MSc Thesis

Optimization of SCF's of Multiplanar Joints for Offshore Structures

H.M.Hanzil





Challenge the future

MSc Thesis

Optimization of SCF's of Multiplanar Joints for Offshore Structures

By

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In partial fulfilment of the requirements for the degree of

Master of Science in Offshore and Dredging Engineering

at the Delft University of Technology,

to be defended publicly on Thursday June 12, 2013 at 2:30 PM.

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This thesis was done in collaboration and guidance from



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Acknowledgements

I would like to take this opportunity to thank the institution and people who have directly and indirectly contributed to this thesis. First of all I would like to thank the members of the thesis committee Mr. Mirek Kaminski for his guidance and help with finding me the research topic with Keppel. I would like to express my gratitude to Professor Arie Romeijn for embracing this research and always giving me the feedback needed. My special thanks for Mr. Yilmaz Salman for creating the environment that allowed me to work on this research, but above all for his confidence, continuous support and personal coaching. I would also like to thank the other members of my graduation committee Mr. Robert Hekkenberg.

I would also like to thank the personnel at Keppel Verolme Mr. Wouter Henstra and Mr. Mariano Otheguy who have provided me with valuable inputs and focus for the research. I hope the results of this research are valuable for Keppel Verolme, as the execution phase of the thesis was for me.

One of the most important persons I would like to thank is my wife Asmi and daughter Izza, for their love and support, not only during my studies, but throughout my life. They make my effort all the more valuable.

Finally, I would like to thank my colleagues at Keppel Verolme, friends at TU Delft, my roommates and all other family members for their interest and support.

List of Symbols

| $d_{_0}$ | Chord Diameter | [mm] |
|---------------------------------------|--|-----------|
| d_1 | Brace Diameter | [mm] |
| <i>t</i> ₀ | Chord Thickness | [mm] |
| t_1 | Brace Thickness | [mm] |
| L | Chord length | [mm] |
| 8 | In Plane gap between brace members | [mm] |
| g_t | Out of Plane gap between brace members | [mm] |
| е | In Plane eccentricity | [mm] |
| e_t | Out of Plane Eccentricity | [mm] |
| θ | In plane Chord-Brace angle of intersection | [degrees] |
| ϕ | Out of plane brace angle | [degrees] |
| α | Chord length Parameter | [-] |
| β | Chord Brace Diameter Ratio | [-] |
| γ | Chord radius to thickness ratio | [-] |
| τ | Brace Chord thickness ratio | [-] |
| ζ | Gap to Chord Diameter ratio | [-] |
| SCF _{ax.chr.cr} | SCF on the chord crown due to axial loading | [-] |
| SCF _{ax.br.cr} | SCF on the brace crown due to axial loading | [-] |
| SCF _{ax.chr.sa} | SCF on the chord saddle due to axial loading | [-] |
| SCF _{ax.br.sa} | SCF on the brace saddle due to axial loading | [-] |
| SCF _{chr.ipb} | SCF on the chord due to in plane bending | [-] |
| SCF _{br.ipb} | SCF on the brace due to in plane bending | [-] |
| SCF _{chr.opb} | SCF on the chord due to out of plane bending | [-] |
| SCF _{br.opb} | SCF on the brace due to out plane bending | [-] |
| KKu | Strength of a Multiplanar KK Joint | [N] |
| Ku | Strength of a Uniplanar K Joint | [N] |
| $\Delta\sigma_{\scriptscriptstyle R}$ | Stress Range | [MPa] |
| σ | Stress | [MPa] |
| D | Chord Diameter | [mm] |

| d | Brace diameter | [mm] |
|------------------|---------------------------------|------|
| Т | Chord thickness | [mm] |
| t | Brace thickness | [mm] |
| Р | Axial Load | [N] |
| P _k | Strength of Uniplanar K joint | [N] |
| P _{T/Y} | Strength of Uniplanar T/Y joint | [N] |

Subscripts

| AC | Crown Axial loading |
|-----|-------------------------------|
| AS | Saddle Axial Loading |
| MIP | Moment in plane direction |
| MOP | Moment out of plane direction |
| my | Bending moment y direction |
| mz | Bending moment z direction |
| ax | axial loading |
| ipb | in plane bending |
| opb | out of plane bending |

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IIntroduction

Offshore support structures have extensive use of tubular structures which are welded together to form tubular space frames which extend from the seafloor to just above the water surface where the topsides are installed. These structures are subjected to environmental forces of wind, waves and current which causes stress concentration on the joints affecting the fatigue life of the structure. One of the procedure for the calculation of Stress Concentration Factors (SCF) for tubular joints involves the use of parametric equations as a means of identifying the critical joints to be considered for further detailed investigation. The guideline's insufficient clarification on the methodology to be employed for multiplanar joints caused difficulties in the calculation of fatigue life of support structures especially for OWEC (Offshore Wind Energy Convertors). The design of these structures are driven by Fatigue Limit State (FLS) and to be cost effective in the competitive Offshore Wind Energy market the structures needs to be designed such that their total weight and cost of fabrication are less. Some of the challenges faced in the design of Multiplanar Tubular Joints for offshore support structures are

- The calculation of SCF's using the parametric equations for Multiplanar Joints are not well defined.
- When there are a large number of critical joints in a jacket, Finite Element (FE) analysis is tedious.
- Improvement of the fatigue life of the structure without any drastic change in geometry and total weight of the structure.

An attempt to tackle these issues was carried out by studying effect of fatigue life of multiplanar joints. The joint configuration was modified such that the gap between the connected braces and the brace – chord angles were kept constant. This helps to optimize the joint geometry while keeping the overall geometry of the jacket the same. The static strength of the joint is also calculated and verified. The following research have been carried out in this thesis.

- The thesis describes the procedure followed for the calculation of SCF's for multiplanar joints using time domain fatigue analysis. In this case a multiplanar KK joint is considered for the purpose.
- Development of a program to calculate the best configuration of the geometry such that the fatigue life of the joint is improved.
- Study of the influence of Static strength over the Fatigue strength of tubular joints.

The thesis is aimed to provide an easy to use and simple method for the calculation of SCF's without the use of FE methods and also a program to find the optimum joint configuration improving the fatigue life of a multiplanar tubular joint.



The thesis is assorted into the below listed chapters with their relevant description for accessibility

CHAPTER 2 Literature Review

A study on the previous work conducted on both uniplanar and multiplanar tubular joints on a timeline basis. The study was useful to understand the approaches followed by different researchers on solving the behavior of uniplanar joints and extending it for multiplanar joints. The chapter provides an overview of the work carried out on the fatigue and static strength of tubular joints from the period of 1960. The study helps to understand how the development of new analysis techniques like FEM methods and testing methodology where applied to solve the uncertainties with the design of tubular joints

CHAPTER 3 Fatigue Mechanism

The basic mechanism of fatigue on a microscopic and macroscopic level are discussed. The different stages in the fatigue of a structure with respect to fatigue design. Which stage is critical with respect to the design of offshore structures are discussed. A brief overview of the tubular joint parameters and the classification is also discussed.

CHAPTER 4 Method for FLS calculation

The description of the procedure used for the calculation of the FLS of tubular joints using the guidelines specified by the classification societies. The prevalent problems encountered while applying them and how to solve them are discussed.

CHAPTER 5 Method for ULS calculation

The description of the procedure used for the calculation ULS of the tubular joints is discussed. The importance of ULS in the design of tubular joints are discussed and which parameters in the formulations affect and control the ULS design of a tubular joint and especially in the case of multiplanar tubular joint is discussed.

CHAPTER 6 Optimization Algorithm

The description of the different steps involved in the procedure for finding the optimum joint configuration is explained. In this chapter the program is spilt into its different modules and how each module functions is explained. The different inputs and outputs required for the modules to functions are illustrated.

CHAPTER 7 Joint Classification

This chapter focuses on the procedure used to breakdown a multiplanar joint into an equivalent uniplanar joint. The parametric equations specified for uniplanar tubular joints can then be applied to calculate the SCF's for multiplanar joints. The theory behind the classification is explained and rationalized.

CHAPTER 8 FEM Modelling and Analysis

The chapter explains the different steps used to simplify the modelling and meshing of multiplanar tubular joints. The different parameters which affect the accuracy of the results of the analysis is explained. The type of elements and different approaches used to calculate the SCF is also explained.

CHAPTER 9 Results and Conclusions

The results from the analysis done on a sample multiplanar KK joint is explained and the performance of the program while doing the analysis under different constraints are discussed and analyzed. The important parameter which affect the fatigue are identified and suitable recommendations are proposed.

2 Literature Review

A literature review on the earlier studies conducted for tubular joints in the industry was researched. The research is done for both the static strength formulations and stress concentration factors specific to tubular joints. Earlier research was more concentrated on uniplanar joints and subsequently developed in time for multiplanar joints. The study shows how the research into tubular joints developed within a period of time and the various tests conducted in different parts of the world.

2.1 Development of Static Strength Formulations for Tubular Joints

Tubular sections were very much dominant early in the offshore sector as they were mainly used in the fabrication of Jacket structures in the Gulf of Mexico. The designs of these structures were generally based on the experienced gained from building onshore civil structures. The same methodology was used however with a much larger safety factor was used for the application of designs at sea. The formulation of equations and design rules for the strength of joints were developed at a much later stage. The earliest of approaches was to formulate a theoretical model to simulate the joint characteristics under different type loadings. This approach proved to be difficult and involved a great deal of approximations. Much of the research on tubular joints was carried out during this period in Japan and US.

Early models were developed on the theory of shallow cylindrical shell equations to describe the behaviour of cylindrical shells weakened by a circular hole and the behaviour or intersecting cylinders Lekkerkerker[1]. The research was important to help describe the maximum stress and stress distribution on branch pipes and nozzles of reactor components. The Shell Model was later developed as an analytical model to describe the stresses developed in cylindrical shells due to application of external pressure and patch loads Bijlaard[2]. Later experimental stress analysis that were carried out were compared with the results that was produced by Bijlaard[3]. The results were not very satisfactory leading to a decrease in confidence of the approach. Later Prof A.C.Scordelis from University of California developed a solution for cylindrical shells subjected to localized line loads running parallel to cylinder axis. Using the principle of superposition a varying load was simulated by integrating impulsive loads using a Duhamel integral. The results showed the uneven peaking of the load at the cylinder intersections which were more realistic than the Bijlaard [2] solution. Further Dundrova.V [4] provided a general solution by developing a computer program covering multi planar connections. The analysis was based on assuming a membrane representation of the brace which was coupled with a complete shell theory representation of the chord. However even though these solutions gave insight on how the stresses peaked at joint intersections they were usually very high even above the yield strength of steel. In the Scordelis method the brace member was assumed to be rigid while Dundrova.V [4] assumed a branch member stiffness rather than being rigid, both the solutions provided comparable results which proves that the assuming the branch member is sufficiently rigid with respect to the chord is more or less valid.

The above methods failed to provide satisfactory solutions in the case of complex loading patterns and were eclipsed gradually by the development of Finite Element Methods (FEM) due to their robustness and the availability of increased computing capabilities. In addition the large reserve capacity of tubular joints after first yield also caused these approaches to produce unreasonably conservative results. Three subsequent models were later formulated to describe the Ultimate strength of Tubular joints. The detailed explanation of these models are further explained in Appendix A :

- The Ring Model for Chord Face Failure
- The Punching Shear Model
- The Chord Shear Model

The punching shear model was later implemented in the AWS code [5] and later involved editions by P.W.Marshall [6]. The equations were later modified for chord stress effects and implemented in the API RP-2A [7] and subsequently later used in ISO 19902 [8] practice code.

2.2 Development of Parametric SCF for Uniplanar Tubular Joints

In response to limited guidance on the design of tubular connections in 1967 Beale and Toprac [9] conducted a study which involved the test of ten welded specimens under axial loading on a test rig to find the stress distributions around the weld toe. The specimens were tested to failure in the elastic range to observe the behaviour during failure. A set of parametric equations were later formulated by performing regression analysis. Later Visser [10] in 1974 developed FE models using shell elements to verify and make amendments to the API formulations for the design of tubular joints. Visser [10]also developed a set of parametric equations to predict hot spot stresses resulting from testing a range of joint configurations. Identifying the importance of fatigue cracking in offshore structures Kuang et al [11] developed semi empirical equations for stress concentration factors for simple, non-reinforced T, K and TK joints. FE models were developed and verified by testing similar geometries in Oak Ridge National Laboratory (ORNL). Welds were not modelled in the FE models so there were discrepancies from the FE model and Specimen testing.

A total of 18 equations were developed by Kuang et al [11] for predicting the SCF's in the chord and braces of T, Y, K and KT joints. These equations later formed the basis of the equations of Efthymiou [12]. Kuang also specified the ranges of the geometrical parameters for the equations to be valid.

In 1978 Wordsworth and Smedley [13] did research using acrylic model testing as part of Lloyd's Register of Shipping for SCF's of tubular joints. Testing was done on T, Y and X joint specimens made of acrylic for axial loading, in plane bending (IPB) and out of plane bending (OPB). The model was loaded and strain measurements obtained by strain gauges placed around the weld toe to find locations of maximum stress. The variations due to changes in chord length was also examined. It was found that the bending stresses increased due to an increase in chord length. Chord length correction factors were as a result developed by this research. Since the weld profile could not be included in the model a weld correction factor was included in the results. This approach was further applied to K and KT joints with gap. The SCF equations obtained from Wordsworth were not verified with similar work.

Efthymiou and Durkin [14] started to develop comprehensive equations for T/Y and gap/overlap K joints which were not developed at that time. The study was a result of the discrepancies between the results of Kuang and Wordsworth. The research identified the following difficulties of using the Parametric SCF equations

- Difference in the prediction of SCF's between the formulation of Kuang et all and Wordsworth for certain joints and loadings
- No details or equations for certain load combinations in K and KT joints
- No details or equations for overlapped configurations
- Insufficient details on modelling and design of multiplanar joints

Models where designed using PMB-Shell software using shell elements. The models were developed for different loading configurations and end fixity conditions. The SCF's were obtained by extrapolating the maximum principal stresses to the weld toe and regions of extrapolation were also defined. The equations also provided correction for the short chord lengths. The obtained SCF's were later compared with that of Kuang and Wordsworth .Discrepancies exist between these studies especially in the axial loading, however similar graph shapes for chord SCF versus β can be observed for Wordsworth . The poor correlation between Kuang where due to limitations on modelling the weld and end fixity conditions assumed. The research was extensive in that all ranges of inclinations where attempted to be included in the study. Brace inclinations of 45° and even 30° and 60° where tested. Unequal brace inclinations of 90°/45° known as N type joints were also tested. The study also included a new geometrical parameter ζ for the first time to include the effects of the gap between braces.

Efthymiou [12] in 1988 further extended the application of the Parametric SCF formulae to include X and KT joints. Influence functions were introduced to model joints with different end loading conditions. Multiplanar effects were modelled in the analysis with the conclusion that these had little effect on the fatigue life of the joint. SCF Equations were also developed for T/Y joints for different chord end fixity conditions with the inclusion of chord end fixity parameter C.

Efthymiou developed influence functions as an alternative to find hot spot stress .When a nominal unit stress is applied to a brace of the joint, the hot spot stress (HSS) at a certain location on another brace of the joint can be computed. The method of superposition can then be implemented for each brace by multiplying the nominal stress by the outcome of the influence function for each brace and adding them together. A range of influence functions for X, K and KT joints under axial load and OPB are developed. The influence functions can be also used to analyze joints without the need for the joint to be under balanced or unbalanced loading. A comparison of finding SCF's using the SCF equations and the influence function where done. It was found that in the analysis of K and KT joint configurations where the OPB stresses play a significant role, the use of SCF equations resulted in a considerable over prediction of hot spot stress. As the SCF equations and thus give a greater hot spot stress than what would be calculated using influence functions.

SCF equations developed by Efthymiou are still the more favored approach to designing tubular joints. Further work has been completed by other authors on the subject with the formulation of new SCF equations for tubular joints however the design code DNV-RP-C203 [15] still recommends the use of Efthymiou.

Lalani et al [16] conducted an investigation into the methods used for the calculation of fatigue life using the parametric SCF equations. A total of 50 elastic tests were carried out on large scale steel models. The main points identified to be clarified were

- Design codes give different definitions of hot spot stress
- 103 parametric equations exist the output of these depending on which equations is used
- Variations in the methods used to determine and combine hot spot stress i.e. load combination techniques
- Limited SCF equations exist for overlapping, multiplanar and stiffened joints

Lalani compared the Efthymiou, Wordsworth, Kuang, Gibstein [17], UEG and Buitrago [18] formulations. A graph plotting there variations where provided as shown in Figure 2.1

Lalani further shows that the SCF's predicted by the equations underestimate the value in 16% of the cases for which data are available.

Hellier, Connolly and Dover [19] further researched into the discrepancies of the SCF's obtained by different equations. Around 900 thin shell FE models of T and Y joints were developed and tested.



Figure 2.1 Variation of SCF for different Formulation¹

Output from the models where verified with steel model tests. They found that the majority of the SCF's over predicted the values while only 3% gave conservative results. However they considered that such over prediction in the results is reasonable since it gave an additional level of safety in the design. The study concluded that due to difference in extrapolation methods and modelling of welds the equations doesn't give converging results and SCF's calculated maybe overestimated.

Smedley and Fisher [24] did experiments on over 350 acrylic joints with major emphasis on ring stiffened joints. The results were verified by two separate independent FEM using PMBSHELL and PAFEC with further testing of full scale steel complex joints. A comparison of the SCFs from steel and acrylic specimen testing and those determined by FE modelling was undertaken. As the acrylic models and the FE models from the PAFEC program did not include weld details, a direct comparison was made between these methods and with the outcomes from PMBSHELL and the steel models. It was noted that exclusion of the weld fillet in FE and acrylic models resulted in an increase in SCF of up to 18% for an unstiffened joint.

Due to the large no of discrepancies with different researches and no agreement found on the basis of tubular joint design the Lloyds's Register of Shipping developed a study to document the studies and provide some clarity. The equations that were investigated were

- Kuang [11]
- Wordsworth and Smedley [20]
- Underwater Engineering Group (UEG)
- Efthymiou and Durkin [14]
- Hellier, Connolly and Dover [19]
- Smedley and Fisher [20]

The study gives guidance on performing FEM, acrylic and steel testing. The study also specifies acceptance criteria based on experimental details, geometrical parameters and load cases.

Chang and Dover [21] developed a concept of presenting SCF's of distributions for saddle and crown locations. Thin shell analyses for 330 T and Y joint configurations were carried out resulting in database of SCF's. From this database they derived SCF distribution equations which helped to determine SCF's at any point on the brace chord intersection. These equations were functions of the dihedral angle φ measured around the intersection from crown toe.

¹ Figure from Lalani [16]

Karamanos, Romeijn and Wardenier [22] tried to simplify the equations for SCF's for K joints from the study of lattice girders and FE models. They developed graphs of SCF's on the chord and brace depending on the β and γ parameters. They proposed the **Error! Reference source not found.**

$$SCF = \left(\frac{\gamma}{\gamma_0}\right)^{X_1} \cdot \left(\frac{\tau}{\tau_0}\right)^{X_2} \cdot SCF_0 = \left(\frac{\gamma}{12}\right)^{X_1} \cdot \left(\frac{\tau}{0.5}\right)^{X_2} \cdot SCF_0$$

Equation 2-1

Where X1 and X2 depends on the loading and location of interest. The formulations take into account carry over bending effects when the loading in an adjacent brace causes stress concentration on the other. The main objective of their study was to make the design process of tubular joints simple and less cumbersome. In the formulations also the results had a good deal of correlation with the FE analyses conducted.

Van Wingerde, Packer and Wardenier [23] further simplified the SCF equations applicable to both CHS and RHS. FE models have been analyzed in order to determine simplified SCF formulae for uniplanar RHS (rectangular hollow sections) and CHS K joints and multiplanar CHS K joints. The procedure utilizes stresses perpendicular to the weld toe instead of principal stresses. A series of graphs and a reduced number of simplified SCF formulae have been developed which use the Eurocode 3 correction factors. Provided in the paper is the graph for balanced axial load on a tubular K-joint only. The SCF equations developed in the research is considered to be a conservative approach to the design of tubular connections.

Lotfollahi-Yaghin and Ahmadi [24] researched on stress distribution equations with formulae determined for KT-joints. 105 FE models comprising 3D solid elements and weld profiles were built and tested in ANSYS under balanced axial loading, the output of which was compared with expected SCFs from LR equations. An equation for determining the stress distribution around the weld toe of a KT joint under balanced axial load was derived. The paper specifies the importance of determining the location of HSS by determining the SCF distribution because fatigue induced surface crack initiates from the position of the hot-spot stress. Previous research gives only information whether the HSS occurs either on the crown or saddle of the chord or brace. The paper gives very good details on the method of mesh generation and modelling of tubular joints for FEM analysis.

2.3 Conclusion

Significant research has been done on the formulation of SCF's for the determination of fatigue life of tubular joints. Earlier research involved tests on specimens which were too small to be considered for offshore purpose and inclusion of then in the dataset created problems until acceptance criteria and validity ranges for the geometrical specimens where specified. Even then most of the joints where modelled without the inclusion of weld details and confusion in methods used for extrapolating the stresses from weld toe. There were also difference caused due to the selection of element type used for modelling the tubular joint example shell element or solid element. There was confusion with regards to which stresses principal stresses or nominal stresses to be used for the calculation of the HSS as the American API guideline recommends using the nominal stresses perpendicular to the weld toe and the European guidelines favor the use of principal stresses. The ISO -9902 finally came forward combining the approaches of both the API and DNV methods with the use of Efthymiou formulations for the SCF for tubular joints. The Efthymiou formulation was selected because the model includes weld details, chord length effects and different types of loading under different end fixity conditions. The SCF equations where further simplified with the use of graphs and included in the CIDECT design guide but these guidelines where however more suited to the design of onshore civil structures. The design guidelines however don't provide any guidance on the approach to be followed for multiplanar joints and suggested they should be analyzed using FEM.

2.4 Development of Parametric SCF for Multiplanar Tubular Joints

A considerable amount of investigation was carried out on uniplanar joints. Design regulations like DNV –RP-C203 [15] and API-RP-2A[7] also gives guidance on using Efthymiou equations for the design of uniplanar tubular connections. No guidance is given for the case of multiplanar connections but advice to perform FEM analysis for the case of multiplanar connections. The main debate on multiplanar joints were the effect of carry over effects.

Efthymiou [12] had accounted for the effects for carry over effects in multiplanar joints. He developed influence functions for determining the chord and brace hot spot stresses for both uniplanar and multiplanar braces. The effect of the carry over effects were to redistribute the loading and concluded that they were not so important as they only increased or decreased the hot spot range by around 15%.

Smedley and Fisher [25] conducted experiments on acrylic models to verify whether the uniplanar equations from Efthymiou can be applied to multiplanar joints. The test included 3 joints in multiplanar configurations of K and KT profile. They found that certain loading conditions caused very high differences in SCF. The research however concluded that IPB effects did not have much effect on the SCF's

Romeijn [26] conducted a study on the fatigue design of multiplanar tubular joints for guidance on the formulation of design standards to be included in the CIDECT EUROCODE. Romeijn carried out experimental testing of four different multiplanar triangular lattice girders fabricated from steel circular hollow sections. Overlap and gap KK joints were tested with the braces of joint repeatedly stressed to failure to establish an S-N curve for multiplanar joints. During the cycles of load, the strains at locations around the weld profile on both chord and brace were measured at regular intervals to check whether changes in hot spot stress and stress distribution occurred. The progression of cracks through members of the joint were observed and noted with failure occurring mostly in the chord. The test models where verified with FE models using 20 node solid elements with the inclusion of welds. They received good correlation between the test results and FEM analysis.

The following observations were identified in the study.

Influence of changes in Y and τ is generally small compared to changes in β and φ

- Chord and brace saddle locations, load cases Fbr,ax,b and Mbr,op,b cause large carry-over effects especially with increasing β
- SCF results for the two saddle locations on both chord and brace can vary
- Carry-over effects for Mbr, ip, b are negligible
- Carry-over effects for Mbr,op,b are negligible for chord and brace crown locations
- Varying φ gives a harmonic function for SCFs due to carry-over effects with largest SCFs found in the region forming the shortest gap

3 Fatigue Mechanism

Fatigue can be described in a simple manner as the phenomena by which a material failure or damage occurs due to repetitive loading. It can also be described as a mechanism by which repetitive loading cause microscopic cracks in a material which may grow to large cracks within a period of time due to the cumulative effect of the repetitive loads leading to fracture. The period from crack nucleation to the stage when the crack grows to a size such that the material no longer can withstand the load and becomes unsafe for operation is determined as the fatigue life time of the structure. The importance associated with fatigue is the fact that the due to the weakening of the structure the structure may fail under a load much smaller that the ultimate load for which the structure maybe designed for. So it becomes important to avoid such unanticipated failures which can lead to loss of life and money.

The understanding of the fatigue mechanism involves identification of conditions which influence fatigue lifetime and crack development. Hence it becomes important to understand the fatigue on a microscopic scale to better predict the phenomena on a large scale. In order to understand the different factors that affect the fatigue life of a structure. The factors influencing the fatigue is different for each stage of development of the cracks and so they can be isolated into two phases as shown Figure 3.1

- Crack Initiation Period
- Crack Growth Period



Cycles

Figure 3.1 Crack Size vs Number of Cycles

Microscopic cracks originate in the material in the form of defects during the fabrication process. They may also not exist and may be created immediately due to cyclic stress above the fatigue limit. These crack are not visible to the naked eye and are formed within the metallic crystalline structure very early in the fatigue life time of the structure. Due to repeated loading these crack grow and also new cracks get formed. These cracks eventually group together to form a micro crack which may be at a location away from the site of first crack nucleation. Further cumulative loading causes the crack to grow and propagate and eventually form fracture which are visible. During the crack growth period we can see that the size of the crack after the micro crack growth increases rapidly. A large percentage of the fatigue life occurs during the crack initiation period.

3.1 Crack Initiation period

Crack initiation and subsequent growth occurs by the mechanism of cyclic slip which is a result of plastic deformation or shear. They occur at amplitudes below the yield stress level and because of this it is limited to a very small number of grains of material. Since this occurs at low stress level they are mostly formed on the surface than inside the material where the stress level required would be higher. Due to the cyclic shear stress new material gets exposed to the environment from the surface as shown in Figure 3.2. The exposed surface gets oxidized. The slip band formed will be strain hardened and the characteristics will be different from that of the parent material. The formation of these slip band depends on the cyclic shear stress and will be not homogeneous due to the grain size of the material and their orientation.



Figure 3.2 Development of Slip Bands²

It is important to note that the mechanism for the formation of micro crack occurs at a stress lower than the yield stress and for that to be achieved it happens on the surface. More over in structures due to the geometry the stress distribution is inhomogeneous and causes formation of stress concentrations at the surface. This is further amplified due to surface roughness and corrosion pitting. Hence in the crack initiation period stress concentrations and surface characteristics govern the formation of cracks. It can also be seen from Figure 3.2 for such a protrusion to form on an otherwise smooth surface stress reversal is required also the profile of the loading also has an effect on the development of the slip band.

The formation of these micro cracks further distorts the stress distribution within the structure by increasing the stress concentration on the crack tips. The formation of theses cracks constrain the slip displacements. Also more than one micro crack can occur. The crack growth can then deviate from the initial orientation. In general the crack shows a tendency to grow perpendicular to the loading direction. The crack growth meets with resistance on the grain boundary once it penetrates this its rate of growth increases till it reaches the next boundary and so on. After passing the grain boundaries the crack growth rate steadily increases. The resistance to crack growth as it starts penetrating the material no longer depends on the surface properties but rather on the material property. This stage when the surface conditions no longer influence the crack propagation marks the end of crack initiation period.

The crack initiation period is important for the design stage of a structure as the structure should be designed such that it has sufficient fatigue lifetime until such cracks start formation. The FLS design of a structure should guarantee that that the structure can withstand sufficient cyclic loadings until crack initiation due to fatigue might appear. This is because the fatigue cracks as explained before can occur under regular loads rather than extreme loads so it will be advantageous to avoid any unexpected damages to structure.

3.2 Crack Growth

Crack growth starts when the resistance of the material over crack propagation is more dominant. This is because after some crack growth the crack tip stress field changes from plane stress to plane strain deeper in the material. This is because during the crack growth period larger strains are developed due to the same stress during the crack initiation period. Also due to formation of cracks the stress distribution is concentrated on the crack tip and hence the stress concentration factor no longer becomes valid as it may be assumed to be infinite since a crack tip has zero radius. In this stage Stress Intensity Factor is used to give an idea of the stress severity around the crack. This is an elastic concept but due to high stress levels around the crack plastic deformation can occur. Further crack growth depends on the mode of crack opening described as

- MODE-I Opening in Tension
- MODE –II Opening in Plane Shear and
- MODE-III Opening in Transverse Shear

As the crack grows it will start interacting with the geometry of the structure further transforming the stress field due to increased flexibility in these stage. This is because of the increased stresses at the crack tip causing plastic deformation. This is controlled by the property of the material and described by Fracture Toughness which gives the sensitivity of the material for cracks under loading.

It must be noted that crack growth analysis is essentially performed so see how long the structure will survive with cracks or to estimate the reserve strength of the structure. The understanding of these concepts helps to determine proper inspection intervals of the structure so that precautions and repair can be taken accordingly which will help in further extending the life of a structure. This stage however is not the main focus of the study as the study involves the design of a structure such that the occurrence of these crack may be successfully resisted for the designed lifetime of the structure or the cracks may not grow to such a size for the designed life that the operability of the structure may be compromised.

3.3 Design of Tubular Joints for Offshore Structures

In an offshore structure the members in a frame are connected together by welding at joints. The profile mainly used in offshore structure and jackets subjected to wave loading are of the circular hollow section (CHS) profile. The advantages of a CHS profile over other profiles are due to

- Lesser forces due to coefficients of the Morrison equation which are dependent on the cross section profile and area
- Better buckling strength
- Lower costs for painting and protective coating
- Better resistance under torsion
- Internal areas can be used for stiffeners or grout

3.3.1 Tubular joint geometrical parameters

The chord is the through member where the rest of the members are welded to. The chord member diameter will be in most of the cases greater than or equal to the brace member. The chord need not be of uniform diameter they can vary and in cases to improve the life of a joint which is critical the section of the chord where the brace connects can be made of larger and thicker diameter than the rest of the chord member. This section is known as the Joint Can. The Figure 3.3, Figure 3.4 and Figure 3.5 from ISO 19902 [8] below show the various parameters with respect to Joint Types that needs to be identified to properly define a joint.



Figure 3.3 –Y Joint

Figure 3.4- X Joint



Figure 3.5 – K Joint

| Key |
|-----|
|-----|

| 1 | crown | $\beta = dlD$ | $\beta_{A} = d_{A}/D$ | $\beta_{B} = d_{B}/D$ | $\beta_{\rm C} = d_{\rm C}/D$ |
|---|---------|------------------|------------------------------|---------------------------------|-------------------------------|
| 2 | saddle | $\tau = t/T$ | $\tau_{\rm A} = t_{\rm A}/T$ | $\tau_{\rm B} = t_{\rm B}/T$ | $\tau_{\rm C} = t_{\rm C}/T$ |
| 3 | brace A | $\zeta = g/D$ | $\zeta_{AB} = g_{AB}/D$ | $\zeta_{\rm BC} = g_{\rm BC}/D$ | |
| 4 | brace B | $\gamma = D/2 T$ | | | |
| 5 | brace C | $\alpha = L/2 D$ | | | |

List 1 – Defined Non Dimensional Parameters

The following shows the joint definitions for a uniplanar joint.

The multiplanar joint specification are as shown below in Figure 3.6



Figure 3.6 – Out of Plane and In Plane angle definitions for Multiplanar KK Joint

ISO19902 [8] specifies the validity ranges for which the SCF's can be calculated which are based on the Efthymiou equations they are provided in List 2

| 0,2 | \leq | β | ≤ | 1,0 |
|---------------|--------|----------|--------|-----|
| 0,2 | \leq | τ | \leq | 1,0 |
| 8 | \leq | γ | \leq | 32 |
| 4 | \leq | α | \leq | 40 |
| 20° | \leq | θ | \leq | 90° |
| -0,6 β | _ | ۶ | _ | 10 |
| sinθ | | 5 | | 1,0 |

List 2 – Validity ranges of Geometry Parameters as per DNV-RP-C203

There are tolerances provided for the gap to be maintained between adjacent braces. The gap should not be less than 50mm in the in plane as well out plane braces. Design guidelines recommend to avoid overlapping of welds of non-overlapping braces. Although overlapped joints have better performance in resistance to fatigue as they provide better load paths for redistribution of the loads reducing the stress concentration at the joints. However they are commonly avoided due to difficulties associated with fabrication. ISO-19902 gives clear specifications for maintaining gaps in overlap and non-overlapped joints

3.3.2 Classification of Joints

The joints are classified not by the geometry they represent but by the configuration in which the axial loadings are configured for the joint to be in equilibrium. So for example in the case of a T/Y joint the axial load in the brace should be balanced by the shear force in the chord. For the joint to be classified as an X joint the axial loads in the braces should balance each other or with the shear force in the chord. The K joint can be configured when the axial loads in the brace are balanced by the axial and shear forces in the chord. The balanced configuration of these joint with

respect to loads is provided in Figure 3.7. Detailed explanation of this procedure with the help of examples as per the DNV RP-C203 [15] guide is provided in Figure 3.8



Figure 3.7 Balanced T/Y,K and X Joint Configurations

There is no specific detail as to the approach to be followed for multiplanar joints. CIDECT DG8 [27] provides a method to be followed in the case of a multiplanar joint. The procedure involves the specification of using the same SCF formulae for K joint while using a multiplication factor depending on the loading condition. This is explained in CIDECT DG8 Guideline [27].





³ From ISO 19902 [8]

A Method for FLS calculation

Fatigue analysis of any structure involve 3 procedures

- Global estimation of the loads and extrapolation of a short term data to the probability of the load during the entire lifetime or design life of the structure for which it needs to be designed.
- Conversion of the global loads into the local stresses concentration taking into account the structural detail. This gives long-term hotspot stress variations for every fatigue sensitive location or joints as in this case.
- Calculation of the fatigue damage due to these long term hot spot stress variations

The first two parts are the most difficult as it involves a large amount of uncertainties. The assumptions made to solve these can have a large effect on the fatigue life estimated. This thesis mainly involves with the second part where the global loads which are assumed known is used to estimate the hotspot stress distribution in fatigue sensitive joints in a structure.

4.1 Stress Concentration Factor for Tubular Joints

Elementary stress formulas are based on cross sections with constant section or gradual change of cross section. When there is a change in cross section or geometry as in the case of tubular joints the brace chord intersection the simple stress distributions get modified and results in highly localized stresses in the intersection regions as shown in Figure 4.1. The magnitude of these stress concentration depend on the geometrical parameters of the joint. The equations for the stress concentration factors for different loading conditions and boundary conditions are specified in the ISO-19902 [8] as per the Efthymiou[14] formulae. The equations are different for each joint type whether T/Y, K, X and KT joint. These are provided in the Appendix 10.2

From the SCF's obtained the HSS are estimated around the brace chord intersection as shown for the 8 positions around the chord and the brace.



The HSS at the 8 positions are found out by the below formulae

$$\begin{split} &\sigma_{1} = SCF_{AC} \ \sigma_{x} + SCF_{MIP} \ \sigma_{my} \\ &\sigma_{2} = \frac{1}{2} (SCF_{AC} + SCF_{AS}) \ \sigma_{x} + \frac{1}{2} \sqrt{2} \ SCF_{MIP} \ \sigma_{my} - \frac{1}{2} \sqrt{2} \ SCF_{MOP} \ \sigma_{mz} \\ &\sigma_{3} = SCF_{AS} \ \sigma_{x} - SCF_{MOP} \ \sigma_{mz} \\ &\sigma_{4} = \frac{1}{2} (SCF_{AC} + SCF_{AS}) \ \sigma_{x} - \frac{1}{2} \sqrt{2} \ SCF_{MIP} \ \sigma_{my} - \frac{1}{2} \sqrt{2} \ SCF_{MOP} \ \sigma_{mz} \\ &\sigma_{5} = SCF_{AC} \ \sigma_{x} - SCF_{MIP} \ \sigma_{my} \\ &\sigma_{6} = \frac{1}{2} (SCF_{AC} + SCF_{AS}) \ \sigma_{x} - \frac{1}{2} \sqrt{2} \ SCF_{MIP} \ \sigma_{my} + \frac{1}{2} \sqrt{2} \ SCF_{MOP} \ \sigma_{mz} \\ &\sigma_{7} = SCF_{AS} \ \sigma_{x} + SCF_{MOP} \ \sigma_{mz} \\ &\sigma_{8} = \frac{1}{2} (SCF_{AC} + SCF_{AS}) \ \sigma_{x} + \frac{1}{2} \sqrt{2} \ SCF_{MIP} \ \sigma_{my} + \frac{1}{2} \sqrt{2} \ SCF_{MOP} \ \sigma_{mz} \end{split}$$

The formulae used can be increased to check the stresses at more than 8 locations by

$$\sigma_n = SCF_{ax} \cdot \sigma_{ax}(t) \pm SCF_{ipb} \cdot \sigma_{ipb}(t) \cdot sin\theta \pm SCF_{opb} \cdot \sigma_{opb}(t) \cdot cos\theta$$



Figure 4.2 Polar Distribution Format of HSS around chord brace intersection

This can be used to determine the SCF around the intersection at as many points as required .For the calculation of the SCF's however not more than 8 spots are required because the SCF's occur mainly either at the crown or saddle position of the brace or chord section.

SCF is a term which gives idea of the ratio of the stresses at a certain local coordinate to that of the applied load. This occurs due to amplification of stresses due to local geometry details. There were many confusions in code as to the nature of the stress to be used for the calculation of the SCF's i.e. whether principal stresses or nominal stresses. The stresses that are used to calculate the SCF's are the Principal Stresses but since the principal stresses changes with the geometry section their distribution in space cannot be defined properly. The nominal stresses are the stresses which are perpendicular to the cross section. The advantages of using nominal stresses over principal stresses are

• They are more uniform over the cross section perpendicular to the weld toe

• The testing of Tubular joints involve strain gauges which are placed near the weld toe and they measure the change in displacements or strain which are converted to stresses. The strains that are measured between two strain gauges are the nominal strain

The American codes like API-RP-2A [7]use nominal stresses while the European codes like the DNV-RP-C203[15] use principal stresses. The difference in using these stresses are that they give different SCF's at the crown position but at the saddle position they are moreover the same.

The nominal stress that needs to be used to calculate the HSS should actually depend on the type of loading. The HSS due to an SCF caused in any crown/saddle position on the brace/chord should be calculated with the nominal stress due to the member that caused the SCF i.e. for example in the case of only brace loading if the SCF occurs on the chord the HSS is calculated with the SCF multiplied by the nominal stress on the brace member. For this condition to be satisfied it also requires that the SCF's are not affected by the boundary conditions as shown in Figure 4.3 and Figure 4.4 in the case of a brace loading causing SCF's on the chord.



Figure 4.3 Pinned Support



Figure 4.4 Fixed Support

The mode of support used for the analysis causes internal forces as shear in the chord section causing lesser displacements and SCF's. In the case of multiplanar joints with multi axial loading pattern this is very difficult to achieve.

4.2 Calculation of Stress Ranges

The joint will fail due to generation of fatigue crack in any of these 8 points for which the HSS are calculated depending on the force fluctuation. No plastic redistribution of the stresses are permitted. Simple elastic theory is used assuming plane sections remain plane after bending. Local

stress due to weld profile or the notch stresses are neglected as they are assumed to be included in the SN curve. From the stress time history large variation in stresses are important as they contribute largely to the initiation and propagation of cracks and hence fatigue. Small stress variations can be disregarded as they don't contribute to fatigue damage. The stress variations in time are simplified by breaking down the stress time history data into a set off corresponding stress ranges that occur for an equivalent number of cycles. This is done by using a rainflow counting method. Stress reversal is defined as a point where the first derivative changes sign or the slope changes. Since large stress reversals are of importance they shouldn't be separated when a small stress variation occurs in between a large stress reversal. The small stress variation should be counted as a separate stress reversal from the larger stress reversal as shown in Figure.



Figure 4.5 Stress Cycle Counting

The number of stress reversals whether as a half cycle or full cycle can be specified. When half cycle counting is specified it captures in detail the stress reversals than the full cycle method. The range of the cycle and the number of times it occurs are also evaluated by the rainflow counting algorithm. The rainflow counting however is not able to give any detail about the sequences of occurrence of these stress ranges and it is lost in the counting process. The sequence is important in the case of the variable amplitude loading as the sequence of the stress reversals affect the crack propagation. From the counting algorithm a histogram is generated with the stress ranges and the number of the cycles the stress ranges occur into corresponding bins which is specified by the user

4.3 Calculation of number of Cycles to Failure

The two main parameters that influence fatigue life are

- The stress ranges $\Delta \sigma_R$ at the critical HSS location
- The Fatigue Strength of the detail. This is dependent on the nature of the geometry. SN curves for tubular joint have been generated on the basis of tests conducted on samples.

The SN curves are based on mean and the standard deviation of the experimental test conducted on similar specimens so that they have a probability of survival of 97%. Marshall [28] improved the SN curves while defining them for the AWS codes by specifying a minimum diameter of 100 mm and improved weld profiles as selection criteria.

The Number of cycles to failure can be calculated by using the expression

 $N = \frac{a}{\Delta \sigma_R}$

Or

 $logN = loga - m \cdot log\Delta\sigma_R$

The curve also includes the thickness effect due to change in thickness by including a modification on the term $\Delta \sigma_R$.

$$logN = loga - m \cdot log \left(\Delta \sigma_R \cdot \left(\frac{t}{t_{ref}} \right)^k \right)$$

Where,

| t _{re} | f (Reference Thickness) | = 32mm for tubular joints |
|-----------------|--|---------------------------|
| k | (Thickness exponent on fatigue strength) | = 0.25 for SCF ≤ 10 |
| | | = 0.30 for SCF > 10 |

loga is the intercept of log N axis

m is the slope of the SN curve.

The increase in thickness doesn't necessarily increases the fatigue life in every situations. The thickness effect is related to the size of the local notch effect zone to the toe of the weld.



Figure 4.6 Size Effect in Fillet Joints from [28]

For example from Figure 4.6 the geometries A and B have almost the same fatigue strength even though the thickness increases i.e. thickness of the lower web increases but the weld notch remains the same. The fatigue life however decreases drastically from A to C where thickness effect includes increase in thickness of the notch weld.

Since the structure is subjected to air loads and loads due to waves in the splash zone the SN Curve to be used is as shown in Figure 4.7



Figure 4.7 SN Curve for Tubular Joint

There is separate SN curve used for the air as well as sea water with cathodic protection. The curve used is bilinear with a two slopes with m and m+2. The SN curve is specified with a slope of m+2 after 1E +07 cycles because it can be assumed that for high cycle fatigue under constant amplitude loading that stress below a certain range under 1 E+07 do not contribute in the propagation of cracks which is known as the threshold value. But in real life situation loading is variable amplitude and when a structure is sufficiently weakened by fatigue smaller stress ranges do in fact contribute to the propagation of cracks. Hence to include then in the calculation of damage a slope of m+2 is suggested.

4.4 Calculation of Damage

In the case of Variable amplitude loading the number stress rages (n) are arranged into bins from

the details of the stress spectrum. The damage due to each band is calculated as $\frac{n}{N}$.

Since the loading applied is variable amplitude some sort of rule needs to be used to calculate the damage from the different stress ranges. This is not the case for constant amplitude loading. To avoid failure before the end of design life the Palmgren Miner hypothesis is to be satisfied. The Miner's Rule sates that

$$\sum_{i=1}^{n} \frac{n_n}{N_n} \le 1$$

The diagram showing the procedure of how the fatigue damage is calculated under variable amplitude loading in the time domain is shown in Figure 6.5

5 Method for ULS calculation

Fixed offshore Structures are redundant and have a multiplicity of load paths for failure. This helps a member of the structure to fail and still avoid catastrophic failure of the entire structure. This introduces the concept of redundant structures to have sufficient residual strength so that they have a level of safety even if a member in the structure fails. The offshore support structure usually made of tubular frames joined to one another have sufficient residual strength in their design. The loads exerted on the structure are transmitted onto the members through complex load paths. They mostly depend on the loading profile, direction and the type of joint configuration used in the design. In offshore jacket structures the load transfer is considered to be taken up by the brace members which are relatively more flexible and weaker than the chord section. The brace members takes up the individual loads and are transfer them to the chord section. Often more than one brace members are connected to the chord and all the individual force from the braces combine and are transmitted by the chords to the foundation.

The location where these forces combine that is the joints are the critical points since these are the location where the extreme loading occurs. Furthermore the type of joint at location also determines the strength capacity of the joint. The joints at these location need to be checked for all loading cases i.e. Axial, In Plane Bending (IPB) and Out of Plane Bending (OPB).

The loading condition such as tension and compression have different magnitude on the joint. Joints are to be designed such that they cannot exceed their yield stress under tension while under compression due to the local joint eccentricity and chord forces local instability can occur even before reaching the yield stress of the member. Therefore while modelling the structure to analyze the local joint forces the extra flexibility due to the particular configuration of the joint maybe modelled with springs in the skeletal model of the structure to account for these effects.

Empirical formula for the determination of the ultimate strength of the joint are developed on the basis of theoretical analyses on three basic types of joint correlated with a large number of experimental results .The parameters of the joint which affect the joint strength are determined from the model and the results that are obtained are tuned by the use of factors and coefficients such that they are congruent with the experimental results. The three basic models on which the empirical formulae of the static strength are based are :

- Punching shear
- Ring Model
- Chord Shear Model

These three models for static strength refer to the failure profiles which are normally encountered in design. So the strength formulae are derived such the joint is sufficient to withstand that particular mode of failure. The explanation of these models are described in the Appendix 10.1 in detail.

5.1 The Ultimate Strength according to ISO-9902[8]

The ultimate strength for tubular joints has to be calculated for joint axial strength P_u and joint bending moment strength M_u .

$$P_{u} = \frac{f_{y} \cdot T^{2}}{sin\theta} \cdot Q_{u} \cdot Q_{f}$$
$$M_{u} = P_{u} \cdot D = \frac{f_{y} \cdot T^{2} \cdot D}{sin\theta} \cdot Q_{u} \cdot Q_{f}$$

This equation is basically obtained from the Punching shear stress model. Where

 P_u is the Joint axial strength

 M_u is the Joint bending strength

 f_{y} is the yield strength of the joint

T is the chord wall thickness

D is the chord wall diameter

 Q_u is the joint strength factor

 Q_f is the chord force factor

The design strength of the joint is calculated by dividing the partial safety factor $\gamma_R = 1.05$

$$P_d = \frac{P_u}{\gamma_R}$$
$$M_d = \frac{M_d}{\gamma_R}$$

 γ_R

Where

 P_d is the Joint axial design strength and M_d is the Joint bending design strength.

The joint classification is to be used for the determination of the joint for the appropriate equations for both Q_u and Q_f . The effect of joint combinations occurs such as 50% K and 50% T/Y. Then for example $Q_u = 50\% Q_u(K) + 50\% Q_u(T/Y)$.

The Strength factor Q_u is formulated empirically from a large number of experiments and associated FE analysis.

| Table ! | 5-1 |
|---------|-----|
|---------|-----|

| Joint classification | Brace force | | | |
|-------------------------|--|---|-------------------------------|---|
| | Axial tension | Axial compression | In-plane bending | Out-of-plane bending |
| к | $(1,9+19\beta)Q_{\beta}^{0.5}Q_{g}$ | $(1,9+19\beta)Q_{\beta}^{0,5}Q_{g}$ | 4,5 β γ ^{0,5} | 3,2 $\gamma^{(0,5\beta^2)}$ |
| Y | 30 <i>β</i> | $(1,9+19\beta)Q_{\beta}^{0,5}$ | 4,5 β γ ^{0,5} | 3,2 $\gamma^{(0,5\beta^2)}$ |
| х | 23 β for $\beta \le 0.9$ 20,7 + (β – 0,9) (17 γ – 220) for β >0,9 | $\left[2,8+(12+0,1\gamma)\beta\right]\underline{\mathcal{Q}}_{\beta}$ | 4,5 <i>β</i> γ ^{0,5} | $3,2 \gamma^{\left(0,5 \beta^2\right)}$ |

Where,

 Q_β is the geometrical factor which depends on the chord - brace diameter ratio β

$$\begin{aligned} Q_{\beta} &= \frac{0.3}{\beta(1-0.833\beta)} & \text{for } \beta > 0.6\\ Q_{\beta} &= 1.0 & \text{for } \beta \leq 0.6 \end{aligned}$$

 Q_g is the gap factor which accounts for the effect of the gap in between the brace members

$$\begin{aligned} Q_{g} &= 1.9 - 0.7 \cdot \gamma^{-0.5} \cdot (g \ / \ T)^{0.5} & \text{for } g \ / \ T \geq 2.0, but \ Q_{g} \geq 1 \\ Q_{g} &= 0.13 + 0.65 \cdot \phi \cdot \gamma^{0.5} & \text{for } g \ / \ T \leq -2.0 \end{aligned}$$

Where $\phi = (t \cdot f_{y,b}) / (T \cdot f_{y,c})$

Where $f_{y,b}$ is the representative yield strength of the brace member.

The gap for values of g/T between -2 and 2 should be interpolated and estimated.

The chord force factor Q_f accounts for the factored action on the chord due to the presence of forces in the brace in axial, IPB and OPB.

 $Q_f = 1 - \lambda \cdot q_A^2$

Where, $\lambda = 0.030$ for brace axial force

= 0.045 for brace IPB

= 0.021 for brace OPB

The parameter

$$q_{A} = \left[C_{1}\left(\frac{P_{c}}{P_{y}}\right)^{2} + C_{2}\left(\frac{M_{c}}{M_{P}}\right)^{2}_{ipb} + C_{2}\left(\frac{M_{c}}{M_{P}}\right)^{2}_{opb}\right]^{2} \cdot \gamma_{R,q}$$

Where

 P_{C} is the axial force in the chord member from factored actions

 M_c is the bending moment in the chord member from factored actions

 P_{y} is the representative axial strength due to yielding of the chord member without buckling

 M_{p} is the representative plastic moment strength of the chord member

 $\gamma_{R,q}$ is the partial resistance factor for yield strength = 1.05

 C_1 and C_2 are coefficient as specified in the Table 5-2

| Table ! | 5-2 |
|---------|-----|
|---------|-----|

| Joint Type | C1 | C ₂ | |
|---|----|----------------|--|
| Y-Joints for calculating strength against brace axial forces | 25 | 11 | |
| X-Joints for calculating strength against brace axial forces | 20 | 22 | |
| K-joints for calculating strength against balanced brace axial forces | 14 | 43 | |
| All joints for calculating strength against brace moments | 25 | 43 | |
6 Optimization Algorithm

The Algorithm is written in MATLAB as separate modules. There are 4 modules

- MLKK_I.m
- KKForce_I.m
- JComp.m
- SS.m

The working of these modules are described in further chapters. The program can be used to find the optimum joint configuration for the required design life by conducting a time domain analysis for fatigue life design. The user can input the required joint geometry to be optimized specifying the ranges to look for and program will calculate the optimum geometry. The user also has the option to define which particular joint parameter to optimize while keeping others constant. The optimization can be conducted in 3 ways

- Finding the joint parameters that reduces all the SCF's
- Finding the joint parameters that reduces either one or two critical SCF's
- Finding the Joint parameters that gives the lowest damage

The methodology used is described in further chapters.

6.1 Problem Formulation

The objective of the research was to find the optimum joint configuration for a given type of loading for an offshore support structure. In this case the OWEC Quattropod was used for the analysis. The objective was to optimize the joint configuration so as to make the structure comply with the required design life. The approach was to minimize the SCF's which consecutively will minimize the stress ranges. These stress ranges which in turn will affect the number of cycles to failure from the SN curve hence increasing the design life or fatigue life. The Static Strength of the joint is also checked to see for failure if both the conditions are satisfied the joint is assumed to be optimized.

Minimize: SCFax.chr.cr, SCFax.br.cr, SCFax.chr.sa, SCFax.br.sa, SCFchr.ipb SCFchr.ipb, SCFchr.opb, SCFbr.opb

Subject to:

| 0,2 | < | β | < | 1,0 |
|--------------------------------|--------|----------|--------|-----|
| 0,2 | < | τ | \$ | 1,0 |
| 8 | \leq | γ | \leq | 32 |
| 4 | \leq | α | \leq | 40 |
| 20° | \leq | θ | \leq | 90° |
| $\frac{-0,6\beta}{\sin\theta}$ | ≤ | ζ | \leq | 1,0 |

The geometry parameters α , β , γ , τ , ζ and θ are within the ranges specified by the DNV –RP-CP-203 [15] code .The SCF's are depend only on the geometry and the loading. The stress ranges are computed from the SCF's with the use of the extrapolation along the weld using the crown and saddle SCF's for the brace and chord. Hence the HSS which varies in time are obtained. These are used to calculate the number of cycles to failure (N) and the number of stress cycles (n). From which the fatigue life is calculated

To have an idea how the variation of the important parameters specified in the parametric equations affect the different SCF's an example set of equations for a K joint is analyzed .There are six SCF equations as specified by Efthymiou for a K joint that are followed in the design standard. The equation are checked to see if there are any discontinuities or not. By fixing three of the geometrical parameters $\zeta = 0.1566$, $\tau = 0.2$ and $\theta = 50^{\circ}$ the variation in the SCF's for varying α , β , and γ are plotted in Figure 6.1 for the case of a K joint. For example the the SCF's change in color from blue to red from a value of 2 to 8 and for SCF_{ax.chr} the minimum is at $\beta = 0.5$, $\alpha = 20$ and $\gamma = 8$ but the minimum of SCF_{chr.opb} is not a this position but at a different value of α , β and γ



Figure 6.1 – Plot of SCF with varying α , β and γ for a K joint

There are no discontinuities, sharp variations and more importantly multiple minima's for a particular SCF's. However when the SCF's are being calculated such that the all the SCF's need to be minimized at the same time occurrence of a single global minima cannot be guaranteed.

It was decided not to change the joint geometry such that the entire geometry of the jacket is affected. Since a change in the geometry of the jacket structure will again changes the loads applied on the structure changing the input load data. The joints are optimized with the same gap and inclination angles for the brace chord connections. Only the brace and chord diameters and wall thicknesses are varied to obtain the final joint configuration with an improved fatigue life.

6.2 Optimization Algorithm



Figure 6.2 Flow Chart of Algorithm

The User inputs which are mainly the geometry parameters and user constraints are used by the solver which is empty as inputs to the Minimum SCF Module to find the Minimum SCF for the Initial Inputs .The Joint Classification Module provides multiplication factors to be multiplied by the SCF obtained from the parametric equations. This factor is determined based on the influence of the type of joint i.e. whether K, T/Y and X type. This is calculated from the loading history. These percentage influence of joints are used for the calculation of SCF and Static Strength factors. The minimum SCF found is later used to find the Fatigue Life and Static Strength with inputs of force time history. The solver checks if the obtained fatigue life is within the required limit. If not the obtained minimum SCF is used again as the new input and the program is run till the given number of simulations till the fatigue life is within limits. The coming chapters will explain in detail the operations done in each module.

The user can control the program by specifying the number of iterations to be performed, the range and spread of the parameters under which the minimum should be found. Since the program is made as modules it is easy for doing error checking and editing of the functions if required. The matrix for the search increases as the range increases. So while specifying the range it will be advantageous to keep in mind of the size of the computations involved.

6.3 User Inputs

The User Inputs provided to the solver are

- Geometry parameters: Chord Diameter (d₀), Chord Thickness (t₀), Brace Diameter (d₁), Brace Thickness (t₁), Brace member gap (g), Brace member angles (θ_A and θ_B)
- Search Parameters: Number of search loops, Range of Search and Time Step between ranges
- Yield Strength: Brace Member Yield Strength f_{vb} , Chord Member Yield Strength f_{vc}
- Fatigue Life Required

6.4 Force Time History

The data for a site location is provided contains the 2D wave and wind scatter. This is a long term statistical representation of the region where the structure is to be used or installed. The Wave Scatter diagram provides the Significant Wave Height H_s and Zero Mean Crossing Period T_s which are short term statistics of a 3 hour sea state. The scatter also shows the probabilities of occurrence for the different wind speeds for different wind directions. For the calculation purposes a long term statistics of a location with at least 12 different wind speeds is required to have sufficient confidence in the load history used.

The Load time histories are specific for a particular wind direction. They may be calculated for each wind direction which involves a lot of computational effort or use a conservative approach by treating them as unidirectional. From these the global loads are calculated with the help of the Morrison equation. The actual stress response at the point of interest can be found using either the Time domain method or the Frequency domain method from the wave and wind scatter diagram. In this particular program Time Domain Analysis.

6.5 Joint Classification Module

Depending on the forces applied on the different members of a particular joint the joint configuration is determined. The DNV has specified the required loading configuration for different joints as shown in Figure 3.7.

There is however no specific criteria for Multiplanar joints. The multiplanar configuration was assumed as shown in Table 6-1 with guidance from CIDECT DG 8 [27] manual.

Depending on the pattern of forces in the brace that is whether in compression or in tension the loading on a Multiplanar KK joint is specified in

The brace loads are inspected for the entire force time history and the weighted average of the different joint configurations due to loading are calculated. The corresponding SCF equation for the joint is multiplied with the value to give the SCF for the KK joint to be used for the Fatigue Check Module and the Static Strength Module.

SCF (KK) = % K Joint · (SCF K Joint) + % Y Joint · (SCF Y Joint) + % X Joint · (SCF X Joint)

| Load Case | Force Configuration | Joint Configuration |
|-----------|---------------------|-----------------------------|
| 1 | | 1.25·K Joint |
| 2 | | K Joint |
| 3 | | 0.5·(K Joint + T/Y Joint) |
| 4 | | T/Y Joint |
| 5 | | T/Y Joint |

Table 6-1

There are no guidance as to the loading configuration for case 3, 4 and 5 in any of the standards as to the author's knowledge.

The Joints can be further broken down in to uniplanar joints along the plane of symmetry along the chord generating 2 K joints as shown in Figure 7.4. The individual K joints can be later resolved for the vertical component of the axial forces to yield the respective percentages of T/Y and K joints to generate the SCF's for the brace chord intersection points. This is further explained in detail in Chapter 7. This is a better solution to resolve the Multiplanar KK joint into equivalent K joint to estimate the resulting SCF's. The Joint Classification Module that calculates the percentage influence of joint types makes use of this methodology.

6.6 Minimum SCF Module

This module to find the minimum SCF for all the possible combinations of the different parameters. The module is explained in Figure 6.3



Figure 6.3- Flow Chart for Minimum SCF Module

The inputs given by the user is stored in the module. The program is designed only to vary the diameters and thickness of the brace and chord members. So by using the range up to which the parameters needs to vary and how many different values within each range is calculated. The brace and chord diameters and thickness are varied within this limit. The different values of the parameters are combined in all possible combinations to form a matrix. The matrix size depends on the size and number of values within each range. The larger the range, larger is the size of the matrix and also the computation time required.

The non-dimensional geometrical parameters (GP) α , β , γ , τ , , ζ and θ are calculated and the set that doesn't satisfy any of the ranges as specified are eliminated. This helps to reduce the initial matrix size and hence reduces the computational time significantly. The set that comply within the range criteria are stored in a new matrix. The SCF's for the brace and saddle are calculated with the percentage inputs of the K, Y and X joints. These values are provided from the Joint classification module. The set with the minimum SCF's is selected. The minimum requirement can be specified in three configurations. Any of the below methods can be used

• Sum of all SCF's are minimum $\sum_{i=1}^{8} SCF_i = Minimum$ • Sum of either one or two SCF's are minimum $\sum_{i=1}^{2} SCF_i = Minimum$ • SCF set for which minimum Damage is obtained $\sum_{i=1}^{8} SCF_i \Rightarrow Min \sum_{i=1}^{n} \frac{n_n}{N_n}$

The optimized joint configuration for which sum of all SCF is minimum reduces all the SCF's and is mostly used when it is not sure which input parameter to restrict and want to find the optimized input by varying all the input parameters.

The optimized joint configuration can also be obtained by selecting the sum of only 1 or 2 SCF's .These SCF's may be selected specifically as they may be critical locations or might be the maximum among the set of SCF's. In most cases only 1 or 2 SCF's are peculiarly higher than the other SCF's and maybe advantageous to optimize the joint configuration by reducing only these SCF's

The optimized joint configuration for which the damage is minimum is the third option. In this method all the different combinations which are in the validity range are used to calculate the damage from the load time history. The SCF combination with the minimum damage is selected to run the next loop to see if the required fatigue design is achieved. However it should be noted that as the computation time involved is large as it also has to do the time domain analysis to find the damages for all the combinations. It will be practical to use this while varying only 1 or 2 input parameters while keeping the rest of the input parameters the same so as to reduce the number of combinations and hence computation time. This is used by a separate code named FATcheck

Each different search criteria module may be selected to run every loop with the inputs for the search criteria until the fatigue life isn't within range. The program rums the loop until it finds the minimum or it reaches the maximum number of iteration loop that is specified by the user. Once the Fatigue life is within the required range the optimized inputs are used to calculate the Static strength of the tubular joint to see if it is satisfactory. The Static strength is not checked for each and every combination as done for the fatigue. But the optimized input which satisfies fatigue is used to check the static strength.

It should be noted that the static strength is done only for the joints which satisfies the search criteria rather than checking for static strength for every set that satisfies the validity range of the geometrical parameters. This in effect makes sure that the parameters selected satisfy both the static strength criterion and the fatigue strength.

6.7 Fatigue Strength Module

The inputs parameters from the minimum SCF found are used calculate the fatigue life of the joint. The flow chart of the module is shown in Figure 6.4



Figure 6.4 Flow Chart for Fatigue Strength Module

The response forces Fy, My and Mz which are varying in time are used to calculate the corresponding stresses which vary in time. The nominal stresses in the joint braces and chords are calculated from the optimized geometrical inputs obtained from the Minimum SCF module. The Stresses which are varying time are reduced to a manageable set of stress reversals by means of rainbow counting method. The breakdown of the stress time history into bins helps to use the Miner's Rule to evaluate the damage due to the loading. The method helps to represent the stress spectrum as a statistical distribution of the amplitudes of the fluctuating stress in time. The stress reversal can be considered as one full cycle or half cycle. The rainflow counting mainly captures the larger variation in stresses. However the smaller variations can still be considered if the counting is done for half cycle. Neglecting small variations will not have a major effect on the damage calculation as the smaller vibrations do not contribute to crack propagation.

The disadvantage associated with rainflow counting is that it works well for uniaxial loading under constant but that is not the case in general as there is loading from different directions in varying amplitudes. In these environment the sequence of load history is influential. From the load sequence the combination of forces can have the largest stress range which when evaluated using the rainflow counting method might be lost. The rainflow doesn't take into consideration the sequence as it counts the extremes and stress reversals in the time history to group them in bins for calculation of the stress ranges and their corresponding number of cycles. However since it not practical to obtain the entire load sequence data for 10 years and we are just extrapolating the 3hr sea state data based on the probability of occurrence of wave and wind forces this is not so critical.

The Stress ranges that are obtained from the stress history are used to calculate the endurance or Number of cycles to failure (N) from the SN curve with respect to the thickness of the Brace and

chord. The SN curve with the specifications under T in the table provided by DNV is used for the formulation of the SN curve.

The procedure of formulation of the stress time history into the final stress ranges and number cycles to calculate the Number of cycles to failure is shown in Figure 6.5



Figure 6.5 Time Domain Analysis

6.8 Static Strength Check Module

The Static Strength used in the program follows the procedure as specified in the ISO-19902 [8] directive. The flow chart of the algorithm used is shown in Figure 6.6



Figure 6.6 Flow Chart for Static Strength Check

The forces in the brace members affect the forces in the chord depending on the eccentricity of the joint. These forces need to be included in the Chord force factor Qf. Depending on the eccentricity of the joint the moment distribution in the chord changes. This has been explained by Vugts [29]. The example of a K joint is shown in Figure 6.7



Figure 6.7 Effect of joint eccentricity on the bending moment distribution due to axial loading

The eccentricity of the joint can be negative or positive depending on the gap and the angle between the braces. There is no eccentricity for the K joint where the braces and the chord meet at one point. In this condition the horizontal components of the brace axial forces N_1 and N_2 cancel each other if the both the brace forces are equal. In this condition the chord is loaded only axially.

The horizontal components of the brace force $(N_1Sin\theta_1 + N_2Sin\theta_2)$ act on the brace.

Assuming
$$L_1 = L_2 = L$$
 and $A_1 + A_2 = A$

$$M_{1} = R_{1} \cdot (L - A_{1}) = \frac{A \cdot N_{1}}{2 \cdot L} (L - A_{1})$$

 $M_2 = R_2 \cdot (L - A_2) = \frac{A \cdot N_2}{2 \cdot L} (L - A_2)$

These moments need to be included in the chord forces while checking for punching shear. Another effect of the eccentricity is that there are no moment caused due to the axial loading in the chord which is $(N_1Sin\theta_1 + N_2Sin\theta_2)$ that acts through the center of the chord. While in the case of eccentricity causes a bending moment in the chord of the magnitude $(N_1Sin\theta_1 + N_2Sin\theta_2) \cdot e$ is generated .This is also added to the chord as factored actions in the case of eccentricity in K joints.

The Qu factor or strength factor mainly depends on the β parameter of the joint. The γ parameter has little effect on the joint strength and only comes into effect for IPB and OPB and even the contribution of the γ parameter is less when compared to the β parameter. The effect of the γ parameter depends on the gap maintained between the braces and applies for positive eccentricities.

The chord force factor Qf takes into account the effect of the factored component of the force in the chord due to axial, IPB and OPB. The contributions due the brace axial forces on the chord are added to the chord force factor.

Further the Qu for the joint for configuration K, Y and X are calculated they are multiplied by the corresponding weightages from the joint classification module to calculate the punching shear force Pu. This helps to include the effect of the loading profile on the joint.

The punching shear is multiplied by the specified partial safety factor and the used with the interaction equation to check for the joint strength. The interaction equation checks the joint strength under the combined action of the axial loading, IPB and OPB.

$$\left|\frac{P}{Pu}\right| + \left(\frac{M}{Mu}\right)_{ipb}^{2} + \left|\frac{M}{Mu}\right|_{opb} \le 1$$

The contribution due to the IPB moment is squared because the effect of the in plane bending moment on the joint strength is very less when compared with that of axial loading and OPB.

It should be noted that the static strength is calculated for the optimized joint based on the design fatigue life. The static strength is not checked for each and every joint configuration set and is not a factor that determines the joint configuration.

Static strength becomes a major factor only in the case of low cycle fatigue where the loads are in the range of the yield strength of the chord and brace members. Offshore structures are normally designed under high cycle fatigue loading and hence the fatigue strength of the structure becomes an important parameter controlling the geometry of the structure.

7 Joint Classification

In the joint classification module it was earlier explained how the loading configuration affects the joint type to be used for the calculation of SCF's. Depending on the load configuration which varies in time the type of joint changes. To account for this effect for every load combination in the history the particular joint is noted and the weighted average of the contribution of each joint type is calculated i.e. 70% K + 30% Y. The criteria for a joint type whether it is K, T/Y or X depends how the vertical component of the force is balanced by the shear in the chord.

To be able to use this factor for the varying time history the ovalization parameter α specified by Marshall [28] is used to determine the joint type where the ovalization parameter is defined as follows



Figure 7.1 Ovalizing parameter for multiplanar joints according to P.W.Marshall[28]

The α parameter was used in the earlier AWS code revisions for classification of joints and evaluating their joint capacity. The formula basically has three parts as shown in Figure 7.1 (a)

The $\exp\left(\frac{-Z}{0.6\gamma}\right)$ accounts for the decay effect which causes to K joint to have the same

characteristics of a T/Y joint as the gap between opposite braces in the same plane tends to infinity. In such a case the given K joint may be assumed as two separate Y joint. This is proven by tests conducted and tabulated from the UEG and AWS database as shown in Figure 7.2



Figure 7.2 Strength ratio of K/Y approaches to 1 as gap tends to infinity⁴

The $\frac{\sum P \sin \theta}{[P \sin \theta]}$ includes the resolution of the vertical components of the brace member forces

The $\cos 2\phi$ parameter is further explained in Figure 7.1(c) shows how the change in the angle between the braces causes the variation in joint type classification. There are however certain issues with the usage of this formula and its application to Joint Type Classification.

- The $cos2\phi$ parameter becomes 0 at $\phi = 45^{\circ}$ which indicates that irrespective of all the other parameters there is no interaction between the braces in the adjacent plane when $\phi = 45^{\circ}$ which is not true.
- No specific information on how to classify a joint if the braces in adjacent planes have positive or negative eccentricity between them.



Figure 7.3 Out of Plane eccentricity in Multiplanar Joints

To include the effect of the resolution of the forces to check the percentage influence of other joint types the KK joint can be broken down into two K joints along the symmetry plane as shown in Figure 7.4



Figure 7.4 – Breakdown of a Multiplanar KK joint along the System Plane

The resolution of the forces for K-1 and K-2 are done separately to obtain the SCF in the braces to be used as detailed below.

The percentage influence for each joint due the combined axial action of the forces in K-1 and K-2 are computed

$$C_{Kn} = abs \left| \frac{P_n \sin \theta}{P_{n+1} \sin \theta} \right|$$

if $C_{Kn} < 1$ $B_1 = C_{K1} \cdot K$
 $B_2 = C_{K1} \cdot K + (1 - C_{K1} \cdot Y)$

if
$$C_{Kn} \ge 1$$
 $B_1 = (1/C_{K1}) \cdot K + (1 - (1/C_{K1})) \cdot Y$
 $B_2 = (1/C_{K1}) \cdot K$

This is evaluated for K-2 from where joint influence contributions for B3 and B4 are calculated

The load history is analyzed according to this criteria. The multiplication factor for the contributions of K and Y are calculated as a weighted average of the entire load history. This is used to calculate the individual SCF's in the braces as

$$SCF(B_n) = K_n \cdot SCF_K + Y_n \cdot SCF_Y$$

 K_n and Y_n are the weighted averages calculated from the resolution of the forces from the load time history data.

The influence of the gap and the effect of unbalanced axial loading on the chord due to the brace are further studied and was found that the gap between the braces influence the strength of the joint and is influenced by the β paramaeter. To account the gap between braces in adjacent planes the joint geometry is defined as follows for a typical multiplanar KK joint.



Figure 7.5 Definition of Multiplanar Joint with details of Out of plane gap ${g_{t}}^{\scriptscriptstyle 5}$

In this configuration which is similar to the previous design guidelines a new parameter g_t and e_t are defined.

Where

 g_t is the gap between the opposing braces from the system plane as defined a

 e_t is the eccentricity due to the opposing braces from the system plane with the chord axis.

The effect of the variation of g_t which in turn is a function of ϕ helps to better understand the joint properties. This will help to eliminate the problem due to the use of $cos2\phi$ in the ovalizing parameter equation.

It is explained in the work of J.C.Paul [30] and later included in the CIDECT 5BF [31] report by Kurobane that the non-dimensional parameter g_t/do has an effect of causing the KK multiplanar joint to fail in 2 different failure modes when the $g_t/do > 0.215$ this holds true for the case when the KK joint is subjected to balanced axial loading and unbalance axial loading. Due to the influence of g_t/do parameter the strength of the KK joint also varies when $g_t/do > 0.215$. The Figure 7.7 and Figure 7.8 shows the effect of Mode I and Mode II failure under balanced and unbalanced axial loading condition



Figure 7.6 Balance and Unbalanced Loading

⁵ From CIDECT 5FB [31]







Figure 7.8 Mode I and Mode II Failure under Unbalanced axial loading condition

The g_t/do is an important parameter that can be included in the joint classification as it is dependent on β unlike the $cos2\phi$ parameter as defined in Marshall's ovalization parameter which neglects it



Figure 7.9 Geometry details of the Multiplanar Joint

From the equation of circle $X^2 + Y^2 = (d_0/2)^2$

At
$$X = BC = d_1 / 2$$
, $Y = AC = \sqrt{(d_o / 2)^2 - (d_1 / 2)^2}$
So $\Omega = \tan^{-1}(BC/AC) = \tan^{-1}\left(\frac{d_1 / 2}{\sqrt{(d_o / 2)^2 - (d_1 / 2)^2}}\right)$

Assuming for the case of equal brace diameter d_1

$$g_t = 2 \cdot \sin(\Phi - \Omega) \cdot \frac{d_0}{2} = \sin(\Phi - \tan^{-1}(\beta)) \cdot d_0$$

Therefore, $\frac{g_t}{d_0} = \sin(\Phi - \Omega)$

It should be noted that $\Omega \neq \tan^{-1}(\beta)$ but can be expressed in terms of β as follows

$$\Omega = \tan^{-1} \frac{\beta}{\sqrt{1 - \beta^2}}$$

It can be seen from the Joint Strength equation proposed by J.C.Paul [30] that the joint strength of a KK joint is lesser than that of a K joint when g_t/do < 0.215 also it is evident from the plot that unbalanced axial loading has also has a lower strength as shown in the Figure 7.10



Figure 7.10 Influence of g_t/d_0 on the Strength of Multiplanar KK Joint with respect to a uniplanar K joint as per the CIDECT 5BF guideline

It has also been specified in the CIDECT design guide [27] to assume $SCF_{KK} = 1.25 \cdot SCF_K$. But should be noted that for balance loading also for $g_t/do < 0.215$ the strength of KK joint is also less than K so it can be logical to assume 1.25 times SCF of K as in the CIDECT guideline.

8 FEM Modelling and Analysis

The joint is modelled in ANSYS FEM to validate the results obtained by the calculation programme. The model is made using 3D brick elements rather than shell elements due to difficulty in modelling the weld profile of the joint. The weld can be modelled as a sharp notch with a fillet of 1mm on the chord and brace to have a very fine mesh for the model. Shell elements were used by most researches to formulate the parametric SCF equations due to its simplicity and requirement for less computing power. However this resulted in discrepancies between the results obtained from thin shell FE results and experimental results.

Due to the complexity of the KK joint it is very difficult to achieve uniform mesh distribution especially in areas of interest like the brace chord weld intersection. To achieve this the model is divided into zones by slicing to maintain uniform mesh generation as shown in Figure 8.1.



Figure 8.1 Submodeling by slicing of geometry of KK joint

The Section where the brace meets the chords are subdivided further by slicing to maintain uniform mesh distribution



Figure 8.2 Division of Weld Intersection of Chord and Brace connection

There are problems with modelling the weld profile in the FE model as the weld profile needs to be maintained as per the AWS code specifications. The weld thickness varies with respect to the dihedral angle ψ of the joint. In most cases the weld profile is simplified for the purpose of modelling the joint. The extent of the weld profile is maintained by means of concentric cylinders as mentioned in the work of M.M.K.Lee [32]which is been used for the modelling and meshing of the multiplanar KK joints by Yaghin and Ahmadi [24], [33]as shown in Figure below



Figure 8.3 Detail of Weld location slicing in KK joint

The nodes on the mesh are kept for quadratic displacement behavior is used .The geometry is meshed and loads suitably applied to check for stress concentrations.



Figure 8.4 Meshing of KK joint with detail view of mesh in the weld intersections

9 Results and Conclusions

9.1 Analysis of Joint

A Multiplanar KK joint was provided which was to be analyzed for fatigue life the joint parameters provided where the following

| Joint Parameter | Value |
|---------------------------------------|---------|
| Chord Diameter, do | 864mm |
| Brace Diameter, d1 | 559mm |
| Chord thickness, to | 40mm |
| Brace Thickness, t1 | 12mm |
| Brace Angles, θ_A , θ_B | 55°,57° |

Table 9-1 Joint Dimension for analysis



Figure 9.1 Sample Joint

Al shown in the geometry a chord length of 3000mm and a brace length of 1000mm is defined

The global and local forces in the joint were also provided which was used for the analysis. A sample force profile in one end of the brace B1 is shown in Figure 9.2



Figure 9.2 Load time history sample

Since the load time history data provided was only for 10 minutes containing 30,000 cycles the load history was converted into a set of time histories for wind speeds from 2 to 24 km/h by increasing the amplitude of each load history as a function with respect to the wind speed as shown in Figure 9.3



Figure 9.3 Amplitude and Probability variation w.r.t wind speed from 2-24 km/h

A particular probability of occurrence for the wind speeds was also assumed where the the amplitude of the wind speed increases as a function $WindSpeed(2:24) = (Amplitude)^{1.95}$

The fatigue damage calculation due to each wind speed where then extrapolated with respect to the probability of occurrence of the wind speeds to find the design life of the KK joint. The design life was fixed for 70 years. The programme optimize the joint configuration till the damage is less than 1 so that the fatigue design life is 70 years . The total number of simulations were set at 20 and the program reached the minimum fatigue life within a time of 10 minutes.

It was found that the fatigue life improved by reducing the SCF's but not in all the cases as will be explained in the conclusion. The analysis was done in 4 different variations. Since the cost of fabrication needs to be minimized in each of these cases the percentage reduction in volume is determined and compared as an acceptance criteria for the best possible joint configuration. The Fcheck module is used to do the analysis as the search criteria employed in the program is simple and fast.

- Fcheck changing all the parameters
- Fcheck with constant β
- Fheck with constant *τ*
- Fcheck with constant γ

If any of the analysis do not converge they are analyzed using the FATCheck module where the joint configuration for minimum damage rather than minimum SCF is searched for

9.2 Fcheck changing all the parameters







Figure 9.5 Variation of Damage with search criteria and iterations

| Table | 9-2 |
|-------|-----|
|-------|-----|

| | L(mm) | do(mm) | d1(mm) | to(mm) | t1(mm) | gap(mm) | θ _A (°) | θ _B (°) |
|-----------|-------|--------|--------|--------|--------|---------|--------------------|--------------------|
| Initial | 3000 | 864 | 559 | 40 | 12 | 87 | 55 | 57 |
| Optimized | 3000 | 816 | 589 | 51 | 10.5 | 87 | 55 | 57 |

The Joint configuration is first checked with changing all the Geometry parameters except the gap

and brace – chord angles. The optimum geometry that satisfies the criteria $\sum_{i=1}^{8} SCF_{i} = Minimum$

is used to find the joint geometry that satisfied the fatigue life of the joint specified at 75 years is used to determine the end of the computations. The optimum joint geometry is found in the 8th iteration before the maximum number of iterations specified which is 20 .The optimized joint geometry found is specified in the Table 9-2 .It can be seen from the plot that the program searches for the minimum by reducing the β , γ and τ values. The range of τ is quite limited as the initial geometry has a τ value of 0.3 so the program is limited with the range of 0.3 and 0.2 which is the minimum as specified in the DNV [15] regulation . It is evident that the min τ reached first followed by the minimum γ at 8. The program still searches with the minimum γ and τ decreasing β till the fatigue life is satisfied. It is found from the results that the optimized geometry does not have a very large change in the dimensions from the initial joint dimensions. A criteria for selecting which method is the best to use for finding the Fatigue can be evaluated by using the percentage change in volume which obviously has an effect on the cost of production which determines the weight and cost of steel used. The optimized geometry has a percentage increase of 11.47 % in volume from the initial geometry. This can be later evaluated for selecting the best joint configuration for the same fatigue life improvement.

The SCF's in the brace number 2 is the largest and the reduction in SCF's can also be seen from the Figure 9.7 which shows the variation of search criteria with Damage. The individual SCF values are given in Table 9-3

| SCF | | SCF _{ax.chr.cr} | SCF _{ax.br.cr} | SCF _{ax.chr.sa} | SCF _{ax.br.sa} | SCF _{chr.ipb} | SCF _{br.ipb} | $SCF_{chr.opb}$ | $SCF_{br.opb}$ |
|-----------|----|--------------------------|-------------------------|--------------------------|-------------------------|------------------------|-----------------------|-----------------|----------------|
| | B1 | 2.15 | 0.36 | 2.06 | 1.19 | 0.68 | 1.50 | 1.67 | 1.77 |
| Initial | B2 | 2.28 | 0.62 | 2.37 | 2.03 | 0.76 | 1.78 | 1.93 | 2.07 |
| Initial | B3 | 1.90 | 0.42 | 1.90 | 1.39 | 0.62 | 1.41 | 1.55 | 1.65 |
| | B4 | 2.05 | 0.71 | 2.23 | 2.31 | 0.70 | 1.72 | 1.83 | 1.97 |
| | | | | | | | | | |
| | B1 | 1.30 | 0.18 | 1.64 | 1.08 | 0.43 | 1.29 | 0.93 | 1.24 |
| | B2 | 1.39 | 0.30 | 1.96 | 1.85 | 0.49 | 1.53 | 1.07 | 1.44 |
| Optimized | B3 | 1.16 | 0.23 | 1.60 | 1.44 | 0.40 | 1.25 | 0.88 | 1.18 |
| | B4 | 1.22 | 0.32 | 1.83 | 1.97 | 0.44 | 1.42 | 0.98 | 1.32 |
| | | | | | | | | | |

| Та | bl | е | 9. | 3 |
|----|----|---|----|---|
| | _ | - | - | - |

9.3 Fcheck with constant β







Figure 9.7 Variation of Damage with search criteria and iterations

Table 9-4

| | L(mm) | do(mm) | d1(mm) | to(mm) | t1(mm) | gap(mm) | θ _A (°) | θ _B (°) |
|-----------|-------|--------|--------|--------|--------|---------|--------------------|--------------------|
| Initial | 3000 | 864 | 559 | 40 | 12 | 87 | 55 | 57 |
| Optimized | 3000 | 864 | 559 | 53.5 | 10.95 | 87 | 55 | 57 |

In this analysis the β is kept constant while the rest of the parameters are varied. Since the diameters are not changed the α which is 2L/do is also constant. So as explained in the analysis earlier done the τ parameter which has the least range for variation reaches the minimum followed by the γ parameter which reaches minimum at a value of 8. The program then cycles between the values without improving the fatigue life. This occurs because there is no other parameter to vary unlike the earlier case where β reduced to improve the fatigue life. The program was not able to obtain an improved joint geometry satisfying the fatigue life in this case.

In this case there is percentage increase of 18.8 % in the volume of the optimized geometry from the initial geometry with an improvement in fatigue life. The improvement in fatigue life can be seen in the plot but it doesn't satisfy the design requirement of 70 years.

| SCF | | SCF _{ax.chr.cr} | SCF _{ax.br.cr} | SCF _{ax.chr.sa} | SCF _{ax.br.sa} | SCF _{chr.ipb} | SCF _{br.ipb} | $SCF_{chr.opb}$ | SCF _{br.opb} |
|-----------|------------|--------------------------|-------------------------|--------------------------|-------------------------|------------------------|-----------------------|-----------------|-----------------------|
| | B1 | 2.15 | 0.36 | 2.06 | 1.19 | 0.68 | 1.50 | 1.67 | 1.77 |
| Initial | B2 | 2.28 | 0.62 | 2.37 | 2.03 | 0.76 | 1.78 | 1.93 | 2.07 |
| Initial | B3 | 1.90 | 0.42 | 1.90 | 1.39 | 0.62 | 1.41 | 1.55 | 1.65 |
| | B 4 | 2.05 | 0.71 | 2.23 | 2.31 | 0.70 | 1.72 | 1.83 | 1.97 |
| | | | | | | | | | |
| | B1 | 1.32 | 0.19 | 1.70 | 1.15 | 0.42 | 1.30 | 0.90 | 1.25 |
| | B2 | 1.41 | 0.32 | 2.03 | 1.96 | 0.47 | 1.54 | 1.04 | 1.45 |
| Optimized | B3 | 1.18 | 0.25 | 1.66 | 1.52 | 0.39 | 1.26 | 0.85 | 1.19 |
| | B4 | 1.24 | 0.34 | 1.89 | 2.09 | 0.43 | 1.43 | 0.95 | 1.33 |
| | | | | | | | | | |

Table 9-5

The SCF's reduction sequence is the same as for the earlier analysis but in this case since β was constant so no further reduction in the maximum SCF's was possible for the program.

9.4 Fheck with constant τ







Figure 9.9 Variation of Damage with search criteria and iterations

| Table | 9-6 |
|-------|-----|
|-------|-----|

| | L(mm) | do(mm) | d1(mm) | to(mm) | t1(mm) | gap(mm) | θ A(°) | θ B(°) |
|-----------|-------|--------|---------------|--------|--------|---------|---------------|----------------|
| Initial | 3000 | 864 | 559 | 40 | 12 | 87 | 55 | 57 |
| Optimized | 3000 | 694 | 644 | 40 | 12 | 87 | 55 | 57 |

The analysis is done with keeping the τ value constant and changing the rest of the parameters. The optimum is found by increasing the β value and decreasing the γ parameter. The alpha parameter doesn't have any major impact but rather follows the β parmater due to decrease in *do*. The minimum fatigue is obtained for the joint when the β and γ reaches a certain minimum.

The joint configuration obtained has a 15 % increase in volume from the initial joint configuration for the same fatigue life of 70 years. Also there is large change in the parameters of the optimized joint with a β ratio close to 1 which almost makes the chord and braces to have almost the same diameters.

| SCF | | SCF _{ax.chr.cr} | SCF _{ax.br.cr} | SCF _{ax.chr.sa} | SCF _{ax.br.sa} | SCF _{chr.ipb} | SCF _{br.ipb} | SCF _{chr.opb} | SCF _{br.opb} |
|-----------|----|--------------------------|-------------------------|--------------------------|-------------------------|------------------------|-----------------------|------------------------|-----------------------|
| | B1 | 2.15 | 0.36 | 2.06 | 1.19 | 0.68 | 1.50 | 1.67 | 1.77 |
| Tuitial | B2 | 2.28 | 0.62 | 2.37 | 2.03 | 0.76 | 1.78 | 1.93 | 2.07 |
| Initial | B3 | 1.90 | 0.42 | 1.90 | 1.39 | 0.62 | 1.41 | 1.55 | 1.65 |
| | B4 | 2.05 | 0.71 | 2.23 | 2.31 | 0.70 | 1.72 | 1.83 | 1.97 |
| | · | | | | | | | | |
| | B1 | 1.77 | 0.18 | 1.64 | 0.69 | 0.63 | 1.35 | 1.25 | 1.26 |
| | B2 | 1.92 | 0.31 | 1.96 | 1.18 | 0.73 | 1.60 | 1.44 | 1.45 |
| Optimized | B3 | 1.60 | 0.24 | 1.60 | 0.91 | 0.60 | 1.31 | 1.19 | 1.20 |
| | B4 | 1.71 | 0.33 | 1.82 | 1.25 | 0.67 | 1.48 | 1.32 | 1.33 |
| | | | | | | | | | |

Table 9-7

The optimized join configuration have almost the same chord and brace dimensions with a $\beta \approx$ 0.925 which is not suitable for jacket structure causing it have a large area of interaction with the waves . This will eventually increase the Morison forces on the jacket structure.

9.5 Fcheck with constant γ







Figure 9.11 Variation of Damage with search criteria and iterations

Table 9-8

| | L(mm) | do(mm) | d1(mm) | to(mm) | t1(mm) | gap(mm) | θ _A (°) | θ _B (°) |
|-----------|-------|--------|--------|--------|---------------|---------|--------------------|--------------------|
| Initial | 3000 | 864 | 559 | 40 | 12 | 87 | 55 | 57 |
| Optimized | 3000 | 864 | 734 | 40 | 8.25 | 87 | 55 | 57 |

The analysis is done with constant γ and changing all the other parameters. Since the chord diameter do is kept constant the α parmater is also constant. The optimized configuration is searched by increasing the β and since τ has a lower range It reaches minimum. Since τ cannot be changed the β parameter is futher increased till the fatigue life is satified. The optimized joint fonfiguration has a 1.8 % increase in volume from the initial joint configuration.

| SCF | | SCF _{ax.chr.cr} | SCF _{ax.br.cr} | SCF _{ax.chr.sa} | SCF _{ax.br.sa} | SCF _{chr.ipb} | SCF _{br.ipb} | $SCF_{chr.opb}$ | SCF _{br.opb} |
|-----------|----|--------------------------|-------------------------|--------------------------|-------------------------|------------------------|-----------------------|-----------------|-----------------------|
| | B1 | 2.15 | 0.36 | 2.06 | 1.19 | 0.68 | 1.50 | 1.67 | 1.77 |
| Initial | B2 | 2.28 | 0.62 | 2.37 | 2.03 | 0.76 | 1.78 | 1.93 | 2.07 |
| muai | B3 | 1.90 | 0.42 | 1.90 | 1.39 | 0.62 | 1.41 | 1.55 | 1.65 |
| | B4 | 2.05 | 0.71 | 2.23 | 2.31 | 0.70 | 1.72 | 1.83 | 1.97 |
| | | | | | | | | | |
| | B1 | 1.42 | 0.18 | 1.58 | 1.04 | 0.50 | 1.33 | 1.03 | 1.12 |
| | B2 | 1.52 | 0.30 | 1.88 | 1.77 | 0.57 | 1.57 | 1.20 | 1.32 |
| Optimized | B3 | 1.27 | 0.24 | 1.54 | 1.38 | 0.47 | 1.29 | 0.99 | 1.08 |
| | B4 | 1.33 | 0.32 | 1.74 | 1.89 | 0.52 | 1.46 | 1.10 | 1.22 |
| | | | | | | | | | |

Table 9-9

This is analysis in which only the brace dimensions are varied to find the joint with lower SCF's to improve the fatigue life. This methos has the lowest percentage increase in volume and also the hisghest reduction in SCF's from all the above methods.

9.6 Results with Fcheck

A comparison is made of the percentage change in volume for the different constraints imposed on the analysis to determine the most suitable methods and the important parameter that govern the SCF and eventually the fatigue life of the joint. For calculating the percentage change in volume a joint volume is calculated by using the joint parameters given in Table 9-1 and assuming a chord length of 3000mm and brace length of 1000mm.

| Method | % Change in Volume | Fatigue Life |
|------------------------|--------------------|--------------|
| Varying all parameters | 11.5 | 70 years |
| Constant β | 18 | 56 years |
| Constant $	au$ | 15 | 70 years |
| Constant γ | 1.8 | 70 years |

| Table 9-10 | 0 |
|------------|---|
| | |

The best reduction in SCF's are obtained by fixing the chord diameter do and thickness to and varying the brace dimensions. This has to do with the fact that the major influence in the reduction of the SCF's occur with the increasing of the β parameter. Increasing the β parameter alone will not effectively decrease the SCF's as at some point the τ parameter needs to be decreased also to effectively reduce the SCF's. The α parameter has not much influence in the control of the SCF's as it mostly follows the trend of the β and γ parameter. Even while varying all the parameters the percentage change in volume is less it is the least when the brace dimensions are changed keeping the chord dimensions the same. This however depends on the geometry of the jackets and also the amount of brace members present in the jacket structure.

The Joints which satisfy the fatigue life in all cases satisfy the static strength criteria when the Static Strength Check module SS.m is run. This mainly has to do with the fact that the do/to ratio is maintained within 16 and 64. This is apparently maintained by the γ ratio which is fixed to fall

within the validity range as specified in the DNV RP-C203 [15] code because $8 \le \left(\gamma = \frac{d_0}{2t_0}\right) \le 32$

which helps to avoid local buckling of the joint.

9.7 Using FATCheck with constant β







Figure 9.13 Variation of Damage with search criteria and iterations

Table 9-11

| | L(mm) | do(mm) | d1(mm) | to(mm) | t1(mm) | gap(mm) | θ _A (°) | θ _B (°) |
|-----------|-------|--------|--------|--------|---------------|---------|--------------------|--------------------|
| Initial | 3000 | 864 | 559 | 40 | 12 | 87 | 55 | 57 |
| Optimized | 3000 | 864 | 559 | 52.5 | 15.75 | 87 | 55 | 57 |

The Fatcheck module can be used the find the optimum joint configuration . The search criteria specified for FAT check searches for the joint congiguration that gives the minimum dmamge for

the applied load time history. The search criterion to be satisfied is $\sum_{i=1}^{8} SCF_i \Rightarrow Min \sum_{i=1}^{n} \frac{n_n}{N_n}$. The

FATcheck is used to search for the optimum joint configuration under a constraint of constant β which earlier failed in the case of Fcheck. The optimization based on joint configuration having the minimum damage is used which runs successfully. It is interesting to note that the program also keeps the τ parameter constant during each iteration. The optimized joint configuration obtained has a 22.7 % increase in volume. This is because the chord and brace thicknesses are both increased from the initial geometry.

| SCF | | SCF _{ax.chr.cr} | SCF _{ax.br.cr} | SCF _{ax.chr.sa} | SCF _{ax.br.sa} | $SCF_{chr.ipb}$ | SCF _{br.ipb} | SCF _{chr.opb} | SCF _{br.opb} |
|-----------|----|--------------------------|-------------------------|--------------------------|-------------------------|-----------------|-----------------------|------------------------|-----------------------|
| | B1 | 2.15 | 0.36 | 2.06 | 1.19 | 0.68 | 1.50 | 1.67 | 1.77 |
| Initial | B2 | 2.28 | 0.62 | 2.37 | 2.03 | 0.76 | 1.78 | 1.93 | 2.07 |
| mua | B3 | 1.90 | 0.42 | 1.90 | 1.39 | 0.62 | 1.41 | 1.55 | 1.65 |
| | B4 | 2.05 | 0.71 | 2.23 | 2.31 | 0.70 | 1.72 | 1.83 | 1.97 |
| | · | | | | | | | | |
| | B1 | 1.89 | 0.29 | 1.95 | 1.00 | 0.59 | 1.41 | 1.34 | 1.51 |
| | B2 | 2.01 | 0.50 | 2.27 | 1.72 | 0.66 | 1.67 | 1.55 | 1.75 |
| Optimized | B3 | 1.68 | 0.39 | 1.87 | 1.33 | 0.55 | 1.36 | 1.27 | 1.44 |
| | B4 | 1.77 | 0.53 | 2.09 | 1.83 | 0.60 | 1.55 | 1.41 | 1.60 |
| | | | | | | | | | |

Table 9-12

The SCF distribution shows that the SCF in the optimized joint does not have a large reduction in SCF's because the joint configuration is optimized based on the combination that satisfies the specified design life requirement. The major reduction in SCF's occur for the OPB loading configuration in this case. The FAT check can be used for checking the fatigue life when not more than two parameters are constrained as the amount of computations performed are large and time consuming. The change in fatigue occurs due to the change in thickness of the cross sections involved as the thicker sections have a better fatigue life. This can be verified from the SN curve data.



9.8 FATCheck with constant β increasing damage





Figure 9.15 Variation of Damage with search criteria and iterations

Table 9-13

| | L(mm) | do(mm) | d1(mm) | to(mm) | t1(mm) | gap(mm) | θ _A (°) | θ _B (°) |
|-----------|-------|--------|--------|--------|---------------|---------|--------------------|--------------------|
| Initial | 3000 | 864 | 559 | 52.5 | 15.75 | 87 | 55 | 57 |
| Optimized | 3000 | 864 | 559 | 51 | 11.25 | 87 | 55 | 57 |

It might be required in most cases that certain joints have a fatigue life time which are more than the recommended requirement. In such cases the programme can be used to find the joint configuration which has the specified fatigue design life. In this example the earlier joint configuration which was optimized using FATcheck under constant β given in Table 9-11 which has a satisfactory design life of 70 years is used to find a new configuration with a lesser design life of 60 years. The FATcheck programme can be used for this purpose by changing the optimization criteria to look for joint configuration that maximizes the damage as given by

$$\sum_{i=1}^{8} SCF_i \Longrightarrow Max \sum_{i=1}^{n} \frac{n_n}{N_n}$$

Table 9-14

| SCF | | SCF _{ax.chr.cr} | SCF _{ax.br.cr} | SCF _{ax.chr.sa} | SCF _{ax.br.sa} | SCF _{chr.ipb} | SCF _{br.ipb} | SCF _{chr.opb} | SCF _{br.opb} |
|-----------|----|--------------------------|-------------------------|--------------------------|-------------------------|------------------------|-----------------------|------------------------|-----------------------|
| | B1 | 1.89 | 0.29 | 1.95 | 1.00 | 0.59 | 1.41 | 1.34 | 1.51 |
| Initial | B2 | 2.01 | 0.50 | 2.27 | 1.72 | 0.66 | 1.67 | 1.55 | 1.75 |
| Initial | B3 | 1.68 | 0.39 | 1.87 | 1.33 | 0.55 | 1.36 | 1.27 | 1.44 |
| | B4 | 1.77 | 0.53 | 2.09 | 1.83 | 0.60 | 1.55 | 1.41 | 1.60 |
| | | | | | | | | | |
| | B1 | 1.45 | 0.21 | 1.76 | 1.15 | 0.46 | 1.33 | 1.01 | 1.33 |
| | B2 | 1.54 | 0.36 | 2.08 | 1.97 | 0.52 | 1.58 | 1.16 | 1.55 |
| Optimized | B3 | 1.29 | 0.28 | 1.70 | 1.53 | 0.43 | 1.29 | 0.96 | 1.27 |
| | B4 | 1.35 | 0.39 | 1.93 | 2.09 | 0.47 | 1.46 | 1.07 | 1.42 |
| | | | | | | | | | |

The joint configuration is optimized with reducing the thickness the thickness of the chord and brace such that the fatigue life of 60 years is achieved. It can be seen that the SCF's of the brace chord intersection were decreased and still the fatigue life of the joint was increased which proves that minimizing the SCF's necessarily doesn't mean that the fatigue life can be decreased. It depends rather on the combination of the SCF's. The optimized geometry had a decrease of percentage volume by 8.7% from the initial geometry due to the decrease of the thickness.
9.9 Conclusions

The analysis of the sample joint provided can be done successfully by using multiplication factors obtained from the analysis of the force time history data. The process can be simplistically explained as the division of the SCF's among the 4 brace chord intersection depending on the loading. The fatigue life of a joint can be improved by decreasing the SCF's of the joint but this cannot be assumed to give the optimum solution in all cases. As can be seen from the analysis using FATcheck where the optimum joint configuration is found by minimizing the damage the SCF's are not reduced by a large margin as in the analysis done with Fcheck where all the SCF's were reduced considerably. This confirms that the optimum solution where the damage is minimized the most depends on the combination of the SCF's as can be seen when all the parameters are plotted in Figure 6.1.

From the analysis of the joints it can said that the damage can be minimized by decreasing the γ and τ parameter while the β parameter is increased. This trend is reflected in all the analysis done. From the analysis done we can see that the τ parameter doesn't have a large range to be varied as the initial input itself has a low τ value of 0.3. The τ is decreased in most of the analysis and hence it reaches its minimum the earliest and stay at 0.2. The next parameter γ which has an initial value of 10.8 which is also low reaches its minimum of 8 in the validity range and stay at this point. The β has an initial value of 0.6 and it is increased up to 1 which is its maximum in the validity range. The α and ζ basically is depended on the other parameters and basically follows the trend of the other parameters. From the analysis it can be seen that the β parameters is the governing parameter and even without the other parameters the damage can be reduced by increasing the β parameter especially for β values more than 0.5 for β values less than 0.5 SCF's from the parameter can be analyzed that for β less than 0.5 the damage increases rapidly as seen in Figure 9.16



Figure 9.16 Variation of Damage for varying β

The multiplanar effect of the KK joints is mainly governed by the β parameter as it affects the out of plane gap of the joint. As seen from the FEM simulations and also the test conducted by Kurobane the failure mode of the KK joint is in effect governed by the gt/do parameter which is dependent on the out plane angle ϕ and β . The importance of the β parameter is due to the fact that the gap be dependent on the β parameter even for fixed out of plane angle ϕ as shown in the derivation in Chapter 7 . From the tests and parametric formulation based on the tests given by J.C.Paul[30] it can be justified why for an unbalanced axial loading condition especially for a KK joint the strength is less. This is one of the reasons why the CIDECT guide[27] also proposes a magnification factor of 1.25 for unbalanced loading condition. But this is not true for all cases as from Figure 7.10 for decreasing gap the unbalanced loading has a higher strength configuration and the strength matches that of the uniplanar K joint.

The priority of static strength over the fatigue strength of the joint mainly depends on the loading to which the joint is exposed. Static failure of joint is mainly considered in the low cycle range of the SN curve in the 1E+04 range where plastic effects are more governing. There is plastic deformation of the joints connection leading to failure. The forces involved in such a failure mechanism are more in the range of the yield stress of the material of the chord and braces. Hence the static strength failure is more associated with extreme loads which occur in the load spectra of the design environment. Static strength can be critical when the probability distribution assumed has a large probability of occurrence of forces in the extreme range close to the yield strength of the joint.

Fatigue failure is associated with forces that are lesser than the yield stress of the chord and brace material. Since fatigue failure is a cumulative effect and complex due to effects of the multi-axial effects of the load a lot of uncertainty is associated with this scheme of failure. Hence fatigue failure becomes critical as there occurs a requirement to avoid all types of unanticipated failure that can occur in the service history of a structure.

9.10 Recommendations

Although a lot of analysis on multiplanar tubular joints are being carried out but the parametric equations formulated are yet to be standardized. This had to do with the uncertainties associated with multi-axiality and carry over effects predominant in multiplanar tubular joints. Further study on the effect of multi-axial fatigue on the stress concentration of multiplanar tubular joints needs to be investigated. The rainflow algorithm to be used in the case of multi-axial and variable amplitude loading needs to be developed further even though new methods are being developed the design guidelines needs to standardize a pragmatic methodology to be used for cycle counting.

The Miner's rule is still the most favorite approach to calculate the damage of a structure under variable amplitude loading even with the short comings associated with it. A single damage parameter is used to define the fatigue damage in the case of Miner's rule. This is a very weak assumption considering that the fatigue mechanism behaves differently in its different phases of development. Further the damage criteria doesn't take into consideration effects of local plasticity and residual stresses. These factors needs to be included and damage criteria specified for different phases in the fatigue development of a joint.

Appendix

10.1 Appendix A

10.1.1 The Ring Model for Chord Face Failure



Figure 10.1 Ring Model for a X Joint

Here an effective length of B_e is defined. The shear and axial forces are neglected the Strength of the joint is provided by

$$N_p = \frac{C_0}{(1 - C_1)\beta} \cdot f_y \cdot \frac{t_o^2}{\sin \theta_1}$$

Where,

 C_0 and C_1 are constants and θ_1 is the angle between the diagonal and chord and t_o is the chord wall thickness.

10.1.2 The Punching Shear Model



Figure 10.2 Punching Shear Model of Y Joint

The Strength of the Joint is specified by

$$N_p = \frac{f_y}{\sqrt{3}} \cdot \pi \cdot d_2 \cdot t_0 \cdot \frac{1 + \theta_2}{2\sin^2 \theta_2}$$





Figure 10.3 Chord Shear Model for a K joint

The Static strength of the joint is given by the below criteria and formulae

$$N_1 \sin \theta \le 2 \frac{f_y}{\sqrt{3}} (d_0 - t_0) t_0$$
$$N_{0,gap} \le \pi (d_0 - t_0) t_0 \cdot f_y$$
$$M_{0,gap} \le (d_0 - t_0)^2 t_0 \cdot f_y$$

The interaction formulae is used to check the stability of the joint under combined action of axial and bending moments

$$\left(\frac{N_{0,gap}}{\pi(d_0 - t_0)t_0 \cdot f_y}\right)^2 + \left(\frac{N_1 \sin \theta_1}{\frac{2 \cdot f_y}{\sqrt{3}}(d_0 - t_0)t_0}\right)^2 \le 1$$

10.2 SCF Equation s for Tubular Joints DNV RP-C20310.2.1SCF Equations for Tubular T/Y Joint

| Table B-1 Stress Concentration Factors for Simple Tubular T/Y Joints | | | |
|--|--|-------------|------------------------------|
| Load type and fixity conditions | SCF equations | Eqn. No. | Short chord correction |
| Axial load- Chord ends fixed | Chord saddle: $\gamma \tau^{1.1} (1.11 - 3(\beta - 0.52)^2) (\sin \theta)^{1.6}$ | (1) | Fl |
| | Chord crown: $\gamma^{0.2} \tau (2.65 + 5 (\beta - 0.65)^2) + \tau \beta (0.25 \alpha - 3) \sin \theta$ | (2) | None |
| | Brace saddle: $1.3 + \gamma \tau^{0.52} \alpha^{0.1} (0.187 - 1.25\beta^{1.1}(\beta - 0.96)) (\sin \theta)^{(2.7-0.01\alpha)}$ | (3) | Fl |
| | Brace crown: $3 + \gamma^{12} (0.12 exp(-4\beta) + 0.011\beta^2 - 0.045) + \beta \tau (0.1 \alpha - 1.2)$ | (4) | None |
| Axial load- General fixity conditions | Chord saddle: $(Eqn.(1)) + C_1(0.8\alpha - 6)\tau\beta^2(1-\beta^2)^{0.5}(sin2\theta)^2$ | (5) | F2 |
| | Chord crown: $\gamma^{0.2}\tau \left(2.65 + 5(\beta - 0.65)^2\right) + \tau\beta (C_2\alpha - 3) \sin\theta$ | (6a) | None |
| | Alternatively $SCF_{Cc} = \gamma^{0.2} \tau (2.65 + 5 (\beta - 0.65)^2) - 3\tau \beta \sin \theta + \frac{\sigma_{BradingChord}}{\sigma_{Autobrace}} SCF_{ar}$ where | (6b) | |
| | $\sigma_{\text{Bending Chord}} = \text{nominal bending stress in the chord}$ $\sigma_{\text{Axial brace}} = \text{nominal axial stress in the brace.}$ $\text{SCF}_{\text{att}} = \text{stress concentration factor for an attachment} = 1.27$ | | |
| | Brace saddle: (Eqn. (3)) | | F2 |
| | Brace crown: $3 + \gamma^{1.2} (0.12 \exp(-4\beta) + 0.011\beta^2 - 0.045) + \beta \tau (C_3 \alpha - 1.2)$ | (7a) | None |
| | Alternatively $SCF_{\beta c} = 3 + \gamma^{12} (0.12 \exp(-4\beta) + 0.011\beta^2 - 0.045) - 1.2\beta \tau + \frac{0.4 \sigma_{BandingChord}}{\sigma_{Acultrees}} SCF_{av}$ | (76) | |

Table 10-2



It should be noted that equations (6b) and (7b) will for general load conditions and moments in the chord member provide correct hot spot stresses at the crown points while equations (6a) and (7a) only provides correct hot spot stress due to a single action load in the considered brace. Equations (6b) and (7b) are also more general in that a chord-fixation parameter need not be defined. In principle it can account for joint flexibility at the joints when these are included in the structural analysis. Also the upper limit for the α -parameter is removed with respect to validity of the SCF equations. Thus, these equations are in general recommended used. Equation (6a) and (6b) will provide the same result only for the special case with a single action load in the considered brace and SCF_{att} = 1.0. For long chords the brace can be considered as an attachment to the chord with respect to axial stress at the crown points. This would give detail category F from Table A-7 (for thick braces and E-curve for thinner) which corresponds to SCF_{att} = 1.27 from Table 2-1.

10.2.2 SCF Equations for Tubular X joint

| Table B-2 Stress Concentration Factors for Simple X Tubular Joints | | |
|--|---|----------|
| Load type and fixity conditions | SCF equation | Eqn. no. |
| Axial load (balanced) | Chord saddle: | |
| P | $3.87 \gamma \tau \beta (1.10 - \beta^{1.8}) (\sin \theta)^{1.7}$ | (12) |
| rh - | Chord crown: | |
| | $\gamma^{0.2}\tau (2.65 + 5(\beta - 0.65)^2) - 3\tau\beta\sin\theta$ | (13) |
| | Brace saddle: | |
| | | (14) |
| Ψ 1 | $1 + 1.9 \gamma \tau^{0.5} \beta^{0.9} (1.09 - \beta^{1.7}) (\sin \theta)^{2.5}$ | |
| ۳ | Brace crown: | |
| | $3 + \gamma^{1.2} (0.12 \exp(-4\beta) + 0.011\beta^2 - 0.045)$ | (15) |
| | In joints with short cords (α < 12) the saddle SCF can be reduced by the factor F1 (fixed chord ends) or F2 (pinned chord ends) where | |
| | $F1 = 1 - \left(\ 0.83 \ \beta \ - \ 0.56 \ \beta^2 \ - \ 0.02 \ \right) \gamma^{0.23} \text{exp} \left(\ - \ 0.21 \ \gamma^{-1.16} \alpha^{2.5} \right)$ | |
| | $F2 = 1 - \left(\ 1.43 \ \beta - 0.97 \ \beta^2 \ - \ 0.03 \ \right) \gamma^{0.04} exp \left(- \ 0.71 \ \gamma^{-1.38} \alpha^{2.5} \right)$ | |
| In plane bending | Chord crown: (Eqn. (8)) | |
| <u> </u> | Brace crown: | |
| | (Eqn. (9)) | |
| £ | | |
| l li | | |
| 4 H | | |
| Out of plane bending | Chord saddle: | |
| (balanced) | | (16) |
| м | $\gamma \tau \beta (1.56 - 1.34\beta^4) (\sin \theta)^{1.6}$ | |
| | Brace saddle: | |
| | $\tau^{-0.54} \gamma^{-0.05} \left(0.99 - 0.47 \beta + 0.08 \beta^4 \right) \cdot (\text{Eqn.}(16))$ | (17) |
| | In joints with short chords (α < 12) eqns. (16) and (17) can be reduced by the factor F3 where: | |
| Ψ | | |
| M | $F3 = 1 - 0.55 \beta^{1.5} \gamma^{0.10} \exp \left(- 0.49 \gamma^{-0.59} \alpha^{1.5} \right)$ | |



10.2.3 SCF Equations for Tubular K Joint

| Table B-3 Stress Concentration Factors for Simple Tubular K Joints and Overlap K Joints | | | | |
|---|---|-------------|------------------------|--|
| Load type and fixity conditions | SCF equation | Eqn. no. | Short chord correction | |
| Balanced axial load | Chord: | | | |
| | $\begin{split} &\tau^{0.9}\gamma^{0.5} \Big(0.67-\beta^2+1.16\beta \Big)\sin\theta \left(\frac{\sin\theta_{max}}{\sin\theta_{min}}\right)^{0.30},\\ &\left(\frac{\beta_{max}}{\beta_{min}}\right)^{0.30} \Big(1.64+0.29\beta^{-0.38}\text{ATAN}\left(8\zeta\right) \Big) \end{split}$ | (20) | None | |
| | Brace: $1 + (1.97 - 1.57 \beta^{0.25}) \tau^{-0.14} (\sin \theta)^{0.7} \cdot (Eqn. (20)) + \frac{\sin^{1.8}(\theta_{max} + \theta_{min}) \cdot (0.131 - 0.084 \text{ ATAN} (14 \zeta + 4.2 \beta))}{\cos^{1.5} \theta^{1.5} - \theta^{1.2}}$ | (21) | None | |
| | $C\beta^{(1)}\gamma^{(2)}\tau^{(1)}\tau^{(2)}$ Where: $C = 0 \text{ for gap joints}$ $C = 1 \text{ for the through brace}$ $C = 0.5 \text{ for the overlapping brace}$ Note that τ, β, θ and the nominal stress relate to the brace under consideration ATAN is arctangent evaluated in radians | | | |
| Unbalanced in plane bending | Chord crown: (Eqn. (8)) (for overlaps exceeding 30% of contact length use 1.2 · (Eqn. (8))) | | | |
| | Gap joint brace crown: (Eqn. (9)) | | | |
| | Overlap joint brace crown: (Eqn. (9)) · (0.9 + 0.4β) | (22) | | |
| Unbalanced out-of-plane bending | Chord saddle SCF adjacent to brace A: | | | |
| | $(\text{Eqn. (10)}) A \cdot (1 - 0.08 (\beta_B \gamma)^{0.5} \exp(-0.8 x)) + (\text{Eqn. (10)}) B$ $\left(1 - 0.08 (\beta_A \gamma)^{0.5} \exp(-0.8 x)\right) \left(2.05 \beta_{\max}^{0.5} \exp(-1.3 x)\right)$ where $x = 1 + \frac{\zeta \sin \theta_A}{\beta_A}$ | (23) | F4 | |
| | Brace A saddle SCF $\tau^{-0.54} \gamma^{-0.05} (0.99 - 0.47 \beta + 0.08 \beta^4)$ (Eqn. (23)) | (24) | F4 | |
| $F4 = 1 - 1.07 \beta^{1.88} exp(-0.16 \gamma^{-1.06} \alpha^{2.4})$ | | | | |
| $(Eqn. (10))_A$ is the chord SCF adjacent to brace A as estimated from Eqn. (10). | | | | |
| Note that the designation of braces A and B is not geometry dependent. It is nominated by the user. | | | | |

| Table | 10-6 |
|-------|------|
|-------|------|

| Table B-4 Stress Concentration Factors for Simple Tubular K Joints and Overlap K Joints | | | | |
|--|---|-------------|------------------------------|--|
| Load type and fixity conditions | SCF equations | Eqn. No. | Short chord correction | |
| Axial load on one brace only | Chord saddle: (Eqn. (5)) | | Fl | |
| | Chord crown: (Eqn. (6)) | | - | |
| . | Brace saddle: (Eqn.(3)) | | Fl | |
| | Brace crown: (Eqn. (7)) | | | |
| | Note that all geometric parameters and the resulting SCFs relate to the loaded brace. | | | |
| In-plane-bending on one brace only | Chord crown: (Eqn. (8)) | | | |
| | Brace crown: (Eqn. (9)) | | | |
| | Note that all geometric parameters and the resulting SCFs relate to the loaded brace. | | | |
| Out-of-plane bending on one | Chord saddle: | | | |
| orace only | $(Eqn. (10))A \cdot (1 - 0.08(\beta_B \gamma)^{0.5} exp(-0.8x))$ | | | |
| | where | (25) | F3 | |
| | $x = 1 + \frac{\zeta \sin \theta_A}{\beta_A}$ | | | |
| | Brace saddle: | | | |
| | $\tau^{-0.54}\gamma^{-0.05}(0.99 - 0.47\beta + 0.08\beta^4) \cdot (Eqn. (25))$ | 00 | F2 | |
| | | (20) | | |
| Short chord correction factors: | | | | |
| $F1 = 1 - (0.83 \beta - 0.56 \beta^{2} - 0.02) \gamma^{0.23} exp(-0.21 \gamma^{-1.16} \alpha^{2.5})$ | | | | |
| $F3 = 1 - 0.55 \beta^{1.8} \gamma^{0.16} exp(-0.49 \gamma^{-0.89} \alpha^{1.8})$ | | | | |

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