximum SCF under IPB load case
 △ Maximum SCF under OPB load case

Table 6.14 Trends of geometric parameters on SCF

	AX load case				IPB load case		OPB load case		
	TC-90	TL-90	TL-180	LP-90	LP-180	TL-0	LP-0	TL-90	LP-90
β_{CT}	↑	↑	↑	↑	↑	↑	↑	↑	↑
β_{TL}	↑	↓	↓	↓	↔	↔	↔	↓	↔
τ_{CT}	↓	↓	↓	↓	↔	↓	↑	↓	↓
τ_{TL}	↑	↑	↑	↑	↔	↑	↔	↑	↑
θ	↔	↓	↓	↓	↔	↓	↔	↓	↓
ξ_T	↔	↑	↑	↑	↔	↔	↔	↑	↑
γ_c	↑	↑	↑	↑	↔	↑	↓	↑	↑
γ_T	↑	↑	↑	↑	↔	↑	↓	↑	↑

Note: ↑ SCF increases with increasing geometric parameter
 ↓ SCF decreases with increasing geometric parameter
 ↔ Geometric parameter has neglected effect on SCF

Fig. 6.1 Effect of chord length parameter
(Constants $\theta=45^\circ$, $\xi_T=0.5$, $\beta_{CT}=0.8$, $\beta_{TL}=0.4$, $\tau_{CT}=0.6$ and $\tau_{TL}=0.6$)

Fig. 6.2 Effect of through brace length parameter
 (Constants $\theta=45^\circ$, $\xi_T=0.75$, $\beta_{CT}=0.6$, $\beta_{TL}=0.6$, $\tau_{CT}=0.6$ and $\tau_{TL}=0.8$)

Fig. 6.3 Effect of through brace-to-chord diameter ratio, β_{CT} , and chord radius-to-wall thickness ratio, γ_C (Constants $\theta=45^\circ$, $\xi_T=0.75$, $\beta_{TL}=0.6$, $\tau_{CT}=0.6$ and $\tau_{TL}=0.6$)

Fig. 6.4 Effect of through brace-to-chord diameter ratio, β_{CT} , and through brace-to-chord wall thickness ratio, τ_{CT} (Constants $\theta=45^\circ$, $\xi_T=0.75$, $\beta_{TL}=0.6$, $\tau_{TL}=0.6$ and $\gamma_C=16$)

Fig. 6.5 Effect of lap brace-to-through brace diameter ratio, β_{TL} , and through brace radius-to-wall thickness ratio, γ_T (Constants $\theta=30^\circ$, $\xi_T=0.5$, $\beta_{CT}=0.4$, $\tau_{CT}=0.4$ and $\tau_{TL}=0.4$)

Fig. 6.6 Effect of lap brace-to-through brace diameter ratio, β_{TL} , and lap brace-to-through brace wall thickness ratio, τ_{TL} (Constants $\theta=30^\circ$, $\xi_T=0.5$, $\beta_{CT}=0.4$, $\tau_{TL}=0.4$ and $\gamma_C=32$)

Fig. 6.7 Effect of through brace-to-chord wall thickness ratio, τ_{CT} , and chord radius-to-wall thickness ratio, γ_C (Constants $\theta=60^\circ$, $\xi_T=0.75$, $\beta_{CT}=0.6$, $\beta_{TL}=0.8$ and $\tau_{TL}=0.8$)

Fig. 6.8 Effect of through brace-to-chord wall thickness ratio, τ_{CT} , and lap brace-to-through brace wall thickness ratio, τ_{TL} (Constants $\theta=60^\circ$, $\xi_T=0.75$, $\beta_{CT}=0.6$, $\beta_{TL}=0.8$ and $\gamma_C=24$)

Fig. 6.9 Effect of lap brace-to-through brace wall thickness ratio, τ_{TL} , and through brace radius-to-wall thickness ratio, γ_T (Constants $\theta=45^\circ$, $\xi_T=1.0$, $\beta_{CT}=0.8$, $\beta_{TL}=0.4$ and $\tau_{CT}=0.8$)

Fig. 6.10 Definition of minimum and maximum gap size

Fig. 6.11 Effect of gap size-to-through brace diameter ratio, ξ_T , and chord radius-to-wall thickness ratio, γ_C
(Constants $\theta=45^\circ$, $\beta_{CT}=0.6$, $\beta_{TL}=0.6$, $\tau_{CT}=0.8$ and $\tau_{TL}=0.8$)

Fig. 6.12 Effect of gap size-to-through brace diameter ratio, ξ_T , and lap brace-to-through brace wall thickness ratio, τ_{TL} (Constants $\theta=45^\circ$, $\beta_{CT}=0.6$, $\beta_{TL}=0.6$, $\tau_{CT}=0.8$ and $\gamma_C=24$)

Fig. 6.13 Effect of gap size-to-through brace diameter ratio, ξ_T , and through brace-to-chord wall thickness ratio, τ_{CT} (Constants $\theta=45^\circ$, $\beta_{CT}=0.6$, $\beta_{TL}=0.6$, $\tau_{TL}=0.8$ and $\gamma_C=24$)

Fig. 6.14 Effect of angle between chord and through brace, θ , and chord radius-to-wall thickness ratio, γ_C (Constants $\xi_T=0.75$, $\beta_{CT}=0.6$, $\beta_{TL}=0.8$, $\tau_{CT}=0.8$ and $\tau_{TL}=0.6$)

Fig. 6.15 Effect of angle between chord and through brace, θ , and through brace-to-chord wall thickness ratio, τ_{CT} (Constants $\xi_T=0.75$, $\beta_{CT}=0.6$, $\beta_{TL}=0.8$, $\tau_{TL}=0.6$ and $\gamma_C=32$)

Fig. 6.16 Distributions of maximum SCF for completely overlapped joints under basic load cases

CHAPTER 7

PARAMETRIC EQUATIONS

7.1 Introduction

Despite FE method has successfully been used as a numerical tool for modelling and analyzing tubular joints with various geometrical properties and load conditions, the use of such method in a normal day-to-day design office operation is still not feasible. Instead, parametric equations are developed for fatigue design of tubular joints to achieve the time and cost savings.

In the past, many parametric SCF design equations have been established by researchers for fatigue design of simple tubular joints. These equations are expressed in the form of non-dimensional geometrical parameters. Some of the commonly used parametric equations in practice are those derived by Kuang et al. (1977), Wordsworth and Smedley (1978), Efthymiou and Durkin (1985), and Smedley and Fisher (1991). Recently, several modified and unified parametric equations have also been proposed by Chang and Dover (1999a, 1999b) and Wingerde et al. (2001) for a more reliable prediction of SCF for simple tubular joints. However, research data of tubular joints with complex configuration such as completely overlapped joint is still very limited. It is important to realize that no existing parametric equations are currently available for fatigue design of completely overlapped tubular joints. API (2000) recommended a minimum SCF of six (6) for brace member of overlapped joints in view of insufficient design information and research data. It is still not known if the SCF of six (6) for fatigue design of completely overlapped tubular joints is adequate.

In the present work, a set of parametric equations is derived to predict the SCF at the crown toe, saddle and crown heel of members of completely overlapped tubular joints under basic load cases. A total of 5184 FE models with 8-node thick shell element are considered in the study. The use of the proposed SCF parametric

equations to predict the HSS of completely overlapped joints under combined load cases is also examined. The reliability of the proposed SCF design equations is assessed based on the acceptance criteria of Fatigue Guidance Review Panel.

7.2 Development of Parametric Equations

7.2.1 Range of validity

In the current FE analysis of completely overlapped tubular joints, a total of 5184 FE models are created with various geometrical parameters for the development of SCF parametric equations. Three basic load cases (AX, IPB and OPB) are considered for each FE joint model. The boundary condition at the ends of the chord and the through brace is assumed to be fixed. The length parameters of the chord (α_c) and the through brace (α_T) are set at 16 and 12 respectively. The Young's modulus and the Poisson's ratio of steel material are assumed as 200 kN/mm² and 0.3 respectively. The ranges of geometrical parameters of the joint are limited as follow.

$$\begin{aligned}
 0.4 &\leq \beta_{CT} \leq 0.8 \quad (0.4, 0.6 \text{ and } 0.8) \\
 0.4 &\leq \beta_{TL} \leq 0.8 \quad (0.4, 0.6 \text{ and } 0.8) \\
 0.4 &\leq \tau_{CT} \leq 1.0 \quad (0.4, 0.6, 0.8 \text{ and } 1.0) \\
 0.4 &\leq \tau_{TL} \leq 1.0 \quad (0.4, 0.6, 0.8 \text{ and } 1.0) \\
 8 &\leq \gamma_C \leq 32 \quad (8, 16, 24 \text{ and } 32) \\
 0.5 &\leq \xi_T \leq 1.0 \quad (0.5, 0.75 \text{ and } 1.0) \\
 30^\circ &\leq \theta \leq 60^\circ \quad (30^\circ, 45^\circ \text{ and } 60^\circ)
 \end{aligned} \tag{7-1}$$

7.2.2 Limit on minimum SCF

A limit on minimum SCF is necessary for conservative design of tubular joints under fatigue loading. The bases for minimum SCF values are:

- The SCF are determined along limited fixed lines or locations of interest. The hot spot stresses found may underestimate the “true” hot spot stress if

the direction of the principal stresses deviates from these lines, especially if the stress concentration is less pronounced.

- Difficulties in FE modeling, such as the case where $\beta=1.0$ and the case where weld shapes have strong influence on SCFs.
- Crack initiation from the root of the weld for low SCF values.

A limit of $SCF=1.5$ was previously recommended for simple tubular joints by Smedley and Fisher (1991) and Chang and Dover (1999a, 1999b). A minimum SCF value of 2.0 was recommended in CIDECT Design Guide No.8 (Zhao et al. 2001). For the case of overlapped joints, API RP2A (2000) recommended a minimum SCF of 6.0 for brace member. It is important to realize that the SCF of 6.0 was recommended owing to the lack of test data for fatigue analysis of tubular joints. On the other hand, Efthymiou and Durkin (1985) proposed that the limit of minimum SCF for overlapped joints could be lowered to 1.0 and 1.6 for the chord and brace member respectively. In the current study, the minimum SCF for the chord and the braces is set at 1.5 according to UEG recommendation (1985).

Based on the statistical analysis, the frequency of occurrence of SCF at the crown heel, saddle and crown toe of members under basic load cases can be seen in Table 7.1. The data presented in the table are obtained from the FE analysis of 5184 models. For the completely overlapped tubular joint under lap brace AX compression, the SCF at the crown heel of CH is small and the frequency of occurrence of SCF larger than 1.5 is found to be less than 5%. It is recommended that SCF of 1.5 should be assigned at this location of the joint for fatigue design.

For the completely overlapped tubular joint under lap brace IPB, the SCF at the saddle of members could be neglected as these locations are the neutral axis of rotation. The crown heel and crown toe SCF at the joint intersection of the chord and through brace are also found to be minimum (Table 7.1). The SCF at the joint intersection of the chord and through brace is small because the IPB load is predominantly transferred from the lap brace to the through brace. Hence, the SCF of 1.5 should also be assigned at the locations of CH, TC, TL-90 and LP-90 for the joint under IPB.

For the joint under lap brace OPB, the SCF at the crown heel and crown toe of members could be neglected as these locations are the neutral axis of rotation. It is also observed that the SCF at the saddle of CH is small and the frequency of occurrence of SCF larger than 1.5 is found to be less than 5% (Table 7.1). It is recommended that SCF of 1.5 should be assigned at the locations of CH, TC-0, TC-180, TL-0, TL-180, LP-0 and LP-180 for the joint under OPB. It is noted that SCF=1.5 has been recommended at the locations mentioned above. Thus, the development of parametric equations at these locations is not considered.

7.2.3 Proposed SCF parametric equations

A non-linear regression curve fitting program, DataFit (2001), is adopted in the current study for the development of SCF parametric equations. Each parametric equation consists of four parameters namely F1, F2, F3 and F4. The parameters F1 and F2 take account the effect of stress interactions between the chord and through brace as well as the through brace and lap brace, respectively. The parameter F3 considers the effect of gap size, while F4 considers the influence of angle between the chord and the through brace. The functions of the four parameters F1, F2, F3 and F4 are listed as follow.

$$\begin{aligned}
 F1 &= f(\beta_{CT}, \tau_{CT}, \gamma_C) \\
 F2 &= f(\beta_{TL}, \tau_{TL}, \gamma_T) \\
 F3 &= f(\xi_T) \\
 F4 &= f(\theta)
 \end{aligned}
 \tag{7-2}$$

All the functions of the above parameters are included in the regression models. The regression models and the SCF obtained from FE analysis are input as data into the program. It should be noted that DataFit utilizes the Levenber-Marquardt method with double precision to perform the non-linear regression analysis. As the regression models are solved, they are automatically sorted according to the best fit criteria of Residual Sum of Squares and the results come out with full regression information. In the study, the parametric equations are derived to predict SCF at the crown toe, saddle and crown heel of members. The details of the SCF parametric

equations for completely overlapped joints under basic load cases are listed in Table 7.2.

7.2.4 Application of equations under combined loading

In both experimental and numerical studies, the SCF is determined based on the stress component perpendicular to the weld toe. The HSS caused by any individual load case at a given hot spot is along the same direction. This forms the basis for the application of proposed SCF parametric equations for completely overlapped joints under arbitrarily combined loadings. Furthermore, the comparison of HSS between the test results and the equations proposed by Gulati et al. (1982) for the joint under combined loadings confirmed the reliability of the superposition method used in the current study as presented in Chapter 3 Section 3.4.

To calculate the HSS for completely overlapped tubular joints under combined loadings, the following equation is adopted.

$$\sigma(\phi) = K_A(\phi)f_{ax} + K_{Bi}(\phi)f_{ipb} + K_{Bo}(\phi)f_{opb} \quad (7-3)$$

The procedure to determine the HSS of the joint under combined loadings is briefly outlined as follow.

- Step 1 Decompose combined loading into basic load cases;
- Step 2 Determine nominal stress of each individual basic load case;
- Step 3 Calculate SCF for each individual basic load case using the current proposed SCF parametric equations;
- Step 4 Identify HSS component of each individual basic load case by multiplying SCF with corresponding nominal stress;
- Step 5 Obtain total HSS by superimposing each HSS component of all basic load cases.

Two (2) load cases of the test specimen under combined loading are considered in the current study to illustrate the use of proposed SCF parametric equations for

predicting the HSS of completely overlapped tubular joints. Load case 1 is for the joint under lap brace AX and IPB, while Load case 2 is for the joint under lap brace AX, IPB and OPB combined loadings. The geometrical parameters of the test specimen are shown in Table 3.1 of Chapter 3. The nominal stresses for the joint under basic load cases are given in Table 3.3 of Chapter 3.

The SCF of completely overlapped tubular joints due to individual load case is calculated using the proposed parametric equations and then multiply the respective nominal stress obtained in Table 3.3. The actual stress due to combined loading is obtained by summing up the stress of each individual load case. Table 7.3 summarizes the procedure of stress calculation for the joint under combined load cases. It should be noted that the stresses at the intersection of the chord and through brace are not considered as they are found to be small. Furthermore, the stresses at the saddle for the joint under IPB and at the crown heel and crown toe for the joint under OPB are negligible.

The stresses obtained from test results for comparison are presented in Fig. 7.1. It is observed that the proposed parametric equations predict reasonably well under combined load cases. For Load case 1, the maximum difference of stress at the saddle of TL between the proposed parametric equations and the test results is 12%. For Load case 2, the maximum difference of stress occurs at the saddle of LP and is found to be 22%. However, it should be noted that the large different of stress between the proposed equations and the test results is due to the small value obtained from the test.

7.3 Assessment of Parametric Equations

A detailed assessment of the current proposed SCF parametric equations is conducted to ensure these equations could confidently be used to predict the SCF of completely overlapped tubular joints. The accuracy and the reliability of the proposed SCF parametric equations are considered to be acceptable if the results in comparison with the test data are less scatter. The HSE Review Panel for Fatigue

Guidance (1996) specified fatigue guidance on applicability of SCF for joint design. The requirements for parametric equations to be accepted for fatigue design of simple tubular joints include the scatter of the equation with respect to the measured SCF results, and the total number of SCF under- and over-predictions.

7.3.1 Acceptance criteria for assessment

In the current study, a set of SCF parametric equations has been developed to predict the SCF at the intersections of members of the completely overlapped tubular joint. The reliability and the accuracy of these proposed equations are assessed based on database obtained from the FE models and the test specimens. The Fatigue Guidance Review Panel recommended a set of acceptance criteria for assessment of parametric equations. This is based on predicted SCF (P) to measured SCF (R) ratio of the joint with different geometrical parameters. An exact fit of data is concluded if P/R ratio is equal to unity. However, the equations are commented to underestimate and overestimate the SCF of the joint if P/R ratios are less and greater than 0.8 and 1.5 respectively. The acceptance criteria of Fatigue Guidance Review Panel are stated as follow:

For the given dataset, if percentage SCF under-predicting $\leq 25\%$ ($[\%P/R < 1.0] \leq 25\%$) and if percentage SCF considerably under-predicting $\leq 5\%$ ($[\%P/R < 0.8] \leq 5\%$) then the equation meets the acceptance criteria used in this study. In addition, if the percentage SCF considerably over-predicting $\geq 50\%$ ($[\%P/R > 1.5] \geq 50\%$), then note that the equation is generally conservative.

If the acceptance criteria as used in this study is nearly met (i.e. $25\% < [\%P/R < 1.0] \leq 30\%$ and/or $5\% < [\%P/R < 0.8] \leq 7.5\%$) then the equation is regarded as borderline and engineering judgment has been used.

It is important to note in the current study that the recommended minimum SCF of tubular joints for design is 1.5 (Smedley and Fisher (1991), Chang and Dover (1999a, 1999b)). If SCF at certain location of the joint is found to be small, less

than 1.5, SCF of 1.5 will be assigned at this location. Combined with the assessment criteria recommended by the Fatigue Guidance Review Panel, if $[\%SCF \geq 1.5] < 5\%$, the SCF equation at this location can be assigned as $SCF=1.5$, where $\%SCF \geq 1.5$ refers to the frequency of occurrence of SCF large than 1.5.

The frequency of occurrence of SCF based on statistical analysis at the crown heel, saddle and crown toe of members for the joint under basic load cases is shown in Table 7.1. The results are based on data obtained from FE analysis of 5184 models. According to the criteria, $SCF=1.5$ should directly be assigned at the following locations of the joint as the frequency of occurrence of SCF is found to be $[\%SCF \geq 1.5] < 5\%$.

- CH-0 under AX load case
- CH, TC, TL-90 and LP-90 under IPB load case
- CH, TC-0, TC-180, TL-0, TL-180, LP-0 and LP-180 under OPB.

7.3.2 Assessment with SCF database of FE models

The proposed SCF parametric equations listed in Table 7.2 are assessed with respect to the database of FE models based on the assessment criteria of Fatigue Guidance Review Panel. The SCF of 5184 completely overlapped joint FE models are determined using the current proposed SCF parametric equations. The calculated SCF (P) is compared with SCF (R), the database of FE models, and the detailed results of the assessment can be seen in Table 7.4.

As shown in Table 7.4, the assessment of SCF at the crown heel of CH for the joint under AX load case is neglected. A good fit of FE database with the proposed SCF parametric equations is noted as most P/R ratios are found to be in the range of 0.8 to 1.5. Some data are found to be higher than 1.5. The maximum frequency of occurrence at the crown toe of TC is 6.3%. However, this is considered to be acceptable as the equations are conservative. Despite a small group of SCF is under estimated, the assessment criteria are still met in view of the maximum frequency of occurrence of only 3.0% at the crown toe of CH.

It should be noted that P/R ratios at some locations fail to meet the assessment criteria of Fatigue Guidance Review Panel with $[\%P/R < 1.0] \leq 25\%$ such as at the saddle of CH, TC and TL and the crown toe and saddle of LP. This is attributed to the different criteria imposed in Datafit regression method and Fatigue Guidance Review Panel design requirement. Thus, design factors are recommended in the proposed SCF parametric equations to take account the discrepancy of the use of regression method to satisfy the criteria of Fatigue Guidance Review Panel.

The comparison of SCF for the joint under IPB load case as shown in Table 7.4 indicates a good fit between the database of FE models and the values calculated from proposed parametric equations. Most P/R ratios are found to be in the range of 0.8 to 1.2. P/R ratios greater than 1.5 in the database are not found. The maximum frequency of occurrence of SCF of P/R ratio less than 0.8 is only 1.0%, which occurs at the crown heel of TL and LP. Similar to the case for the joint under AX loading, design factors should be incorporated in the proposed SCF parametric equations to accurately predict the SCF at the crown heel of TL and the crown heel and crown toe of LP as P/R ratios at these locations fail to satisfy the requirement of $[\%P/R < 1.0] \leq 25\%$.

For the joint under OPB loading, the proposed parametric equations are derived only at the saddle of TC, TL and LP as SCF of 1.5 is assigned at those locations with small SCF as shown in Table 7.4. A good fit of SCF of the proposed parametric equations with FE database is noted as most P/R ratios are found to be in the range of 0.8 to 1.2. The maximum frequency of occurrence of P/R ratio greater than 1.5 at the saddle of LP is 3.1%. The maximum frequency of occurrence of P/R ratio less than 0.8 at the saddle of TL is 2.7%. Design factors are necessarily to be included in the proposed SCF parametric equations to predict the SCF at the saddle of TL and LP as P/R ratios at these locations fail to satisfy the requirement of $[\%P/R < 1.0] \leq 25\%$.

The average frequency of occurrence of P/R ratios for all the three (3) basic load cases is 1.6%, 24.4%, 62.9%, 9.5% and 1.6% in the range of 0-0.8, 0.8-1.0, 1.0-1.2,

1.2-1.5 and >1.5 respectively. The performance of the proposed SCF parametric equations based on the statistical analysis is satisfactory with the mean and CoV (coefficient of variation) of 1.04 and 0.13 respectively.

7.3.3 Assessment with current test SNCF data

The accuracy of the proposed parametric equations is also compared with the experimental results obtained from the test conducted at Nanyang Technological University. The geometrical parameters of the completely overlapped joint specimen are shown in Table 3.1 of Chapter 3.

In the current study, the SNCF of the joint under AX, IPB and OPB loadings calculated from the test specimen are converted to SCF with the use of factors of 1.15, 1.14 and 1.13, respectively as defined in Section 4.4 of Chapter 4. As shown in Table 7.5, all P/R ratios are within the range of 0.8 to 1.5 except at the crown toe of CH for the joint under AX load case. P/R ratio at this location is excessively conservative owing to the very small experimental value. The statistical analysis in Table 7.5 showed that the frequency of occurrence of P/R for the joint under all the three (3) basic load cases is 0.0%, 17.6%, 64.7%, 11.8% and 5.9% in the range of 0-0.8, 0.8-1.0, 1.0-1.2, 1.2-1.5 and >1.5 respectively. The performance of the proposed parametric equations based on the statistical analysis is satisfactory with the mean and CoV of 1.11 and 0.21 respectively.

7.2.4 Assessment with previous test SNCF data

The experimental results of SCF and SNCF of completely overlapped tubular joints are very limited. Only Gho et al. (2003) published a set of SNCF obtained from the experimental investigation of a large scale completely overlapped tubular K(N)-joint specimen under lap brace axial compression. The geometrical parameters of the joint specimen are: $\alpha_C=21.43$, $\alpha_T=20.58$, $\beta_{CT}=0.60$, $\beta_{TL}=0.62$, $\tau_{CT}=0.73$, $\tau_{TL}=0.76$, $\gamma_C=18.00$ and $\theta=45^\circ$. The SNCF obtained from the test is used

to assess the accuracy of the current proposed SCF parametric equations for the completely overlapped tubular joint.

In the study, the SNCF is converted to SCF with the use of factor of 1.15 for the joint under AX load case as defined in Section 4.4 of Chapter 4. As shown in Table 7.6, all P/R ratios are within the range of 0.8 to 1.5 except at the crown heel of CH. P/R ratio at this location is excessively conservative owing to the very small experimental value of only 0.30. The statistical analysis in Table 7.6 showed that the frequency of occurrence of P/R ratio is 0.0%, 9.1%, 54.5%, 27.3% and 9.1% in the range of 0-0.8, 0.8-1.0, 1.0-1.2, 1.2-1.5 and >1.5 respectively. Thus, the performance of the proposed parametric equations based on the statistical analysis is concluded to be acceptable with the mean and CoV of 1.21 and 0.27 respectively.

7.4 Discussion and Concluding Remarks

The existing SCF parametric equations derived by Kuang et al. (1977), Wordsworth and Smedley (1978), UEG (1985) and Hellier et al. (1990) for simple tubular joints are based on either small-scale acrylic model tests or thin shell FE analysis. In both methods of analysis, no weld elements are included. As a result, the SCF obtained from these methods are found to be more conservative in comparison with those from large-scale steel joints. On the other hand, the current SCF parametric equations are derived based on a least square fit of FE analysis results of 8-node thick shell models including weld elements. Thus, the SCF calculated from the proposed equations agree better with those from the large-scale steel joints.

It is recommended that design factors should be included in the current proposed SCF parametric equations to take account the discrepancy of regression analysis in order to meet the assessment criteria of Fatigue Guidance Review Panel. Lloyd's Register equations use a factor of one in the standard deviation of statistical analysis to adjust the predicted SCF and thus reduce the probability of SCF from being under-predicted (Smedley and Fisher 1991). In the current study, design factors as shown in Table 7.7 are determined and included in the proposed SCF parametric

equations to satisfy the condition of $[\%P/R < 1.0] \leq 25\%$. The use of these factors increases the SCF by a maximum of 8.5% at the crown toe of LP for the joint under AX loading and results in a more conservative fatigue life estimates for the joint.

With the use of design factors, the assessment of current proposed parametric equations for completely overlapped tubular joints with respect to SCF database of FE models satisfies the criteria of Fatigue Guidance Review Panel. The assessment results confirm the reliability of these equations for predicting the SCF of the joint under basic load cases. Since the superposition method is suitable to determine the HSS of the joint under various combinations of loadings, the proposed SCF parametric equations are concluded to be applicable to predict the HSS of completely overlapped tubular joints under both basic and combined loadings.

Table 7.1 Frequency of occurrence of SCF under basic load cases

	AX load case		IPB load case		OPB load case	
	%SCF<1.5	%SCF $\geq$ 1.5	%SCF<1.5	%SCF $\geq$ 1.5	%SCF<1.5	%SCF $\geq$ 1.5
CH-000	96.8%	3.2%	100.0%	0.0%	100.0%	0.0%
CH-090	44.1%	55.9%	100.0%	0.0%	95.2%	4.8%
CH-180	77.6%	22.4%	100.0%	0.0%	100.0%	0.0%
TC-000	70.2%	29.8%	99.9%	0.1%	100.0%	0.0%
TC-090	27.7%	72.3%	99.1%	0.9%	84.7%	15.3%
TC-180	70.8%	29.2%	100.0%	0.0%	100.0%	0.0%
TL-000	88.6%	11.4%	21.8%	78.2%	100.0%	0.0%
TL-090	25.6%	74.4%	99.0%	1.0%	27.8%	72.2%
TL-180	11.5%	88.5%	47.8%	52.2%	100.0%	0.0%
LP-000	91.4%	8.6%	9.7%	90.3%	100.0%	0.0%
LP-090	13.6%	86.4%	98.0%	2.0%	20.4%	79.6%
LP-180	1.8%	98.2%	45.1%	54.9%	100.0%	0.0%

Fig. 7.1 Comparison of HSS of test results with proposed equations

Table 7.2 Proposed SCF parametric equations for completely overlapped tubular joints

Load case	Location	Parametric equation
AX	CH-090	$SCF_{AX}^2 = (F1 + F2) \times F3 \times F4$ $F1 = (0.136\beta_{CT}^2 - 0.171\beta_{CT} + 0.010)\tau_{CT}^{1.217, 1.070} \gamma_C$ $F2 = (1.217\beta_{TL}^2 - 2.809\beta_{TL} + 0.666)\tau_{TL}^{1.679, 0.324} \gamma_T$ $F3 = 0.291\xi_T + 0.908$ $F4 = \sin^{-0.643} \theta$
	CH-180	$SCF_{AX}^3 = (F1 + F2) \times F3 \times F4$ $F1 = (0.061\beta_{CT}^2 - 0.025\beta_{CT} + 0.009)\tau_{CT}^{0.823, 1.818} \gamma_C$ $F2 = (-0.390\beta_{TL}^2 + 0.400\beta_{TL} + 0.015)\tau_{TL}^{1.854, 0.823} \gamma_T$ $F3 = 0.581\xi_T + 0.351$ $F4 = \sin^{0.129} \theta$
	TC-000	$SCF_{AX}^4 = (F1 + F2) \times F3 \times F4$ $F1 = (-0.367\beta_{CT}^2 + 0.381\beta_{CT} - 0.106)\tau_{CT}^{0.702, -0.071} \gamma_C$ $F2 = (-0.021\beta_{TL}^2 + 0.059\beta_{TL} - 0.004)\tau_{TL}^{0.677, 0.349} \gamma_T$ $F3 = 13.191\xi_T + 12.177$ $F4 = \sin^{-1.026} \theta$
	TC-090	$SCF_{AX}^5 = (F1 + F2) \times F3 \times F4$ $F1 = (1.870\beta_{CT}^2 - 3.350\beta_{CT} + 1.988)\tau_{CT}^{3.424, -0.395} \gamma_C$ $F2 = (0.940\beta_{TL}^2 - 1.747\beta_{TL} + 0.192)\tau_{TL}^{0.861, 0.396} \gamma_T$ $F3 = 0.258\xi_T + 1.516$ $F4 = \sin^{-0.969} \theta$
	TC-180	$SCF_{AX}^6 = (F1 + F2) \times F3 \times F4$ $F1 = (0.765\beta_{CT}^2 + 0.788\beta_{CT} - 0.412)\tau_{CT}^{-1.349, 0.115} \gamma_C$ $F2 = (-0.525\beta_{TL}^2 + 0.549\beta_{TL} + 0.074)\tau_{TL}^{1.197, 1.055} \gamma_T$ $F3 = 0.272\xi_T + 0.322$ $F4 = \sin^{-0.485} \theta$
	TL-000	$SCF_{AX}^7 = (F1 + F2) \times F3 \times F4$ $F1 = (-0.001\beta_{CT}^2 + 0.003\beta_{CT} - 0.001)\tau_{CT}^{-0.935, 1.844} \gamma_C$ $F2 = (-1.511\beta_{TL}^2 + 2.300\beta_{TL} - 1.659)\tau_{TL}^{0.070, 0.126} \gamma_T$ $F3 = -0.027\xi_T + 0.271$ $F4 = \sin^{-2.538} \theta$
	TL-090	$SCF_{AX}^8 = (F1 + F2) \times F3 \times F4$ $F1 = (-0.482\beta_{CT}^2 + 0.279\beta_{CT} + 0.165)\tau_{CT}^{-0.383, 0.206} \gamma_C$ $F2 = (0.820\beta_{TL}^2 - 0.326\beta_{TL} - 0.651)\tau_{TL}^{1.174, 0.616} \gamma_T$ $F3 = 0.644\xi_T + 0.679$ $F4 = \sin^{-1.559} \theta$
	TL-180	$SCF_{AX}^9 = (F1 + F2) \times F3 \times F4$ $F1 = (-0.042\beta_{CT}^2 + 0.010\beta_{CT} + 0.035)\tau_{CT}^{-1.078, 0.668} \gamma_C$ $F2 = (-0.527\beta_{TL}^2 + 0.751\beta_{TL} - 0.814)\tau_{TL}^{0.921, 0.548} \gamma_T$ $F3 = 0.683\xi_T + 1.160$ $F4 = \sin^{-0.806} \theta$

Table 7.2 (Con't) Proposed SCF parametric equations for completely overlapped tubular joints

Load case	Location	Parametric equation
AX	LP-000	$SCF_{AX}^{10} = (F1 + F2) \times F3 \times F4$
		$F1 = (-0.100\beta_{CT}^2 - 0.013\beta_{CT} - 0.660)\tau_{CT}^{-0.122, 0.095} \gamma_C$ $F2 = (0.050\beta_{TL}^2 - 0.081\beta_{TL} + 0.299)\tau_{TL}^{-0.378, 0.433} \gamma_T$ $F3 = -0.410\xi_T + 3.611$ $F4 = \sin^{-0.067} \theta$
	LP-090	$SCF_{AX}^{11} = (F1 + F2) \times F3 \times F4$
		$F1 = (0.001\beta_{CT}^2 - 0.054\beta_{CT} + 0.024)\tau_{CT}^{-0.154, 0.728} \gamma_C$ $F2 = (0.839\beta_{TL}^2 - 0.822\beta_{TL} - 0.105)\tau_{TL}^{-0.553, 0.429} \gamma_T$ $F3 = 1.307\xi_T + 1.547$ $F4 = \sin^{-1.399} \theta$
IPB	LP-180	$SCF_{AX}^{12} = (F1 + F2) \times F3 \times F4$
		$F1 = (0.343\beta_{CT}^2 - 1.390\beta_{CT})\tau_{CT}^{-0.028, 0.116} \gamma_C$ $F2 = (0.575\beta_{TL}^2 - 0.555\beta_{TL})\tau_{TL}^{-0.166, -0.016} \gamma_T$ $F3 = 0.429\xi_T + 1.465$ $F4 = -3.995\sin^2 \theta + 5.280\sin \theta$
	TL-000	$SCF_{IPB}^7 = (F1 + F2) \times F3 \times F4$
		$F1 = (-0.043\beta_{CT}^2 + 0.008\beta_{CT} + 0.004)\tau_{CT}^{-0.460, 0.785} \gamma_C$ $F2 = (-1.452\beta_{TL}^2 + 1.619\beta_{TL} - 1.186)\tau_{TL}^{-1.140, 0.230} \gamma_T$ $F3 = 0.024\xi_T + 1.562$ $F4 = \sin^{-0.917} \theta$
OPB	TL-180	$SCF_{IPB}^9 = (F1 + F2) \times F3 \times F4$
		$F1 = (0.240\beta_{CT}^2 - 0.018\beta_{CT} + 0.008)\tau_{CT}^{-0.754, 0.097} \gamma_C$ $F2 = (0.342\beta_{TL}^2 - 0.341\beta_{TL} + 0.401)\tau_{TL}^{-1.065, 0.484} \gamma_T$ $F3 = 0.035\xi_T + 0.908$ $F4 = \sin^{-1.643} \theta$
	LP-000	$SCF_{IPB}^{10} = (F1 + F2) \times F3 \times F4$
		$F1 = (-0.573\beta_{CT}^2 + 1.247\beta_{CT} + 1.078)\tau_{CT}^{-0.348, 0.347} \gamma_C$ $F2 = (0.277\beta_{TL}^2 - 0.036\beta_{TL} - 3.565)\tau_{TL}^{-0.041, 0.220} \gamma_T$ $F3 = -0.008\xi_T + 1.574$ $F4 = \sin^{0.078} \theta$
OPB	LP-180	$SCF_{IPB}^{12} = (F1 + F2) \times F3 \times F4$
		$F1 = (0.046\beta_{CT}^2 - 0.188\beta_{CT} - 0.080)\tau_{CT}^{-0.839, 0.881} \gamma_C$ $F2 = (-0.402\beta_{TL}^2 + 0.602\beta_{TL} + 0.986)\tau_{TL}^{-0.093, 0.546} \gamma_T$ $F3 = -0.001\xi_T + 0.457$ $F4 = \sin^{-0.939} \theta$
	TC-90	$SCF_{OPB}^5 = (F1 + F2) \times F3 \times F4$
		$F1 = (0.019\beta_{CT}^2 - 0.022\beta_{CT})\tau_{CT}^{-1.748, 1.344} \gamma_C$ $F2 = (-0.272\beta_{TL}^2 + 0.528\beta_{TL} - 0.101)\tau_{TL}^{-0.681, 0.999} \gamma_T$ $F3 = -0.225\xi_T + 0.465$ $F4 = \sin^{-1.570} \theta$

Table 7.2 (Con't) Proposed SCF parametric equations for completely overlapped tubular joints

Load case	Location	Parametric equation
OPB	TL-90	$SCF_{OPB}^8 = (F1 + F2) \times F3 \times F4$
		$F1 = (0.031\beta_{CT}^2 - 0.036\beta_{CT} + 0.005)\tau_{CT}^{-1.542}\gamma_C^{1.112}$ $F2 = (-0.970\beta_{TL}^2 + 1.032\beta_{TL} + 0.043)\tau_{TL}^{1.027}\gamma_T^{0.876}$ $F3 = 0.239\xi_T + 0.577$ $F4 = \sin^{-1.654}\theta$
	LP-90	$SCF_{OPB}^{11} = (F1 + F2) \times F3 \times F4$
		$F1 = (0.003\beta_{CT}^2 - 0.004\beta_{CT})\tau_{CT}^{-1.825}\gamma_C^{1.665}$ $F2 = (-0.943\beta_{TL}^2 + 1.173\beta_{TL} - 0.062)\tau_{TL}^{0.244}\gamma_T^{0.849}$ $F3 = 0.193\xi_T + 0.616$ $F4 = \sin^{-1.427}\theta$

Table 7.3 Stress calculation process based on proposed parametric equations

Case 1								
Load	TL-0	TL-90	TL-180	TL-270	LP-0	LP-90	LP-180	LP-270
AX	-15.88	-67.92	-40.77	-67.92	-9.37	-40.46	-21.97	-40.46
IPB	-38.05	0.00	47.70	0.00	-46.30	0.00	37.70	0.00
AX+IPB	-53.93	-67.92	6.93	-67.92	-55.67	-40.46	15.73	-40.46
Test Results	-47.82	-59.75	6.17	-60.69	-50.77	-42.21	16.09	-44.29
Case 2								
Load	TL-0	TL-90	TL-180	TL-270	LP-0	LP-90	LP-180	LP-270
AX	-15.88	-67.92	-40.77	-67.92	-9.37	-40.46	-21.97	-40.46
IPB	-53.27	0.00	66.78	0.00	-64.82	0.00	52.78	0.00
OPB	0.00	92.34	0.00	-92.34	0.00	44.28	0.00	-44.28
AX+IPB+OPB	-69.15	24.42	26.01	-160.26	-74.19	3.82	30.81	-84.74
Test Results	-61.68	28.16	24.85	-148.18	-66.65	4.67	30.92	-90.36

Table 7.4 Assessment of proposed parametric equations with FE database

Load case	Location	Frequency of Occurrence of SCF P/R (%)					Mean	CoV
		<0.8	0.8↔1.0	1.0↔1.2	1.2↔1.5	>1.5		
AX	CH-090	2.5	24.4	59.4	10.9	2.8	1.05	0.16
	CH-180	3.0	11.2	81.5	3.6	0.7	1.01	0.10
	TC-000	1.3	9.0	77.0	10.7	2.6	1.06	0.15
	TC-090	2.1	29.1	51.8	14.2	2.8	1.06	0.18
	TC-180	2.9	18.3	56.0	16.6	6.3	1.10	0.20
	TL-000	0.8	7.0	91.6	0.6	0.0	1.00	0.05
	TL-090	1.6	26.3	54.2	17.1	0.9	1.06	0.14
	TL-180	2.6	31.2	51.7	13.3	1.2	1.06	0.15
	LP-000	0.2	4.1	90.4	5.3	0.0	1.02	0.07
	LP-090	1.7	34.2	41.9	18.6	3.5	1.08	0.18
IPB	LP-180	1.2	55.1	31.5	9.0	3.2	1.03	0.18
	TL-000	1.0	29.2	61.3	8.4	0.0	1.04	0.10
	TL-180	0.6	21.7	72.2	5.5	0.0	1.02	0.09
	LP-000	1.0	44.7	53.7	0.7	0.0	1.00	0.08
OPB	LP-180	0.0	28.8	68.7	2.5	0.0	1.01	0.07
	TC-090	1.9	7.3	88.0	2.1	0.6	1.00	0.10
	TL-090	2.7	25.1	55.0	16.0	1.3	1.06	0.18
	LP-090	1.9	32.8	46.9	15.2	3.1	1.06	0.18
Average		1.6	24.4	62.9	9.5	1.6	1.04	0.13

Table 7.5 Assessment of parametric equations with current test results

Load case	Location	SCF(P)	SCF(R)	P/R
		Proposed equations	Tested specimen	
AX	CH-090	2.22	1.74	1.28
	CH-180	1.16	0.60	1.93
	TC-090	3.03	2.98	1.02
	TC-180	1.51	1.50	1.01
	TL-000	1.59	1.72	0.93
	TL-090	6.79	6.53	1.04
	TL-180	4.08	3.77	1.08
	LP-000	0.94	1.03	0.91
	LP-090	4.05	3.69	1.10
	LP-180	2.20	1.80	1.22
IPB	TL-000	1.52	1.38	1.10
	TL-180	1.91	1.79	1.07
	LP-000	1.85	1.97	0.94
	LP-180	1.51	1.45	1.04
OPB	TC-090	0.71	0.70	1.01
	TL-090	5.13	4.80	1.07
	LP-090	2.46	2.19	1.12

Frequency of Occurrence of SCF P/R (%)					Mean	CoV	Remark
<0.8	0.8↔1.0	1.0↔1.2	1.2↔1.5	>1.5			
0.0%	17.6%	64.7%	11.8%	5.9%	1.11	0.21	Acceptable

Table 7.6 Assessment of parametric equations with previous test results

Load case	Location	SCF(P)	SCF(R)	P/R
		Proposed equations	Tested specimen	
AX	CH-000	0.64	0.30	2.14
	CH-090	1.84	2.12	0.87
	TC-000	1.07	0.90	1.19
	TC-090	2.56	2.50	1.02
	TC-180	0.96	0.90	1.07
	TL-000	0.31	0.27	1.15
	TL-090	3.41	3.27	1.04
	TL-180	2.41	1.80	1.34
	LP-000	0.67	0.54	1.23
	LP-090	2.75	2.24	1.23
	LP-180	2.11	2.04	1.03

Frequency of Occurrence of SCF P/R (%)					Mean	CoV	Remark
<0.8	0.8↔1.0	1.0↔1.2	1.2↔1.5	>1.5			
0.0%	9.1%	54.5%	27.3%	9.1%	1.21	0.27	Acceptable

Table 7.7 Design factor for proposed SCF parametric equations

Load case	Location	Design factor
AX	CH-090	1.035
	CH-180	1.000
	TC-000	1.000
	TC-090	1.046
	TC-180	1.000
	TL-000	1.000
	TL-090	1.038
	TL-180	1.048
	LP-000	1.000
	LP-090	1.051
	LP-180	1.085
IPB	TL-000	1.028
	TL-180	1.000
	LP-000	1.050
	LP-180	1.031
OPB	TC-090	1.000
	TL-090	1.043
	LP-090	1.051

CHAPTER 8

COMPLETELY OVERLAPPED JOINTS AND SIMPLE T/Y JOINTS

8.1 Introduction

In practice, the completely overlapped tubular joint is commonly considered as two separate T/Y-joint configurations with the through brace member acting as a chord (DEn 1984a, Dexter et al. 1996). The interaction effect on the stress field between the joint intersections of the chord and through brace and the through brace and lap brace is not considered. Thus, the existing parametric equations for simple tubular joints in the recommendations do not provide adequate guidance for the design of completely overlapped tubular joints. It is very important to note that the interpretation of the completely overlapped joint as two separate simple T/Y joints may not be appropriate as the results obtained may not necessarily be conservative. Thus, there is a need to carry out a comparison of SCF between the completely overlapped joint and the existing T/Y-joint equations to verify the suitability of using the existing equations for predicting the SCF of completely overlapped tubular joints.

In the current study, the SCF of completely overlapped tubular joints obtained from the experiment, FE models and proposed parametric equations (referred as New) are compared with those calculated from the existing T/Y-joint parametric equations derived by Efthymiou and Durkin (1985) (referred as Shell) and Smedley and Fisher (1991) (referred as Lloyd). Shell equations are developed based on FE database, while Lloyd equations are based on test data.

8.2 Comparison of SCF between Experiment and T/Y-Joint Equations

The comparison of SCF between the completely overlapped tubular joint test specimen and the two existing T/Y-joint parametric equations is shown in Table 8.1.

For the joint under lap brace AX loading, the maximum SCF at the saddle of TL of the test specimen is identical to that determined from the T/Y-joint equations. From the table, the most SCF of the test specimen are overestimated by the T/Y-joint equations except the saddle of TC and the crown toe of TL. However, the difference of SCF between the test specimen and the T/Y-joint parametric equations at these locations is very small with maximum difference of only 0.49.

For the joint under lap brace IPB, the SCF at the saddle can be ignored as it is the neutral axis of rotation. At the joint intersection of the chord and through brace, the SCF of the test specimen are very small with maximum value of 0.18. However, the existing T/Y-joint equations excessively over predict the SCF at this joint intersection. The SCF at the crown toe of TC can be as high as 3.21. Thus, from the comparison, there is no good agreement of SCF between the completely overlapped joint specimen and the existing T/Y-joint parametric equations.

For the joint under lap brace OPB, only the SCF at the saddle of members of the test specimen are compared with those calculated from the T/Y-joint parametric equations. Similar to the case for the joint under lap brace IPB, the existing T/Y-joint parametric equations over predict the SCF of the completely overlapped joint test specimen at the joint intersection of the chord and through brace.

8.3 Comparison of SCF between FE Models and T/Y-Joint Equations

The SCF of the completely overlapped tubular joint under basic load cases obtained from the FE analysis are compared with those calculated from the existing T/Y-joint equations. In the comparison, the gap sizes on the through brace between the outer surfaces of the chord and the lap brace are set at $0.5d_T$ and $1.5d_T$. The detailed results of the comparison of SCF between the FE models and the existing T/Y-joint equations are presented in Tables 8.2 to 8.4. It should be noted that only the peak hot spot SCF at the weld toe of the joint are considered for comparison.

8.3.1 Effect of chord radius-to-wall thickness ratio, γ_C

As shown in Table 8.2, γ_C varies from 8 to 32 while other geometrical parameters of the joint remain constant. For the joint under AX load case, the T/Y-joint parametric equations overestimate the SCF of the completely overlapped tubular joint model with small gap size. The maximum difference of SCF at large γ_C is 7.12 and 146% in terms of numeric and percentage respectively. On the other hand, the SCF of the joint model with large gap size are found to be underestimated at small γ_C and overestimated as γ_C increases by the T/Y-joint parametric equations. The maximum difference of SCF at large γ_C between the FE models and the T/Y-joint equations is 4.10 and 52% in terms of numeric and percentage respectively. It is noted that the T/Y-joint parametric equations predict better the SCF of the joint model at large gap size and small γ_C .

For the joint under IPB, there is no effect on the SCF with variation of gap size (chapter 6 section 6.7). The SCF obtained for the joint model with small and large gap sizes are identical. As shown in Table 8.2, the T/Y-joint equations predict reasonably well the SCF of the joint model with maximum difference of 1.05 and 41% in terms of numeric and percentage respectively at small γ_C .

For the joint under OPB, the T/Y-joint equations over predict the SCF of the completely overlapped joint with both small and large gap sizes (Table 8.2). The maximum difference of SCF at large γ_C between the joint models with small gap size and the T/Y-joint equations is 5.18 and 101% in terms of numeric and percentage respectively. The maximum difference of SCF at large γ_C between the joint models with large gap size and the T/Y-joint equations is 3.19 and 61%. Similar to the case of AX loading, the T/Y-joint equations predict better the SCF of the completely overlapped joint models at large gap size and small γ_C .

8.3.2 Effect of lap brace-to-through brace wall thickness ratio, τ_{TL}

As shown in Table 8.3, τ_{TL} varies from 0.4 to 1.0 while other geometrical parameters of the joint remain constant. For the joint under AX load case, the T/Y-joint parametric equations overestimate the SCF of the completely overlapped joint models. The maximum difference of SCF between the joint models with small gap size and the T/Y-joint equations is 5.65 and 110% respectively. The maximum difference of SCF between the joint models with large gap size and the T/Y-joint equations is 2.66 and 40% respectively. The T/Y-joint equations predict better the SCF of the joint models at large gap size and small τ_{TL} .

For the joint under IPB, the SCF of the joint models with small and large gap sizes are almost identical. As shown in Table 8.3, the T/Y-joint parametric equations predict very well the SCF of the joint models with maximum difference of 0.82 and 37% in terms of numeric and percentage respectively.

For the joint under OPB, the T/Y-joint parametric equations overestimate the SCF of the joint models with both small and large gap sizes (Table 8.3). The maximum difference of SCF between the joint models with small gap size and the T/Y-joint equations is 4.32 and 88% in terms of numeric and percentage respectively. The maximum difference of SCF between the joint models with large gap size and the T/Y-joint equations is 3.14 and 53%. The T/Y-joint parametric equations predict better the SCF of the completely overlapped joints at large gap size and small τ_{TL} .

8.3.3 Effect of through brace-to-chord wall thickness ratio, τ_{CT}

As shown in Table 8.4, τ_{CT} varies from 0.4 to 1.0 while other geometrical parameters of the joint remain constant. For the joint under AX load case, the T/Y-joint parametric equations overestimate the SCF of completely overlapped joints with both small and large gap sizes. At $\tau_{CT} = 0.4$, the maximum difference of SCF between the joint models with small gap size and the T/Y-joint equations is 13.7 and 235%, while the maximum difference of SCF between the joint models

with large gap size and the T/Y-joint equations is 9.58 and 96% in terms of numeric and percentage respectively. The T/Y-joint parametric equations predict better the SCF of completely overlapped joints at large gap size and large τ_{CT} .

For the joint under IPB load case, the SCF of completely overlapped joints with small and large gap sizes are almost identical. As shown in Table 8.4, the T/Y-joint equations predict reasonably well the SCF of the joint models at large τ_{CT} . At $\tau_{CT}=0.4$, the maximum difference of SCF between the T/Y-joint equations and the joint models is 1.71 and 57% in terms of numeric and percentage respectively.

For the joint under OPB load case, the T/Y-joint equations overestimate the SCF of completely overlapped joints with small and large gap sizes (Table 8.4). At $\tau_{CT}=0.4$, the maximum difference of SCF between the joint models with small gap size and the T/Y-joint equations is 8.83 and 133%, while the maximum difference of SCF between the joint models with large gap size and the T/Y-joint equations is 6.79 and 78% in terms of numeric and percentage respectively. The T/Y-joint parametric equations predict better the SCF of the joint at large gap size and large τ_{CT} .

It can be commented from the above study that the existing T/Y-joint equations are not suitable for use to predict the SCF of completely overlapped joints under AX and OPB load cases. The T/Y-joint equations overestimate the SCF of the joint. However, the T/Y-joint equations predict better the SCF of the joint with large gap size. This is not unexpected as the SCF of completely overlapped joints with sufficiently large gap size is equivalent to that of simple T/Y-joints. It is noted that some geometrical parameters could have significant impact on the SCF of the joint. At small τ_{CT} and small gap size, the maximum difference of SCF between the T/Y-joint equations and the joint models can be as high as 13.71 and 235% in terms of numeric and percentage respectively. It is interesting to realize that the T/Y-joint equations predict reasonably well the SCF of completely overlapped joints under IPB load case. For this load case, the gap size on the through brace between the outer surfaces of the chord and the lap brace has negligible effect on the SCF of completely overlapped joints.

8.4 Comparison of Proposed and Existing Parametric Equations

8.4.1 Effect of through brace-to-chord diameter ratio, β_{CT}

In this study, β_{CT} varies from 0.4 to 0.8. The lower and the upper limits of gap size parameter (ξ_T) of completely overlapped joints are set at 0.5 and 1.0 respectively. Three basic load cases of the joint under lap brace AX, IPB and OPB are considered. From Fig. 8.1, the SCF of the joint due to β_{CT} is noted as follow.

AX load case

The SCF at crown toe of LP predicted by proposed equations is higher than that calculated by T/Y-joint equations (Fig. 8.1(a)). The proposed equations show increasing SCF with β_{CT} . On the contrary, Shell equations show decreasing SCF while Lloyd equations give invariant SCF with β_{CT} . At $\beta_{CT}=0.8$, the maximum difference of SCF for the joint with small and large gap sizes is found to be underestimated by the existing equations by 54% and 59% respectively.

IPB load case

The SCF at crown heel of LP predicted by proposed equations is lower than that calculated by Shell equations but higher than that by Lloyd equations (Fig. 8.1(b)). The proposed equations show increasing SCF with β_{CT} and so do the T/Y-joint equations. Shell equations over predict but Lloyd equations under predict the SCF of the joint by 30% and 17% respectively. It should be noted that the effect of gap size on the SCF of the joint under IPB load case is negligible (chapter 6 section 6.7). Hence, the SCF of the joint with small and large gap sizes predicted by the proposed equations are identical.

OPB load case

The SCF at saddle of LP predicted by proposed equations is lower than that calculated by T/Y-joint equations (Fig. 8.1(c)). The proposed equations show increasing SCF with β_{CT} and so do the T/Y-joint equations. At $\beta_{CT}=0.4$, the

maximum difference of SCF for the joint with small and large gap sizes is found to be overestimated by the existing equations by 51% and 33% respectively.

8.4.2 Effect of lap brace-to-through brace diameter ratio, β_{TL}

Similar to the previous study, β_{TL} varies from 0.4 to 0.8. The lower and the upper limits of gap size parameter (ξ_T) of completely overlapped joints are set at 0.5 and 1.0 respectively. The SCF at the hot spot locations of the joint under three basic load cases due to β_{TL} is shown in Fig. 8.2.

AX load case

The SCF at saddle of TL predicted by proposed equations is lower than that calculated by T/Y-joint equations (Fig. 8.2(a)). Note that the T/Y-joint equations predict the maximum SCF at $\beta_{TL}=0.5-0.6$. On the other hand, the proposed equations show decreasing SCF with β_{TL} . At $\beta_{TL}=0.8$, the maximum difference of SCF for the joint with small and large gap sizes is found to be unreasonably overestimated by the existing equations by 505% and 375% respectively.

IPB load case

The SCF at crown heel of TL predicted by proposed equations is lower than that calculated by T/Y-joint equations (Fig. 8.2(b)). The T/Y-joint equations show decreasing SCF with β_{TL} , while the proposed equations give minimum SCF at $\beta_{TL}=0.5-0.6$. The T/Y-joint equations overestimate the SCF of the joint by 75%. However, the overestimation of SCF in terms of numeric is only 1.28. It should be noted from the curves that the SCF determined by the proposed equations for the joint with small and large gap sizes are identical. This can be attributed to the negligible effect on gap size variation for the joint under IPB loading.

OPB load case

The SCF at saddle of TL predicted by proposed equations is lower than that calculated by T/Y-joint equations (Fig. 8.2(c)). Both Shell and Lloyd equations show increasing SCF with small and medium β_{TL} . However, at $\beta_{TL}=0.7$, the SCF

predicted by the T/Y-joint equations is constant. The proposed equations yield maximum SCF at $\beta_{TL}=0.5-0.6$. At $\beta_{TL}=0.8$, the maximum difference of SCF for the joint with small and large gap sizes is found to be unreasonably overestimated by the existing equations by 315% and 254% respectively.

8.4.3 Effect of through brace-to-chord wall thickness ratio, τ_{CT}

In this study, τ_{CT} varies from 0.4 to 1.0. The lower and the upper limits of gap size parameter (ξ_T) of completely overlapped joints are set at 0.5 and 1.0 respectively. Three basic load cases of the joint under lap brace AX, IPB and OPB are considered. From Fig. 8.3, the SCF of the joint due to τ_{CT} is noted as follow.

AX load case

The SCF at crown toe of TL predicted by proposed equations for the joint with small gap size is between that calculated by existing Shell and Lloyd T/Y-joint equations. However, the SCF predicted by proposed equations with large gap size is higher than that calculated by T/Y-joint equations at small and medium τ_{CT} . As τ_{CT} increases, Shell equations become increasingly conservative (Fig. 8.3(a)). The proposed equations show decreasing SCF with τ_{CT} and so do the T/Y-joint equations. At $\tau_{CT}=0.4$, the maximum difference of SCF for the joint with small and large gap sizes is underestimated by the existing equations by 43% and 53% respectively.

IPB load case

At small τ_{CT} , the SCF at crown heel of TL predicted by proposed equations is lower than that calculated by T/Y-joint equations. As τ_{CT} increases, Shell equations become less conservative (Fig. 8.3(b)). The proposed equations show decreasing SCF with τ_{CT} and so do the T/Y-joint equations. At $\tau_{CT}=0.4$, Lloyd equations over predict the SCF by 21%. At $\tau_{CT}=1.0$, Shell equations under predict the SCF by 12%. The gap size variation has negligible effect on the SCF of the completely overlapped tubular joint under IPB load case.

OPB load case

The SCF at saddle of LP predicted by proposed equations is lower than that calculated by T/Y-joint equations (Fig. 8.3(c)). The proposed equations show decreasing SCF with τ_{CT} and so do the T/Y-joint equations. At $\tau_{CT}=0.4$, the maximum difference of SCF for the joint with small and large gap sizes is found to be overestimated by the existing equations by 105% and 81% respectively.

8.4.4 Effect of lap brace-to-through brace wall thickness ratio, τ_{TL}

Similar to the previous study, τ_{TL} varies from 0.4 to 1.0. The lower and the upper limits of gap size parameter (ξ_T) of completely overlapped tubular joints are set at 0.5 and 1.0 respectively. Three basic load cases of the joint under lap brace AX, IPB and OPB are considered. From Fig. 8.4, the SCF of the joint due to τ_{TL} is noted as follow.

AX load case

The SCF at saddle of TL predicted by proposed equations is lower than that calculated by T/Y-joint equations (Fig. 8.4(a)). The proposed equations show increasing SCF with τ_{TL} and so do the T/Y-joint equations. At $\tau_{TL}=0.4$, the maximum difference of SCF for the joint with small and large gap sizes is found to be overestimated by the existing equations by 138% and 80% respectively.

IPB load case

The SCF at crown heel of TL predicted by proposed equations is lower than that calculated by T/Y-joint equations (Fig. 8.4(b)). The proposed equations show increasing SCF with τ_{TL} and so do the T/Y-joint equations. At $\tau_{TL}=0.4$, Shell equations over predict the SCF of the joint by 23% but the difference in terms of numeric is only 0.40. The SCF of the joint with small and large gap sizes predicted by the proposed equations are almost identical.

OPB load case

The SCF at saddle of TL predicted by proposed equations is lower than that calculated by T/Y-joint equations (Fig. 8.4(c)). The proposed equations show increasing SCF with τ_{TL} and so do the T/Y-joint equations. At $\tau_{TL}=0.4$, the maximum difference of SCF for the joint with small and large gap sizes is found to be overestimated by the existing equations by 71% and 46% respectively.

8.4.5 Effect of angle between chord and through brace, θ

In this study, θ varies from 30° to 60° . The lower and the upper limits of gap size parameter (ξ_T) of completely overlapped joints are set at 0.5 and 1.0 respectively. Three basic load cases of the joint under lap brace AX, IPB and OPB are considered. From Fig. 8.5, the SCF of the joint due to variation of θ is noted as follow.

AX load case

The SCF at crown toe of LP predicted by proposed equations is higher than that calculated by T/Y-joint equations (Fig. 8.5(a)). The proposed equations predict the maximum SCF at $\theta=35^\circ$ - 45° . The T/Y-joint equations show invariant SCF with θ . The maximum difference of SCF for the joint with small and large gap sizes is found to be underestimated by the existing equations by 55% and 60% respectively.

IPB load case

At small θ , the SCF at crown heel of TL predicted by proposed equations is higher than that calculated by T/Y-joint equations. As θ increases, the T/Y-joint equations become conservative (Fig. 8.5(b)). The proposed equations show decreasing SCF with θ and so do the T/Y-joint equations. Lloyd equations over predict the SCF of the joint by 20%, while Shell equations under predict by 8%. The gap size variation has negligible effect on the SCF of the joint under IPB load case.

OPB load case

The SCF at saddle of LP predicted by proposed equations is lower than that calculated by T/Y-joint equations (Fig. 8.5(c)). The proposed equations show

decreasing SCF with θ and so the T/Y-joint equations. At $\theta=45^\circ$, the maximum difference of SCF for the joint with small and large gap sizes is found to be overestimated by the existing equations by 92% and 69% respectively.

8.4.6 Effect of chord radius-to-wall thickness ratio, γ_C

In this study, γ_C varies from 8 to 32. The lower and the upper limits of gap size parameter (ξ_T) of completely overlapped joints are set at 0.5 and 1.0 respectively. Three basic load cases of the joint under lap brace AX, IPB and OPB are considered. From Fig. 8.6, the SCF of the joint due to γ_C is noted as follow.

AX load case

The SCF at saddle of LP predicted by proposed equations for the joint with small gap size is lower than that calculated by T/Y-joint equations. However, the SCF predicted by proposed equations with large gap size is higher than that calculated by T/Y-joint equations at small γ_C . As γ_C increases, T/Y-joint equations become increasingly conservative (Fig. 8.6(a)). The proposed equations show increasing SCF with γ_C and so do the T/Y-joint equations. At large $\gamma_C=32$, the maximum difference of SCF for the joint with small and large gap sizes is found to be overestimated by the existing equations by 92% and 48% respectively.

IPB load case

At small γ_C , the SCF at crown heel of TL predicted by proposed equations is higher than that calculated by T/Y-joint equations. As γ_C increases, the T/Y-joint equations become conservative (Fig. 8.6(b)). The proposed equations show increasing SCF with γ_C and so do the T/Y-joint equations. At $\gamma_C=32$, Shell equations over predict the SCF of the joint by 32%. At $\gamma_C=8$, Lloyd equations under predict the SCF of the joint by 21%. It is noted from the curves that the SCF of the joint with small and large gap sizes predicted by the proposed equations are almost identical.

OPB load case

The SCF at saddle of TL predicted by proposed equations is lower than that calculated by T/Y-joint equations (Fig. 8.6(c)). The proposed equations show increasing SCF with γ_C and so do the T/Y-joint equations. At large $\gamma_C=32$, the maximum difference of SCF for the joint with small and large gap sizes is found to be overestimated by the existing equations by 128% and 94% respectively.

The SCF of completely overlapped tubular joints under AX load case predicted by the existing T/Y-joint parametric equations do not tally well with those predicted by the proposed parametric equations. The proposed equations always under predict the T/Y-joint equations at the saddle of TL and LP and over predict at the crown toe of TL and LP. At large β_{TL} , the maximum difference of SCF for the joint with small and large gap sizes are unreasonably overestimated by the existing equations by 505% and 375% respectively. The SCF of completely overlapped joints predicted by the proposed equations with small gap size is lower than that with large gap size. This implies that the existing T/Y-joint equations predict reasonably well the SCF of the joint at the saddle of TL and LP with sufficiently large gap size. In the current study of the completely overlapped tubular K(N)-joint with parameters $\beta_{CT}=0.77$, $\beta_{TL}=0.53$, $\tau_{CT}=0.89$, $\tau_{TL}=0.78$, $\gamma_C=13.9$, $\gamma_T=12.0$ and $\theta=30^\circ$, it showed that the SCF of the joint is identical to that of the simple Y-joints at gap size parameter (ξ_T) of 1.19. However, the T/Y-joint equations excessively underestimate the SCF of the joint at the crown toe of TL and LP.

For the joint under IPB load case, the difference of SCF between the proposed equations and the T/Y-joint equations is small. At small γ_C , Lloyd equations under predict the SCF of the joint by 21% with difference in terms of numeric of 0.41. At medium β_{TL} , the SCF is found to be over predicted by 75% but the difference of SCF in terms of numeric is only 1.28. In view of the small discrepancy of SCF, it can be commented that the existing T/Y-joint parametric equations predict well the SCF of completely overlapped joints under IPB load case. It is noted that the SCF of the joint with small and large gap sizes are almost identical owing to the negligible effect of gap size under IPB loading.

The SCF at saddle of TL and LP for the joint under OPB loading predicted by proposed equations is lower than that calculated by T/Y-joint equations. At large β_{TL} , the T/Y-joint equations over predict the SCF of completely overlapped joints with small and large gap sizes by 315% and 254% respectively. The T/Y-joint equations excessively overestimate the SCF of the joint. Similar to the case for the joint under AX loading, the proposed equations predict lower SCF for the joint with small gap size than that with large gap size. This indicates that the existing T/Y-joint parametric equations predict reasonably well the SCF of completely overlapped joints with sufficiently large gap size.

8.5 Discussion and Concluding Remarks

A completely overlapped tubular joint is commonly misinterpreted as two T/Y joint configurations. In the current study, the existing T/Y-joint parametric equations are unable to accurately predict the maximum SCF of completely overlapped joints. For the simple T/Y-joint, the chord wall has to be designed to sustain severe stress concentration from brace loading. However, for the completely overlapped joint, the stress concentration on the through brace in contact with the lap brace is most significant. At the joint intersection of the chord and through brace, the SCF of the completely overlapped joint is found to be smaller in comparison to that of the simple T/Y-joint. This is primarily attributed to the load transfer mechanism among the members at the joint.

The research work on the structural behaviour of completely overlapped tubular joints conducted by Gho (2002) revealed that the load distribution at the joint was unbalanced. The experimental results showed that 75% and 25% of the lap brace compression were resisted by the load component of through brace and the supports of chord respectively. In the current specimen of the completely overlapped tubular joint, the test results showed that 67% and 33% of the lap brace compression are resisted by the load component of through brace and the supports of chord respectively. For the joint under lap brace IPB and OPB loadings, the applied load is mainly transferred between the through brace and the lap brace at the joint. As a

result, the SCF at the joint intersection of the chord and through brace is so small that can be neglected.

At the intersection of the through brace and lap brace, the SCF at the saddle is reduced for the joint under AX and OPB loadings. The reduced SCF at these locations of the completely overlapped joint are mainly due to the restriction of through brace ovalization from the weld and the chord wall. As the gap size on the through brace between the outer surfaces of the chord and the lap brace increases, the effect of ovalization reduces and thus results in increasing SCF at the saddle of through brace and lap brace. It is interesting to note that the T/Y-joint parametric equations predict reasonably well the SCF of the completely overlapped joint under IPB loading. It should be noted for this load case that the effect of gap size on the SCF of the joint is negligible.

Table 8.1 Comparison of SCF between test results and T/Y-joint parametric equations

Load case	Location	Test results		* Shell (2)	** Lloyd (3)	Difference	
		(1)	(1)-(3)			(1)-(2)	(1)-(3)
AX	CH-090	1.74		3.71	2.79	-1.97	-1.05
	CH-180	0.60		5.16	2.42	-4.56	-1.82
	TC-090	2.98		2.49	2.57	0.49	0.41
	TC-180	1.50		3.07	2.16	-1.57	-0.66
	TL-000	1.72		4.42	3.28	-2.70	-1.56
	TL-090	6.53		8.06	7.79	-1.53	-1.26
	TL-180	3.77		4.42	3.28	-0.65	0.49
	LP-000	1.03		2.89	2.31	-1.87	-1.29
	LP-090	3.69		5.88	5.35	-2.19	-1.66
IPB	LP-180	1.80		2.89	2.31	-1.09	-0.51
	CH-180	0.18		2.18	2.36	-2.00	-2.18
	TC-180	0.05		3.21	1.61	-3.16	-1.56
	TL-000	1.38		2.76	2.64	-1.38	-1.26
	TL-180	1.79		2.76	2.64	-0.97	-0.85
	LP-000	1.97		2.81	2.04	-0.84	-0.07
	LP-180	1.45		2.81	2.04	-1.36	-0.59
	CH-090	0.67		3.83	4.03	-3.16	-3.36
	TC-090	0.70		2.35	3.14	-1.65	-2.44
OPB	TL-090	4.80		6.09	6.45	-1.29	-1.65
	LP-090	2.19		4.60	4.31	-2.41	-2.12

* Shell – Parametric equations derived by Efthymiou and Durkin (1985)

** Lloyd – Parametric equations derived by Smedley and Fisher (1991)

Table 8.2 Comparison of SCF between FE results and T/Y-joint parametric equations
 - chord radius-to-wall thickness ratio, γ_c
 (Constants $\theta=45^\circ$, $\beta_{CT}=0.6$, $\beta_{TL}=0.6$, $\tau_{CT}=0.8$ and $\tau_{TL}=0.8$)

$\gamma_c=D/2T$	Equations	AX load case			IPB load case			OPB load case		
		MAX SCF		Difference	MAX SCF		Difference	MAX SCF		Difference
		Location	Magnitude		Location	Magnitude		Location	Magnitude	
8	$g_T=0.5dr$ (1)	LP-180	2.92		LP-0	2.51		TL-90	1.71	
	$g_T=1.5dr$ (2)	TL-180	3.83		LP-0	2.55		TL-90	1.99	
	Shell (3)	TL-180	3.05	*-0.13/4%	**0.78/21%	2.45	0.06/2%	TL-90	2.44	-0.73/43%
	Lloyd (4)	TL-180	2.55	■0.37/13%	■1.28/33%	1.50	1.01/40%	TL-90	2.58	-0.87/51%
16	$g_T=0.5dr$ (1)	LP-180	3.60		TL-0	2.64		TL-90	3.01	
	$g_T=1.5dr$ (2)	TL-180	4.77		TL-0	2.66		TL-90	3.62	
	Shell (3)	TL-90	5.88	-2.28/63%	-1.11/23%	2.46	0.18/7%	TL-90	4.87	-1.86/62%
	Lloyd (4)	TL-90	5.23	-1.63/45%	-0.46/10%	2.34	0.30/11%	TL-90	5.15	-2.14/71%
24	$g_T=0.5dr$ (1)	TL-180	4.20		TL-0	2.81		TL-90	4.12	
	$g_T=1.5dr$ (2)	TL-90	6.31		TL-0	2.81		TL-90	5.05	
	Shell (3)	TL-90	8.82	-4.62/110%	-2.51/40%	3.13	-0.32/11%	TL-90	7.31	-3.19/77%
	Lloyd (4)	TL-90	8.50	-4.30/102%	-2.19/35%	2.97	-0.16/6%	TL-90	7.73	-3.61/88%
32	$g_T=0.5dr$ (1)	TL-90	4.89		TL-0	2.94		TL-90	5.13	
	$g_T=1.5dr$ (2)	TL-90	7.91		TL-0	2.92		TL-90	6.40	
	Shell (3)	TL-90	11.76	-6.87/140%	-3.85/49%	3.71	-0.77/26%	TL-90	9.75	-4.62/90%
	Lloyd (4)	TL-90	12.01	-7.12/146%	-4.10/52%	3.52	-0.58/20%	TL-90	10.31	-5.18/101%

Note: * [(1)-(3)]/[(1)-(3))/(1)]
 ■ [(1)-(4)]/[(1)-(4))/(1)]
 ** [(2)-(3)]/[(2)-(3))/(2)]
 ■ [(1)-(4)]/[(1)-(4))/(1)]

Table 8.3 Comparison of SCF between FE results and T/Y-joint parametric equations
 - lap brace-to-through brace wall thickness ratio, τ_{TL}
 (Constants $\theta=45^\circ$, $\beta_{CT}=0.6$, $\beta_{TL}=0.6$, $\tau_{CT}=0.8$ and $\gamma_C=24$)

$\tau_{TL}=\tau_{L/Tr}$	Equations	AX load case				IPB load case				OPB load case			
		MAX SCF		Difference		MAX SCF		Difference		MAX SCF		Difference	
		Location	Magnitude			Location	Magnitude			Location	Magnitude		
0.4	$g_T=0.5dr$ (1)	LP-180	3.56			LP-0	2.18			LP-90	2.73		
	$g_T=1.5dr$ (2)	LP-180	4.08			LP-0	2.16			LP-90	3.18		
	Shell (3)	TL-90	4.12	*-0.56/16%	**0.04/1%	LP-0	2.71	-0.53/24%	-0.54/25%	LP-90	3.73	-1.00/37%	-0.55/17%
	Lloyd (4)	TL-90	4.25	■-0.69/19%	■-0.17/4%	LP-0	2.03	0.16/7%	0.14/6%	LP-90	3.96	-1.23/45%	-0.78/24%
0.6	$g_T=0.5dr$ (1)	LP-180	3.81			LP-0	2.20			LP-90	3.40		
	$g_T=1.5dr$ (2)	LP-90	4.88			LP-0	2.19			LP-90	4.01		
	Shell (3)	TL-90	6.43	-2.62/69%	-1.55/32%	LP-0	3.01	-0.81/37%	-0.82/37%	TL-90	5.48	-2.09/61%	-1.48/37%
	Lloyd (4)	TL-90	6.38	-2.57/67%	-1.50/31%	LP-0	2.10	0.10/5%	0.09/4%	TL-90	5.80	-2.40/71%	-1.79/45%
0.8	$g_T=0.5dr$ (1)	TL-180	4.20			TL-0	2.81			TL-90	4.12		
	$g_T=1.5dr$ (2)	TL-90	6.31			TL-0	2.81			TL-90	5.05		
	Shell (3)	TL-90	8.82	-4.62/110%	-2.51/40%	TL-0	3.13	-0.31/11%	-0.31/11%	TL-90	7.31	-3.19/77%	-2.26/45%
	Lloyd (4)	TL-90	8.50	-4.30/102%	-2.19/35%	TL-0	2.97	-0.16/6%	-0.16/6%	TL-90	7.73	-3.61/88%	-2.68/53%
1.0	$g_T=0.5dr$ (1)	TL-90	5.63			TL-0	3.54			TL-90	5.34		
	$g_T=1.5dr$ (2)	TL-90	8.62			TL-0	3.55			TL-90	6.53		
	Shell (3)	TL-90	11.28	-5.65/100%	-2.66/31%	TL-0	3.78	-0.24/7%	-0.23/7%	TL-90	9.14	-3.80/71%	-2.61/40%
	Lloyd (4)	TL-90	10.63	-5.00/89%	-2.01/23%	TL-0	3.55	-0.01/0%	-0.01/0%	TL-90	9.67	-4.32/81%	-3.14/48%

Note: * [(1)-(3))/((1)-(3))]/(1)]
 ■ [(1)-(4))/((1)-(4))]/(1)]
 ** [(2)-(3))/((2)-(3))]/(2)]
 ■ [(1)-(4))/((1)-(4))]/(1)]

Table 8.4 Comparison of SCF between FE results and T/Y-joint parametric equations
 - through brace-to-chord wall thickness ratio, τ_{CT}
 (Constants $\theta=45^\circ$, $\beta_{CT}=0.6$, $\beta_{TL}=0.8$ and $\gamma_C=24$)

$\tau_{CT}=\tau_{CT}/T$	Equations	AX load case				IPB load case				OPB load case			
		MAX SCF		Difference		MAX SCF		Difference		MAX SCF		Difference	
		Location	Magnitude			Location	Magnitude			Location	Magnitude		
0.4	$g_T=0.5dr(1)$	TL-90	5.82			TL-0	3.00			TL-90	6.63		
	$g_T=1.5dr(2)$	TL-90	9.95			TL-0	3.05			TL-90	8.67		
	Shell (3)	TL-90	17.65	*-11.82/203%	** -7.70/77%	TL-0	4.71	-1.71/57%	-1.66/55%	TL-90	14.62	-7.99/121%	-5.95/69%
	Lloyd (4)	TL-90	19.53	■-13.71/235%	■-9.58/96%	TL-0	4.48	-1.48/49%	-1.43/47%	TL-90	15.46	-8.83/133%	-6.79/78%
0.6	$g_T=0.5dr(1)$	TL-90	4.79			TL-0	2.88			TL-90	5.04		
	$g_T=1.5dr(2)$	TL-90	7.71			TL-0	2.90			TL-90	6.33		
	Shell (3)	TL-90	11.76	-6.97/146%	-4.05/53%	TL-0	3.71	-0.82/29%	-0.81/28%	TL-90	9.75	-4.71/93%	-3.41/54%
	Lloyd (4)	TL-90	12.01	-7.22/151%	-4.30/56%	TL-0	3.52	-0.64/22%	-0.62/22%	TL-90	10.31	-5.27/105%	-3.97/63%
0.8	$g_T=0.5dr(1)$	TL-180	4.20			TL-0	2.81			TL-90	4.12		
	$g_T=1.5dr(2)$	TL-90	6.31			TL-0	2.81			TL-90	5.05		
	Shell (3)	TL-90	8.82	-4.62/110%	-2.52/40%	TL-0	3.13	-0.31/11%	-0.32/11%	TL-90	7.31	-3.19/77%	-2.26/45%
	Lloyd (4)	TL-90	8.50	-4.30/102%	-2.20/35%	TL-0	2.97	-0.16/6%	-0.16/6%	TL-90	7.73	-3.61/88%	-2.68/53%
1.0	$g_T=0.5dr(1)$	TL-180	3.85			TL-0	2.77			TL-90	3.52		
	$g_T=1.5dr(2)$	TL-90	5.33			TL-0	2.75			TL-90	4.24		
	Shell (3)	TL-90	7.11	-3.26/85%	-1.78/33%	TL-0	2.75	0.02/1%	0.00/0%	TL-90	5.89	-2.37/67%	-1.65/39%
	Lloyd (4)	TL-90	6.56	-2.71/70%	-1.23/23%	TL-0	2.61	0.16/6%	0.13/5%	TL-90	6.23	-2.71/77%	-1.99/47%

Note:

* $[(1)-(3)]/[(1)-(3)]/(1)$
 ■ $[(1)-(4)]/[(1)-(4)]/(1)$

** $[(2)-(3)]/[(2)-(3)]/(2)$
 ■ $[(1)-(4)]/[(1)-(4)]/(1)$

Fig. 8.1 Comparison of SCF between proposed and T/Y-joint equations
- effect of through brace-to-chord diameter ratio, β_{CT}
(Constants $\theta=45^\circ$, $\beta_{TL}=0.6$, $\tau_{CT}=0.6$, $\tau_{TL}=0.6$ and $\gamma_C=16$)

Fig. 8.2 Comparison of SCF between proposed and T/Y-joint equations
- effect of lap brace-to-through brace diameter ratio, β_{TL}
(Constants $\theta=30^\circ$, $\beta_{CT}=0.4$, $\tau_{CT}=0.4$, $\tau_{TL}=0.4$ and $\gamma_C=32$)

Fig. 8.3 Comparison of SCF between proposed and T/Y-joint equations
- effect of through brace-to-chord wall thickness ratio, τ_{CT}
(Constants $\theta=60^\circ$, $\beta_{CT}=0.6$, $\beta_{TL}=0.8$, $\tau_{TL}=0.8$ and $\gamma_C=24$)

Fig. 8.4 Comparison of SCF between proposed and T/Y-joint equations
- effect of lap brace-to-through brace wall thickness ratio, τ_{TL}
(Constants $\theta=45^\circ$, $\beta_{CT}=0.8$, $\beta_{TL}=0.4$, $\tau_{CT}=0.8$ and $\gamma_C=24$)

Fig. 8.5 Comparison of SCF between proposed and T/Y-joint equations
- effect of angle between chord and through brace, θ
(Constants $\beta_{CT}=0.6$, $\beta_{TL}=0.8$, $\tau_{CT}=0.8$, $\tau_{TL}=0.6$ and $\gamma_C=32$)

Fig. 8.6 Comparison of SCF between proposed and T/Y-joint equations
- effect of chord radius-to-wall thickness ratio, γ_C
(Constants $\theta=45^\circ$, $\beta_{CT}=0.6$, $\beta_{TL}=0.6$, $\tau_{CT}=0.8$ and $\tau_{TL}=0.8$)

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

Experimental study

A uni-planar completely overlapped tubular joint specimen is tested to determine the HSSN and HSS at the joint intersections of the chord and through brace and the through brace and lap brace. The joint specimen is subjected to lap brace AX, IPB and OPB loadings as well as combination of these basic loadings. In the test, the strain values of the test specimen are recorded via the strain gauges within the elastic limit of steel material.

The experimental results showed that the curve fittings of strain values within the extrapolation region on the outer surfaces of members are fairly linear. For the joint specimen under AX loading, the maximum SNCF of 5.79 occurs at the saddle of through brace near the lap brace. For the joint under IPB and OPB loadings, the maximum SNCF of 1.73 and 4.34 occur at the crown heel of lap brace and the saddle of through brace near the lap brace respectively. The SNCF at the joint intersection of the chord and through brace are found to be negligible.

For the joint under combined loadings, the peak HSS can occur between the crown and the saddle of members. A comparison of HSS showed that the existing equation proposed by Gulati et al. (1982) agrees reasonably well with the test data. However, the offshore design recommendation, API RP2A (2000), over predicts the HSS of the joint specimen. The linear superposition of SCF for simple tubular joints under basic load cases is found to be applicable for predicting the HSS of completely overlapped joints under combined loadings.

Finite element (FE) analysis

The completely overlapped tubular joint specimen is modelled and analyzed using the commercial FE package MARC (2001) to investigate the stress and strain concentrations. Both 8-node thick shell (element type 22) and 20-node solid (element type 57) elements with reduced integration scheme are suitable for modelling the joint specimen. The weld elements of the joint are modelled according to the requirement specified in AWS. The stress component perpendicular to the weld toe is employed to calculate the SNCF and SCF of the joint. A linear extrapolation method defined in CIDECT (2001) is adopted to determine the HSS. A convergence study based on three different mesh refinements of thick shell and solid FE models is conducted.

From the FE analysis results, the SCF always showed larger value than the corresponding SNCF at the joint intersections. The maximum and the minimum SCF to SNCF ratios are 1.30 and 0.92 and the average values are 1.15, 1.14 and 1.13 for the joint under AX, IPB and OPB loading respectively. The recommended SCF to SNCF ratio of 1.2 by UEG is still suitable for use in the current study.

Comparison of test specimen and FE models

The maximum differences of SNCF between the experiment and the 8-node thick shell FE model for the joint under AX, IPB and OPB loadings are 21.4%, 16.5% and 9.9%, while the average differences of SNCF are 7.9%, 10.6% and 5.8% respectively. The maximum differences of SNCF between the experiment and the 20-node solid FE model for the joint under AX, IPB and OPB loadings are 21.2%, 18.9% and 15.9%, while the average differences of SNCF are 8.8%, 10.7% and 10.6% respectively. In view of the difference of SNCF between the experimental results and the FE analysis, not more than 1.5 in terms of numeric, both 8-node thick shell and 20-node solid FE models are concluded to compare reasonably well with the test specimen.

For the joint under AX+IPB, IPB+OPB and AX+IPB+OPB loadings, the comparison of HSS of the 8-node thick shell FE model with the test specimen showed that the minimum ratios are 0.77, 0.76 and 0.83, while the maximum ratios are 1.49, 1.40 and 1.34 respectively. Since the mean ratio and the standard deviation for the joint under AX+IPB, IPB+OPB and AX+IPB+OPB load cases are (1.02, 0.13), (1.04, 0.14) and (1.03, 0.13) respectively, the HSS of the FE model is concluded in reasonable agreement with that of the test specimen.

Parametric study

A parametric study based on FE analysis of 8-node thick shell FE model is extensively carried out to investigate the SCF of completely overlapped tubular joints. A total of 5184 FE models are created with various geometrical parameters. The analysis results showed that the boundary conditions of fixed or pinned at the ends of chord and through brace as well as the chord and through brace length parameters greater than 12 have negligible effect on the SCF of the joint.

For the joint under AX loading, the maximum SCF always occurs at the saddle and crown toe of TL and LP. The SCF increases with increasing β_{CT} , τ_{TL} , ξ_T , γ_C and γ_T , but decreases with increasing τ_{CT} and θ . For the joint under IPB loading, the maximum SCF almost occurs at the crown heel of TL and LP. The SCF increases with increasing β_{CT} and τ_{TL} , but decreases with increasing θ . For the joint under OPB loading, the maximum SCF occurs at the saddle of TL and LP. The SCF increases with increasing β_{CT} , τ_{TL} , ξ_T , γ_C and γ_T , but decreases with increasing β_{TL} , τ_{CT} and θ . The validity ranges are given in EQ (7-1).

SCF parametric equations

A series of parametric equations is proposed for predicting the SCF of completely overlapped joints under basic load cases. The equations are developed based on the FE analysis data of 5184 joint models. A minimum SCF of 1.5 is assigned at locations of the joint with frequency of occurrence of SCF larger than 1.5 less than

5%. These are located at CH-0 for the joint under AX loading; CH, TC, TL-90 and LP-90 for the joint under IPB loading and CH, TC-0, TC-180, TL-0, TL-180, LP-0 and LP-180 for the joint under OPB loading.

The reliability of the proposed SCF parametric equations is verified against the acceptance criteria of Fatigue Guidance Review Panel. The assessment based on the database of the experimental and numerical results showed that the proposed equations are reliable for predicting the SCF of completely overlapped tubular joints under basic load cases. For the joint under combined loadings, the HSS is determined by the superposition of SCF of the joint under basic load cases. The proposed equations predict reasonably well the HSS of the completely overlapped joint under combined loadings.

Completely overlapped joints and simple T/Y joints

The completely overlapped tubular joint is commonly interpreted as two separate T/Y-joint configurations with the through brace acting as a chord. However, this interpretation may not be appropriate as the existing T/Y-joint parametric equations overestimate the SCF of the joint under lap brace AX and OPB loadings. The difference of SCF can be as high as 13.7 at the joint intersection of the through brace and lap brace under AX loading. It is noted that the T/Y-joint parametric equations predict reasonably well the SCF of the completely overlapped joint under IPB loading. For this load case, the effect of gap size on the SCF of the joint is found to be negligible.

9.2 Recommendations

In the current parametric study, 8-node thick shell element is used for modelling the joint. The through brace-to-chord (β_{CT}) and lap brace-to-through brace (β_{TL}) diameter ratios of the joint are limited to 0.8. It is recommended that SCF of the joint with diameter ratios greater than 0.8 should be investigated. It is also recommended that 20-node solid element should be used for modelling the joint

with large diameter ratios so that the weld cut-back at the saddle can be included. Furthermore, the angle variation of lap brace with respect to chord should be investigated to determine the critical angle that causes the maximum SCF at the completely overlapped tubular joint.

The relationship between the completely overlapped joint and the simple T/Y joint could be due to the gap size on the through brace between the outer surfaces of the chord and the lap brace. In the current research, the SCF of the joint with small gap size is lower than that with large gap size under AX and OPB load cases. This behaviour indicated that the existing T/Y joint parametric equations may predict reasonably well the SCF of completely overlapped joint at sufficiently large gap size. Thus, a set of unified SCF parametric equations for predicting the SCF of both simple T/Y joints and completely overlapped joints should be proposed.

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APPENDIX A

Source Program for Post-Processing of the Output Data from FE Analysis Using Extrapolation Method Written in Visual C Language

a) *Source program for 8-node thick shell FE model*

```
#include<iostream.h>
#include<math.h>
#include<stdio.h>
#include<io.h>
#include<stdlib.h>
#include<conio.h>
#define MAX_n 100
#define PRECISION 0.000001

int UpTriangle(float U[][MAX_n],int n)
{
    int i,j;
    for(i=n;i>0;--i)
    {
        if(fabs(U[i][i])<PRECISION)
            return 1;
        for(j=i+1;j<=n;++j)
            U[i][n+1]-=U[i][j]*U[j][n+1];
        U[i][n+1]/=U[i][i];
    }
    return 0;
}

int GaussElimination(float A[][MAX_n],int n)
{
    int i,j,k;
    for(i=1;i<n;++i)
    {
        if(fabs(A[i][i])<PRECISION)
            return 1;
        for(j=i+1;j<=n;++j)
            for(k=i+1;k<=n+1;++k)
                A[j][k]-=A[i][k]*A[j][i]/A[i][i];
    }
    UpTriangle(A,n);
    return 0;
}

void main()
{
```

```
int n=3;
float A[MAX_n][MAX_n];
int nfiles;
int nlines=4;
int i,j,k;
int o;
float file1,file2,file3;
FILE *fp;
FILE *out1;
FILE *out2;
FILE *openfile;
FILE *openfile1;
FILE *input;
char ch,ch1,ch2;
char address[10];
float temp[4][2],temp1;
float c[3];
float om,on,test;
float m[1000][5][3];
float result[1000];
for(i=0;i<MAX_n;i++)
    for(j=0;j<MAX_n;j++)
        A[i][j]=0.0;
printf("Input Numbers of files(1--1000):\n");
scanf("%d",&nfiles);
if(nfiles>1000||nfiles<=0)
{
    printf("Error\n");
    exit(1);
}

openfile=fopen("numbers.txt","w");
for(o=1;o<=nfiles;o++)
{
    putc(' ',openfile);
    if(o<10)
        fprintf(openfile,"00%d",o);
    else if(o>=10&&o<100)
        fprintf(openfile,"0%d",o);
    else
        fprintf(openfile,"%d",o);
    putc('.',openfile);
    putc('t',openfile);
    putc('x',openfile);
    putc('t',openfile);
    fprintf(openfile,"\n");
}
fclose(openfile);
```

```

input=fopen("input.txt","r");
openfile1=fopen("numbers.txt","r");
for(o=1;o<=nfiles;o++)
{
fscanf(openfile1,"%s",address);
printf("%s\n",address);
if(!(fp=fopen(address,"r")))
{
printf("cannot open file.\n");
exit(1);
}
ch1=getc(fp);
ch2=getc(fp);
// putchar(ch1);
// putchar(ch2);
while(!(ch1=='-'&&ch2==10))
{
ch1=ch2;
ch2=getc(fp);
// putchar(ch1);
// putchar(ch2);

}
ch=getc(fp);
printf("the % group data:\n",o);
for(i=0;i<nlines;i++)
{
fscanf(fp,"%f%f%f",&file3,&file1,&file2);
printf("%6.0f %e %e\n",file3,file1,file2);
m[o-1][i][0]=file3;
m[o-1][i][1]=file1;
m[o-1][i][2]=file2;
}
// printf("Input 1st group lengths of OM and ON\n");
fscanf(input,"%f",&m[o-1][i][1]);
fscanf(input,"%f",&m[o-1][i][2]);
fclose(fp);
}
fclose(input);
out1=fopen("out.txt","w");
for(o=1;o<=nfiles;o++)
{
fprintf(out1,"the %d group data:\n",o);
for(k=0;k<nlines;k++)
fprintf(out1,"%6.0f %e
%e\n",m[o-1][k][0],m[o-1][k][1],m[o-1][k][2]);
fprintf(out1,"OM and ON %e %e\n",m[o-1][k][1],m[o-1][k][2]);
}

```

```

fclose(out1);
for(o=1;o<=nfiles;o++)
{
    for(k=0;k<nlines;k++)
    {
        temp[k][0]=m[o-1][k+1][1];
        temp[k][1]=m[o-1][k+1][2];
//        printf("%f    %f\n",temp[k][0],temp[k][1]);
    }
    for(i=1;i<4;i++)
    {
        A[i][1]=temp[i-1][0]*temp[i-1][0];
        A[i][2]=temp[i-1][0];
        A[i][3]=1;
        A[i][4]=temp[i-1][1];
    }
    if(GaussElimination(A,n))
        printf("Failed!!!\n");
    for(i=1;i<4;i++)
    {
//        c[i-1]=A[i][4];
        printf("%f\n",c[i-1]);
    }
//    printf("%f    %f\n",temp[0][0],temp[0][1]);
    temp1=temp[0][1]-(c[0]*temp[0][0]*temp[0][0]+c[1]*temp[0][0]+c[2]);
    if(temp1>0.0001)
        printf("unreliable error\n");
//    printf("%f",temp1);
    om=c[0]*temp[3][0]*temp[3][0]+c[1]*temp[3][0]+c[2];
    on=c[0]*temp[3][1]*temp[3][1]+c[1]*temp[3][1]+c[2];
    result[o-1]=(on*temp[3][0]-om*temp[3][1])/(temp[3][0]-temp[3][1]);
    test=(om-result[j])/temp[3][0];
    temp1=on-(test*temp[3][1]+result[j]);
    if(temp1>0.0001)
        printf("unreliable error\n");
//    printf("%f",temp1);
    }
    out2=fopen("result.txt","w");
    for(o=1;o<=nfiles;o++)
        fprintf(out2,"The result %d:    %8.7e\n",o,result[o-1]);
    fclose(out2);
}

```

b) Source program for 20-node solid FE model

```

#include<iostream.h>
#include<math.h>
#include<stdio.h>
#include<io.h>
#include<stdlib.h>
#include<conio.h>
#define MAX_n 100
#define PRECISION 0.000001

int UpTriangle(float U[][MAX_n],int n)
{
    int i,j;
    for(i=n;i>0;--i)
    {
        if(fabs(U[i][i])<PRECISION)
            return 1;
        for(j=i+1;j<=n;++j)
            U[i][n+1]-=U[i][j]*U[j][n+1];
        U[i][n+1]/=U[i][i];
    }
    return 0;
}

int GaussElimination(float A[][MAX_n],int n)
{
    int i,j,k;
    for(i=1;i<=n;++i)
    {
        if(fabs(A[i][i])<PRECISION)
            return 1;
        for(j=i+1;j<=n;++j)
            for(k=i+1;k<=n+1;++k)
                A[j][k]-=A[i][k]*A[j][i]/A[i][i];
    }
    UpTriangle(A,n);
    return 0;
}

void main()
{
    int n=3;
    float A[MAX_n][MAX_n];
    int nfiles;
    int nlines=4;
    int i,j,k;
    int o,q;

```

```
float file1,file2,file3;
FILE *fp;
FILE *out1;
FILE *out2;
FILE *out3;
FILE *openfile;
FILE *openfile1;
FILE *input1;
char ch,ch1,ch2;
char address[10];
float temp[4][2],temp1;
float c[3];
float om,on,test;
float m[1000][7][5][3];
float result[1000][7];
float kkxx,kkyy,kkzz,kkzy,kkzx,kkxy;
double result1[1000];
float m1,m2,m3;
float mm1,mm2,mm3;
float ll,mm,nn;
float index[1000][3][3];
float index1[1000][3];
for(i=0;i<MAX_n;i++)
    for(j=0;j<MAX_n;j++)
        A[i][j]=0.0;
printf("Input Numbers of files(1--1000):\n");
scanf("%d",&nfiles);
if(nfiles>1000||nfiles<=0)
{
    printf("Error\n");
    exit(1);
}
openfile=fopen("numbers.txt","w");
for(o=1;o<=nfiles;o++)
{
    putc(' ',openfile);
    if(o<10)
        fprintf(openfile,"00%d",o);
    else if(o>=10&&o<100)
        fprintf(openfile,"0%d",o);
    else
        fprintf(openfile,"%d",o);
    putc('.',openfile);
    putc('t',openfile);
    putc('x',openfile);
    putc('t',openfile);
    fprintf(openfile,"\n");
}
```

```

fclose(openfile);
  openfile1=fopen("numbers.txt","r");
  for(o=1;o<=nfiles;o++)
  {
    fscanf(openfile1,"%s",address);
    printf("%s\n",address);
    if(!(fp=fopen(address,"r")))
    {
      printf("cannot open file.\n");
      exit(1);
    }
    for(k=0;k<6;k++)
    {
      ch1=getc(fp);
      ch2=getc(fp);
      // putchar(ch1);
      // putchar(ch2);
      while(!(ch1=='-'&&ch2==10))
      {
        ch1=ch2;
        ch2=getc(fp);
        // putchar(ch1);
        // putchar(ch2);
      }
      ch=getc(fp);
      printf("the %d data of %d group:\n",k+1,o);
      for(i=0;i<nlines;i++)
      {
        fscanf(fp,"%f%f%f",&file3,&file1,&file2);
        printf("%6.0f  %e  %e\n",file3,file1,file2);
        m[o-1][k][i][0]=file3;
        m[o-1][k][i][1]=file1;
        m[o-1][k][i][2]=file2;
      }
    }
    fclose(fp);
  }
  input1=fopen("input.txt","r");
  for(o=1;o<=nfiles;o++)
  {
    fscanf(input1,"%f",&m1);
    fscanf(input1,"%f",&m2);
    for(k=0;k<6;k++)
    {
      m[o-1][k][4][1]=m1;
      m[o-1][k][4][2]=m2;
    }
  }

```

```

        fscanf(input1,"%f",&index[o-1][0][0]);
        fscanf(input1,"%f",&index[o-1][1][0]);
        fscanf(input1,"%f",&index[o-1][2][0]);
        fscanf(input1,"%f",&index[o-1][0][1]);
        fscanf(input1,"%f",&index[o-1][1][1]);
        fscanf(input1,"%f",&index[o-1][2][1]);
        mm1=index[o-1][0][1]-index[o-1][0][0];
        mm2=index[o-1][1][1]-index[o-1][1][0];
        mm3=index[o-1][2][1]-index[o-1][2][0];
        m3=(float)sqrt(mm1*mm1+mm2*mm2+mm3*mm3);
//    printf("%f %f %f",mm1,mm2,mm3);
        index1[o-1][0]=mm1/m3;
        index1[o-1][1]=mm2/m3;
        index1[o-1][2]=mm3/m3;
    }
    fclose(input1);
    out1=fopen("out.txt","w");
    for(o=1;o<=nfiles;o++)
    {
        fprintf(out1,"the %d group data:\n",o);
        for(q=0;q<6;q++)
        {
            for(k=0;k<nlines;k++)
                fprintf(out1,"%6.0f          %e\n",m[o-1][q][k][0],m[o-1][q][k][1],m[o-1][q][k][2]);
            fprintf(out1,"OM and ON          %e\n",m[o-1][q][k][1],m[o-1][q][k][2]);
        }
        fprintf(out1,"the direction data:\n");
        fprintf(out1,"%f          %f\n",index1[o-1][0],index1[o-1][1],index1[o-1][2]);
        fprintf(out1,"\n\n");
    }
    fclose(out1);
    for(o=1;o<=nfiles;o++)
    {
        for(q=0;q<6;q++)
        {
            for(k=0;k<nlines;k++)
            {
                temp[k][0]=m[o-1][q][k+1][1];
                temp[k][1]=m[o-1][q][k+1][2];
//                printf("%f          %f\n",temp[k][0],temp[k][1]);
            }
            for(i=1;i<4;i++)
            {
                A[i][1]=temp[i-1][0]*temp[i-1][0];

```

```

        A[i][2]=temp[i-1][0];
        A[i][3]=1;
        A[i][4]=temp[i-1][1];
    }
    if(GaussElimination(A,n))
        printf("Failed!!!\n");
    for(i=1;i<4;i++)
    {
        c[i-1]=A[i][4];
//        printf("%f\n",c[i-1]);
    }

//    printf("%f  %f\n",temp[0][0],temp[0][1]);
    temp1=temp[0][1]-(c[0]*temp[0][0]*temp[0][0]+c[1]*temp[0][0]+c[2]);
    if(temp1>0.0001)
        printf("unreliable error\n");
//    printf("%f",temp1);
    om=c[0]*temp[3][0]*temp[3][0]+c[1]*temp[3][0]+c[2];
    on=c[0]*temp[3][1]*temp[3][1]+c[1]*temp[3][1]+c[2];
    result[o-1][q]=(on*temp[3][0]-om*temp[3][1])/(temp[3][0]-temp[3][1]);
//    printf("%f\n",result[o-1][q]);
    test=(om-result[o-1][q])/temp[3][0];
    temp1=on-(test*temp[3][1]+result[o-1][q]);
    if(temp1>0.0001)
        printf("unreliable error\n");
//    printf("%f",temp1);
    }
    kkxx=result[o-1][0];
    kkyz=result[o-1][1];
    kkzz=result[o-1][2];
    kkyz=result[o-1][3];
    kkzx=result[o-1][4];
    kkxy=result[o-1][5];
    ll=index1[o-1][0];
    mm=index1[o-1][1];
    nn=index1[o-1][2];

//    printf("%f  %f  %f",kkkk1,kkkk2,kkkk3);

    result1[o-1]=kkxx*ll*ll+kkyz*mm*mm+kkzz*nn*nn+
        2*kkyz*mm*nn+2*kkzx*nn*ll+2*kkxy*ll*mm;
//    printf("%f",result1[o-1]);
    }

    out3=fopen("out1.txt","w");
    for(o=1;o<=nfiles;o++)
    {
        fprintf(out3,"the six stress of %d group: xx    yy    zz    yz    zx

```

```
xy\n",o);
    fprintf(out3,"%e %e %e
\n",result[o-1][0],result[o-1][1],result[o-1][2]);
    fprintf(out3,"%e %e %e
\n",result[o-1][3],result[o-1][4],result[o-1][5]);
    fprintf(out3,"\n\n");
}
fclose(out3);
out2=fopen("result.txt","w");
for(o=1;o<=nfiles;o++)
    fprintf(out2,"The result %d:    %8.7e\n",o,result1[o-1]);
fclose(out2);
}
```