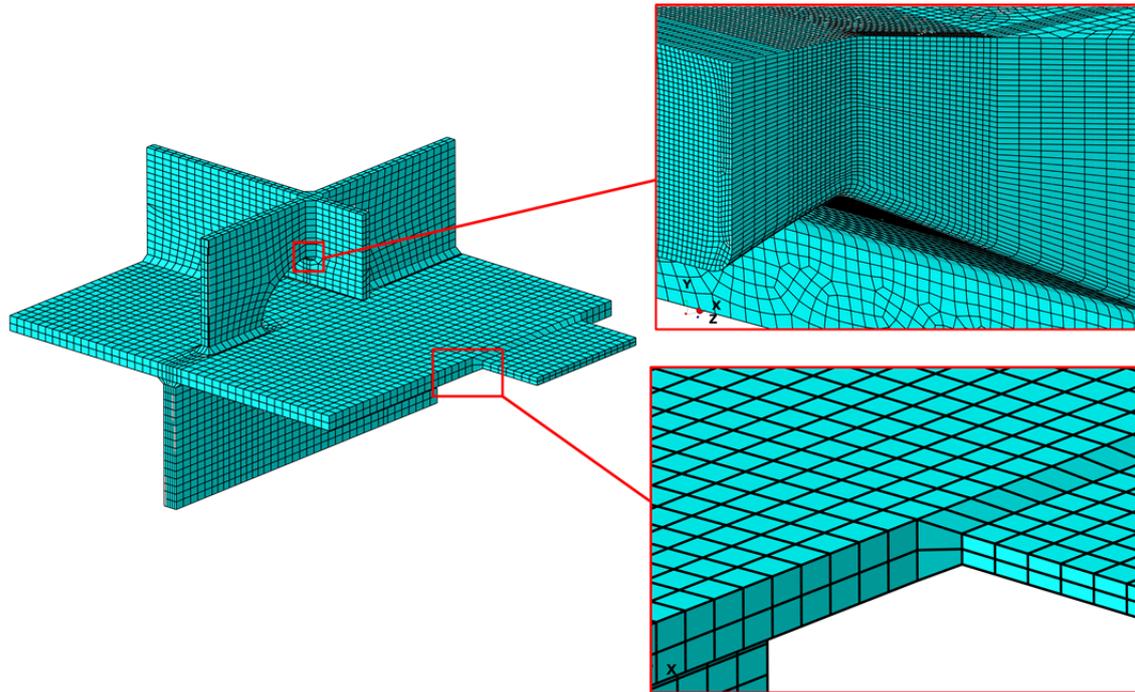


CHALMERS



Fatigue Analysis of Welded Structures Using the Finite Element Method

MUSTAFA AYGÜL

Department of Civil and Environmental Engineering
Division of Structural Engineering, Steel and Timber Structures
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2012

THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

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ABSTRACT

Fatigue design and analysis of steel and composite bridges is generally based on the notion of the nominal stress using the classified S-N curves with corresponding fatigue classes for typical details. Such an approach can yield unrealistic the estimation of the load effects for structure components because of an ever increasing number of structural details and loading situations resulting in a limited number of possible treatable design cases. The hot spot stress method has been developed to enable an accurate estimation of the load effects for the fatigue strength of welded steel structures, in cases where the nominal stress is hard to estimate because of geometric and loading complexities or in cases where there is no classified detail that is suitable to be compared with. Although this method has been used in fatigue design and analysis in tubular structures for several decades, the method has not been applied on a larger scale on steel and composite bridges.

The essential of adopting the finite element method for determining the design stresses for fatigue life calculations has been increased recently especially when utilizing the advanced fatigue assessment methods for welded steel structures. However, the result from finite element analysis can be highly sensitive to modelling technique since the stresses obtaining from these advanced methods such as the structural hot spot stress method and the effective notch stress method are often in an area of high strain gradients, i.e. stress singularities. The resulting stresses may differ substantially depending on the type and size of elements. In this study, this was recognized by evaluating the hot spot and effective notch stresses obtained from the finite element analyses with the fatigue test data collected from the literature.

Orthotropic steel bridges have both complex geometry and loading conditions producing complex bridge deck behaviour which is hard to estimate and analyse using the traditional fatigue assessment methods. The effects of the loading and geometrical conditions, i.e. decks components which are working in a group, need to be considered accurately in the stress calculations. Assuming overall elastic behaviour in such complex structure systems, in which the stress raising sources that have decisive effects on the fatigue strength capacity are partly included, can yield over/underestimated stress values to be evaluated in fatigue design. The application of the advanced life assessment methods using the finite element method studied in this thesis produce more accurate stress results, including stress raising effects at welded details that are prone to fatigue.

Keywords: Hot spot stress, effective notch stress, orthotropic bridge deck, welded details, the finite element method

Utmattningsanalys av svetsade konstruktioner med finita elementmetoden

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SAMMANFATTNING

Dimensionering av utmattningshållfastheten för stål- och samverkansbroar baseras generellt på tillämpning av metoden med nominella spänningar i samband med typdetaljer med angiven utmattningshållfasthet. Dyliga konventionella dimensioneringsmetoder kan orealistiskt utvärdera utmattningsbelastade komponenter på grund av att det ständigt ökande antal förbandsdetaljer och lastkombinationer leder till begränsade antal möjliga designfall som är behandlingsbara. Hot spot spänningsmetoden har utvecklats för att underlätta en mer noggrann utvärdering av utmattningshållfastheten hos svetsade stålkonstruktioner, särskilt tillämpliga är fallen där den nominella spänningen är svår att definieras korrekt på grund av komplexiteten i geometrin och lastförhållandena eller de fall där det saknas ett klassificerat förband som är lämpligt att jämföras med. Även om denna metod under flera decennier har använts för utmattningsdimensionering i rörformiga konstruktioner, har denna dock inte tillämpats i större skala på stål- och samverkansbroar.

Tillämpning av finita elementmetoden på spänningsanalyser innebär däremot mer noggranna spänningsberäkningar som inkluderar både globala och lokala effekter på svetsade detaljer. Resultaten från sådana analyser kan dock vara mycket känsliga för modelleringstekniken eftersom spänningarna som används på de avancerade metoderna såsom hot spot spänningsmetoden och effektiv notch spänningsmetoden ofta är i ett område med stora höga spänningsgradienter, dvs. singulariteter där spänningarna går mot oändligheten. Beroende av elements typ och intensitet kan de dimensionerande spänningarna skilja sig avsevärt.

Broar med ortotrop platta har geometrier och belastningsförhållanden som är komplexa. Denna komplexitet resulterar i invecklade beteenden av plattan vilket kan försvåra att analysera med hjälp av traditionella utmattningsdimensioneringsmetoder. Lasteffekter och geometrisk komplexitet, dvs. komponenter som arbetar i grupp, måste beaktas noggrant i spänningsberäkningarna. Genom att anta en global linjärelastisk balkteori berör sådana komplexa detaljer, där spänningshöjande effekterna som har avgörande inverkan på utmattningshållfastheten bara delvis ingår, kan leda till över- eller underskattade spänningsvärden som i sin tur ger orealistisk uppskattning på utmattningskapaciteten. Vid tillämpning av de avancerade metoderna med finita elementmetoden som studerats i detta arbete, erhålls mer pålitliga spänningsvärden som inkluderar spänningshöjande effekter på svetsdetaljerna.

Nyckelord: Hot spot spänningsmetoden, effektiv notch spänningsmetoden, ortotrop platta, svetsade förband, finita elementmetoden

LIST OF PUBLICATIONS

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text.

- I. Aygül, M., M. Al-Emrani and S. Urushadze, (2011). Modelling and fatigue life assessment of orthotropic bridge deck details using FEM. *International Journal of Fatigue* (Article in Press)
- II. Aygül, M., Bokesjö, M., Heshmati, M. and Al-Emrani, M., (2012). A comparative study on different fatigue failure assessments of welded bridge details. *International Journal of Fatigue* (Submitted article)

ADDITIONAL PUBLICATIONS BY THE AUTHOR

Conference Papers

- I. Aygül, M., Al-Emrani, M., Frýba, L. and Urushadze, S., (2010). *Evaluation of the fatigue strength of an orthotropic bridge deck detail using hot spot stress approach*. 63rd Annual Assembly & International Conference of the International Institute of Welding. AWST-10/63, Istanbul, Turkey. 261-268

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PAPER I

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Preface

The work presented in this licentiate thesis was conducted between January 2009 and November 2011 at Chalmers University of technology, Department of Civil and Environmental Engineering, Division of Structural Engineering, Steel and Timber Structures.

The work has been carried out within the part of BriFaG research project "Bridge Fatigue Guidance – Meeting Sustainable Design and Assessment". The project was financed by European Commission – Research Fund for Coal and Steel and the Swedish transport administration, Trafikverket, all of which are gratefully acknowledged for making it possible for me to accomplish the research work.

The project was carried out with Professor Robert Kliger as examiner and Docent Mohammad Al-Emrani as main supervisor, whom I thank for all good advice. I would also like to express my appreciation to all my colleagues for their cooperation and involvement. Special thanks go to the Swedish transport administration, Trafikverket and to the ITAM (Institute of Theoretical and Applied Mechanics, Prague) for their collaboration.

Finally, I would like to thank my family and friends for their support and never-ending patience.

Gothenburg, February 2012

Mustafa Aygöl

Notations

Roman upper-case letters

E	Modulus of elasticity
H _w	Height of weld
H _b	Height of beam web
R	Stress ration

Roman lower-case letters

t	Thickness
a	Weld thickness

Greek letters

σ_m	Membrane stress
σ_b	Bending stress
σ_{str}	Structural stress range
$\Delta\sigma$	Stress range
$\Delta\sigma_{mean}$	Mean stress range
$\Delta\sigma_C$	Characteristic stress range
$\Delta\sigma_{Hss}$	Hot spot stress range
$\Delta\sigma_{Eff}$	Hot spot stress range
τ	Shear stress
$\Delta\tau$	Shear stress range

Abbreviations

EC	Eurocode
IIW	The international institute of welding
BEM	Boundary element method
FEA	Finite element analysis
FEM	Finite element method
FE	Finite element
St. dev.	Standard deviation
CAFL	Constant amplitude fatigue loading
VAFL	Variable amplitude fatigue loading

1 Introduction

1.1 Background

Fatigue failure is a complex and progressive form of local damage which is significantly influenced by many factors such as magnitude and frequency of the loads causing the fluctuating stress, temperature, environment, geometrical complexities, material imperfections and discontinuities. The geometrical complexities and irregularities as well as load transfer conditions in steel structures can cause difficulties to estimate correctly the load effects on the fatigue strength of structure components. In the case of large steel structures with complex details, such as welded joint components in orthotropic bridge decks, an accurate estimation of the load effects in its welded details is often difficult to obtain applying a global life assessment method. A refined or local failure assessment method, which takes into account of the stress raising effects due to the geometry and/or loading conditions, might provide an accurate estimate of these effects. In an investigation of the fatigue performance of existing steel and composite bridges [1], fatigue damage cases were reported for various bridge types and details. An accurately and precisely calculated fatigue design stress by that the evaluation of loading effects on the fatigue strength of complex welded steel structures might be obtained using advanced fatigue life evaluation techniques.

The main purpose of using the finite element method in fatigue design and analysis is to obtain a more accurate estimation of the load effects in the studied details. As stated earlier, bridges have both details with complex geometry and loading conditions which produce complex bridge deck behaviour. Defining substantially more detailed and accurate information about the stress state of steel and composite bridge structures is extremely laborious without using a finite element analysis. An important aspect with modelling is to be able to create a finite element model without compromising the accuracy of the model in comparison to the required effort time. Simplifying the finite element models may reduce the accuracy of the computed stress which can be resulted in over- or underestimated fatigue life. It is known that volume element based models produce the closest resemblance since the geometry can easily be modelled and the stiffness can be represented in a very high level. However, it is not always clear how a correct determination and extraction of the stresses for a particular fatigue assessment method should be done, even when well-constructed finite element models are used. This is due to fact that the result from FEA can be highly sensitive to finite element modelling technique since the stresses obtaining from the refined methods are often in an area of high strain gradients, i.e. stress singularities. The resulting stresses may differ substantially depending on the type and size of elements.

The implementation of the finite element method into the fatigue design of steel structures has enabled the development of local stress concepts such as the hot spot stress approach, the effective notch stress approach and crack propagation analysis using fracture mechanics. The application range of these methods has extended greatly during the last decades. The main purpose of utilizing refined and local stress concepts is generally to compute the load effects (i.e. stresses) in a complex detail with larger accuracy, by taken into account the effects of various stress raising sources which might have decisive role on the fatigue strength of these details. Although the hot spot stress method has been used in fatigue design and analysis in tubular

structures for several decades [2], the method has not been applied on a larger scale on bridges. A number of modelling recommendations have therefore been presented in various design codes concerned with fatigue assessment methods since modelling technique has significant effect on the obtained results. On the other hand, the recommendations for modelling and stress determination given in fatigue design codes and standards do not cover many complex bridge details, such as orthotropic bridge deck details. Eurocode 3 [3] provides very little information for the application of the hot spot stress method: besides a table of detail categories, no recommendation is given regarding modelling techniques or determination of the hot spot stress.

1.2 Aim and scope

The overall objective of this study is to evaluate the applicability and reliability of the most common fatigue life assessment methods when using the finite element method. Both simple welded details and complex welded bridge details are studied. The fatigue life assessment methods considered are the nominal stress method, hot spot stress method and effective notch stress method. A number of frequently used bridge details have been evaluated for the purpose of comparing the equivalency between these different life assessment methods.

One sub-objective is to provide guidelines for finite element modelling of welded details for fatigue verification when applying the hot spot stress method and notch effective stress method.

A second sub-objective is to demonstrate the application of the hot spot stress method on a complex bridge detail – welded joints with cut-out holes in orthotropic bridge decks – as a fatigue design and analysis tool for steel bridges where the method is believed to be specifically useful.

1.3 Scientific approach

The approach to achieve the aims of the research project was first of all to study the existing recommendations available in the literature and the design codes for the fatigue assessment methods. The focus was mainly on Eurocode 3 which had very limited or no recommendations for the advanced life assessment methods.

Secondly, a database of fatigue tests over a number of the selected welded details by collecting from the literature was also produced.

Thirdly, to establish an appropriate level of finite element modelling and in order to determine the optimal quality of meshing for fatigue analysis of welded steel structures, finite element models with different modelling techniques and meshing with various size and types of elements were created and analysed. The results from the evaluation works were compared with the related fatigue strength S-N curves according to the IIW and Eurocode when it was available.

Finally, the accuracy of the results for the studied welded details when using the various fatigue life assessment methods was validated by evaluating the collected fatigue test data. The results from the different assessment methods were compared to answer the following questions:

- What is an appropriate level of FE modelling of welded steel structures for fatigue assessment?
- How should the results from different FE-models be treated and correlated to suitable detail classes in the design standards for fatigue evaluation?
- Is the accuracy depended on the complexity of the model?

1.4 Limitations

The welded joints studied in this study contain only as-welded type of joints. The treated welded joints and high strength steels are not included in this study. To exclude the beneficial effects of compression stress, only the fatigue test specimens subjected to stress ratios of $R > 0$ are collected. The fatigue test data evaluated in this study contains the fatigue tests performed under constant amplitude fatigue loading.

The fatigues test data evaluated using the life assessment methods contained only failure at the weld toe.

For finite element modelling of the fatigue test specimens presented in this study, the IIW recommendations for modelling and determining of design stresses followed and compared with the recommended fatigue strengths according to IIW and Eurocode 3.

1.5 Outline of the thesis

Chapter 2 provides an introduction to the fatigue assessment methods. A brief description of the methods is given in this chapter. To demonstrate the applicability and reliability of these methods, a welded detail is evaluated. The results are validated by the fatigue test results collected from the literature.

Chapter 3 contains the frequently used weld modelling techniques which are also utilized in this study.

Chapter 4 summarizes very shortly the case studies presented in the appended papers; both the outlined and unmentioned conclusions are presented. In this chapter, the recommendations for modelling technique and relevant fatigue strength categories are also given.

Chapter 5 is the final chapter that the conclusions drawn based on the results from the evaluation works are presented. Suggestions for the future researches are also provided.

2 Fatigue life assessment methods

A variety of fatigue life assessment methods have been introduced to assess the fatigue life of steel structures under fatigue loading. Generally, the methods used for estimating the service life of steel structures are based on strains, stresses, or stress intensity factors. There are four common assessment methods used for the fatigue life estimation of steel structures such as bridges, offshores and ships. These methods may be mainly categorized in two groups: the global and local methods. The simplest and most common method, also categorized as a global method is the nominal stress method. The methods categorized as the local methods are the hot spot stress method, the effective notch stress method and the crack propagation approach using linear elastic fracture mechanics. A common characteristic factor for the first three methods is that these methods considering the linear elastic theory or numerical methods such as the FEM or BEM are based on the S-N curve classification which refers to estimating the total life while the fourth method is based on the principles of fracture mechanics which covers crack growth, independent from any S-N curve. However, the crack propagation approach is not covered in this study.

The use of the finite element method for obtaining the design stress information which is needed to perform a fatigue life calculation requires good understanding of the principles of the FEM and the philosophy behind the fatigue assessment methods. The computation of the local stresses based on the local failure approaches when using FEA are highly sensitive to finite element modelling technique since the stresses are often in an area of high strain gradients, i.e. stress singularities [4-6]. The stress parameters used in the fatigue assessment methods are presented in Figure 2-1.

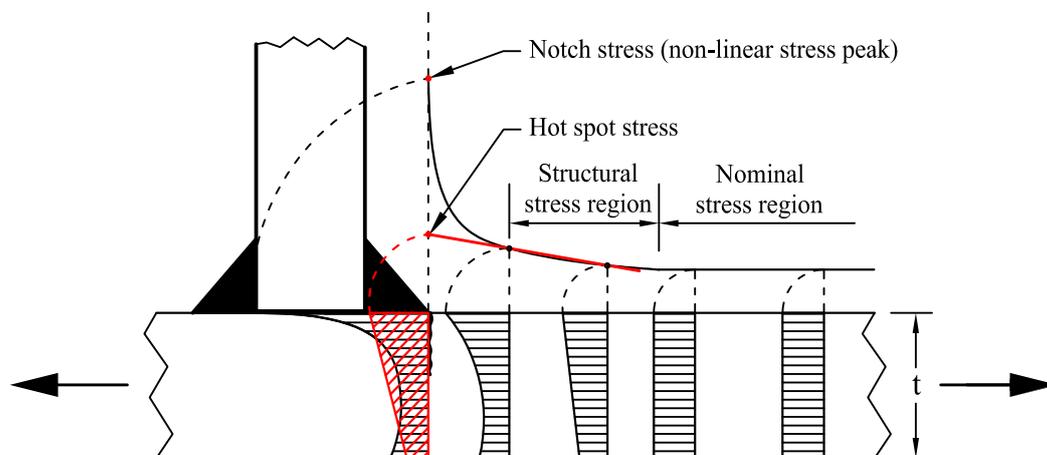


Figure 2-1 Stress distribution through plate thickness and along the surface close to the weld [5].

The intention of this chapter is to provide a review of the most frequently used fatigue assessment methods by demonstrating the application of these methods on a selected welded detail.

To demonstrate the differences in the methods, two different types of plate edge welded joints which are rather common in fatigue loaded structures – a typical example is gusset plates on bridge beams – are chosen as shown in Figure 2-2. The fatigue experiment data of this joint has been collected from the literature to confirm the performance of the methods [7-19]. The variation in dimensions and the number of experiment data are presented in Table 2-1. The computed stresses of the studied

details based on the fatigue life assessment methods were used for evaluating the collected fatigue test data points.

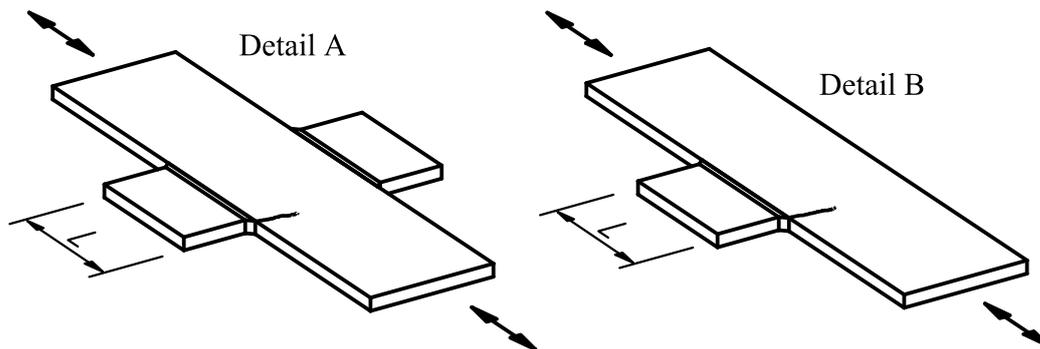


Figure 2-2 Plate edge details.

Table 2-1 Dimensions and number of evaluated fatigue test specimens.

Type of joints	No. of specimens	Main Plate		Gusset plate	
		Thickness [mm]	Width [mm]	Thickness [mm]	Length [mm]
Detail A	446	8 – 20	40 – 170	8 – 20	50 – 400
Detail B	41	10 – 20	50 – 120	10 – 12.7	50 – 450

Fatigue loading is the most important parameter influencing the fatigue strength of steel structures [20]. Fatigue loading causing fluctuating or repetitive stress in structure components can be defined as the variations in the applied loads which are pressure changes, vibrations, temperature fluctuations and wave load. There are mainly two important parameters for defining a fatigue load fully – stress range, $\Delta\sigma$ and stress ratio, R which are illustrated in Figure 2-3. A fatigue loading is divided into two different types with respect to loading history; constant amplitude fatigue loading (CAFL) as shown in Figure 2-3 and variable amplitude fatigue loading (VAFL). The fatigue tests collected from the literature contained only the tests performed under CAFL. Also to exclude the beneficial effects of compression stress, the fatigue test specimens subjected to only stress ratios of $R > 0$ were considered.

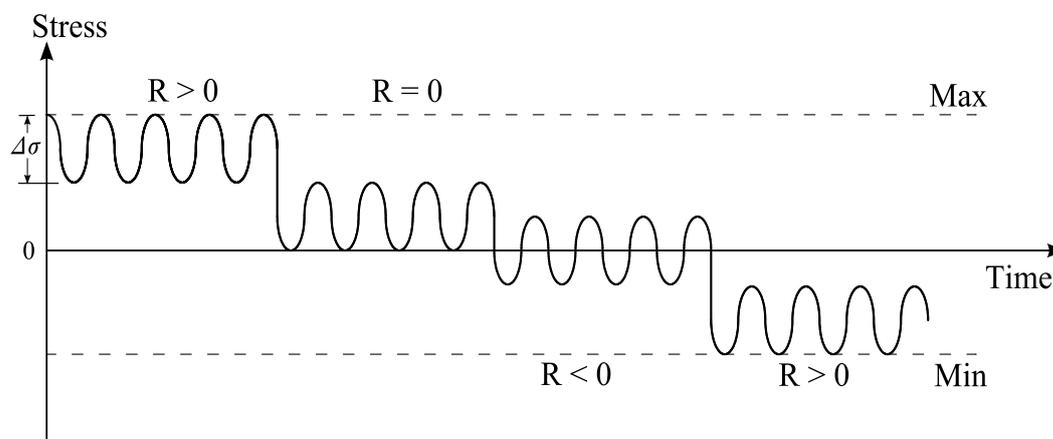


Figure 2-3 Types of constant amplitude fatigue loading.

2.1 Nominal stress approach

The nominal stress approach is the simplest and the most common applied method for estimating the fatigue life of steel structures. This method is mainly based on the average stress in the studied cross section considering the overall linear elastic beam behaviour. The local stress raising effects of the welds and the attached plates are disregarded in the stress calculations. In view of the fatigue design, although the local stress raising effects of the welded joint are not included in fatigue stress calculations, the effects of the geometrical configurations or irregularities of the main component must be included [21, 5]. These geometrical configurations and irregularities can be defined as a cut-out hole, a discontinuity in cross section or a bend/curve in a beam, in other words geometrical modifications that often have a considerable effect on the stress distribution across the entire cross section.

The fatigue classes based on the nominal stress are available in most design codes and guidelines. In case of more complex geometry for which a nominal stress is not possible to define or a design category is not available, the nominal stress method is not directly applicable any more. Instead another fatigue life assessment method needs to be used.

When applying the nominal stress approach to plate edge details, the nominal stress in the cross section of the plate edge detail can easily be calculated by using linear elastic beam theory – force divided by the section area – see Figure 2-4. As mentioned earlier, the nominal stress method requires fatigue classes or S-N curves which can be found in design codes. Eurocode 3 recommends using a detail category of C40 for this detail, irrespective of the length of the gusset plate even though even though the length of the gusset plate plays a dominant role in the magnitude of stress concentrations at the plate termination; i.e. where fatigue cracks initiate.

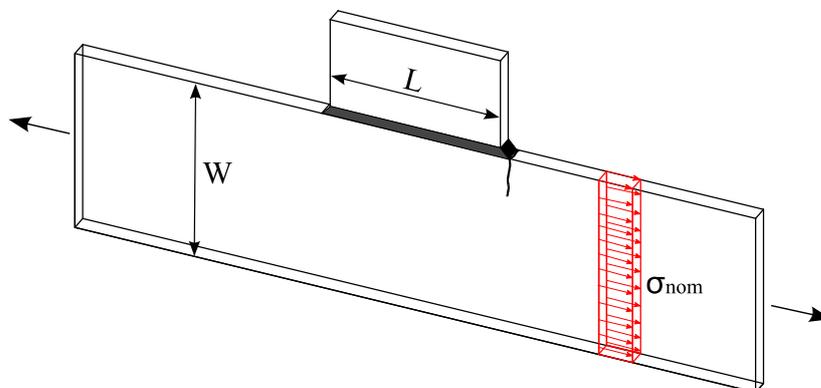


Figure 2-4 Nominal stress definition for plate edge joint.

The evaluation results from the fatigue test data based on the nominal stress range are presented in Figure 2-5. The standard deviation for all experiments data points is 0.211 when performing a linear regression analysis with a free slope. The mean value for the fatigue strength is 75.8 MPa and the characteristic value is 55.3 MPa. With a fixed slope of 3, the mean value is 75.8 MPa and the characteristic value is calculated to 60.3 MPa with the standard deviation increasing to 0.223. This evaluation study shows that the recommended fatigue class seems to be rather conservative.

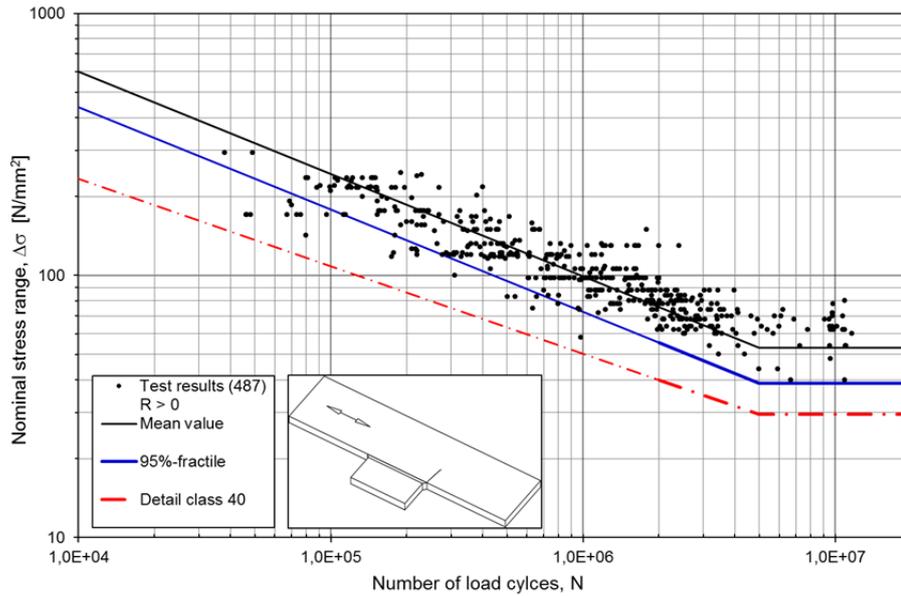


Figure 2-5 Fatigue test results for plate edge details based on nominal stress method.

To demonstrate the variations in fatigue strength according to the length of the plate attachments, the results of the fatigue tests were evaluated considering the length of the attached plates using the nominal stress approach. The results are presented in Table 2-1. As seen in this table, the effect of the length of attached plates could be captured in the fatigue life calculations when using the nominal stress approach. For the length of 100 mm and shorter, the recommended fatigue strength curve is very conservative.

Table 2-2 Statistical evaluation of fatigue test points.

Evaluation method		No. of specimens	St. dev.	$\Delta\sigma_{\text{mean}}$ [N/mm ²]	$\Delta\sigma_{\text{C}}$ [N/mm ²]
Nominal stress	All specimens	487	0.223	80.0	60.3
	$L \leq 100$	428	0.198	82.2	64.0
	$100 < L \leq 200$	42	0.240	67.2	47.0
	$200 < L \leq 300$	17	0.230	65.2	47.7

2.2 Hot spot stress approach

The hot spot stress approach has been developed to enable evaluating the fatigue strength of welded structures in cases where the nominal stress is hard to estimate because of geometric and/or loading complexities. This approach has been used for the fatigue design of pressure vessels and welded tubular connections since 1960s. The method was later applied successfully to welded plated structures [22, 23, 5, 6]. The application of the hot spot stress approach for the fatigue life assessment of welded complex structures has increased rapidly with the increasing use of the finite element method. The major advantage of the hot spot stress approach is that the stress raising effects caused by the joint members are taken into considerations in the fatigue stress calculations except the effects from the weld itself. Another advantage, which

follows the aforementioned statement, is that a reduced number of $S-N$ curves are needed to evaluate the fatigue life of welded details with this approach. However, the approach is only applicable for fatigue failures starting from the weld toe [24]. The fatigue critical points in which the fatigue stress can be determined using this method are referred to the “hot spot” points defined by Niemi and Fricke [25, 26, 5, 27] as shown in Figure 2-6. In the IIW recommendations, the method is included as an alternative fatigue life assessment method introducing two principle fatigue critical hot spot points [21]. The reason for this is that the structural stress distribution at the hot spot points “a” and “c” can be determined in the thickness direction as the sum of membrane and bending stress while the stress distribution at the point “b” should be determined along the plate edge [5]. The calculated stress at such a point is then called as “hot spot stress” or “structural hot spot stress”.

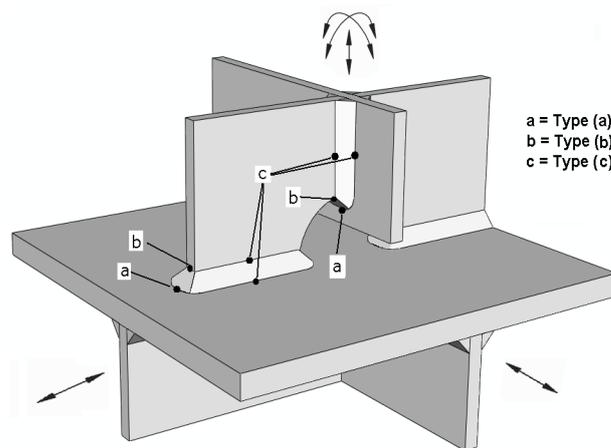


Figure 2-6 Three types of fatigue critical hot spot point at the weld toes [28].

As stated earlier, the use of the structural hot spot stress approach for the fatigue life assessment of welded steel structures has become very widespread in large steel structures and the application range of the method's has extended greatly with the implementation of the FEM for fatigue analysis. However, the result of FEA is highly mesh sensitive, as the structural hot spot stresses are often in an area of high strain gradients, i.e. stress singularities. The resulting stresses may differ substantially, depending on the type and size of elements and the procedure used to extract the values of the hot spot stresses. For this reason, a stress evaluation method is needed to obtain a relevant stress value that can be related to the fatigue strength of the detail. IIW [21] provides the most comprehensive rules and explicit recommendations for the application of structural hot spot stress, such as element type, size and reference points. In Eurocode 3 [3], the method is also included as an alternative fatigue life assessment method. However, the code does not provide any recommendations or instructions, related to the application of the structural hot spot stress method, i.e. modelling and extrapolation techniques and type of hot spot points, apart from some structural details with corresponding fatigue curve.

The structural hot spot stress cannot be read directly from FEA results. The linear surface stress extrapolation using two reference points as shown in Figure 2-7 or quadratic surface stress extrapolation technique using three reference points is usually utilized to determine the structural hot spot stress at the weld toes. In addition, a simple derivation of the hot spot stress at a position of $0.5t$ from the weld toe multiplying by a factor of 1.12– as recommended by Fricke [29] – can also be used [30].

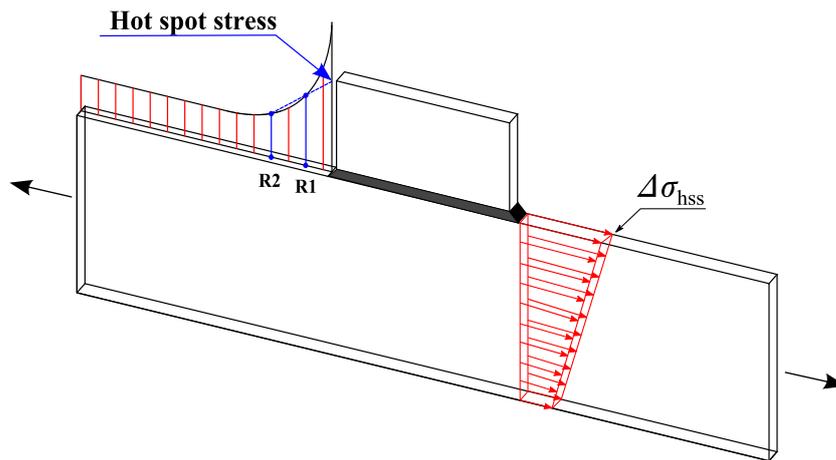


Figure 2-7 Hot spot stress definition at the weld toe in plate edge joint.

The main disadvantage of the structural hot spot stress approach is its mesh-sensitivity. To be able to capture surface stresses at the read out points, finite element models need to be created and generated regarding to the recommendations. In other words, FE models during pre-processing phase need to be created according to the necessities in the post-processing phase. This disadvantage for the method leads mainly to the increased effort for FE modelling. A limitation with the hot spot stress method is the application of the approach is restricted to weld toe cracking [31, 32].

For fatigue analysis of welded structures when applying the hot spot stress method, FE models are in general created by assuming an ideal geometry of structures where misalignments and imperfections are not considered. In fatigue design calculations, misalignments can be taken into account by suitable stress magnification factors which can be found in various design codes and regulations or by importing these irregularities into the models.

Researchers have attempted to develop alternative methods for determining the hot spot stress that is intended to be “mesh-insensitive”. The concept of a linearised structural stress distribution over the plate thickness has been modified by researchers headed by Dong at the Battelle Institute [33-35] in order to fit better fatigue results from different connection types and sizes into a single hot spot stress $S-N$ curve. The Battelle structural stress method is based on evaluating the structural stresses at the weld toe from FEA results by using the principles of elementary structural mechanics such as force-moment balance in the sections through the thickness of the plate, see Figure 2-8. Due to the equivalent stress conditions on the reference planes, the structural stress at the weld toe can be obtained at a small distance, δ^1 , from the weld toe, expressed as the superposition of membrane and bending components. The structural stress linearised equilibrium stress at the weld toe is then obtained by the sum of two stress components, the membrane and bending stress, as expressed Eq.1.

$$\sigma_{str} = \sigma_m + \sigma_b \quad Eq.1$$

¹ Any recommendation for the distance, δ has not been given by Researchers.

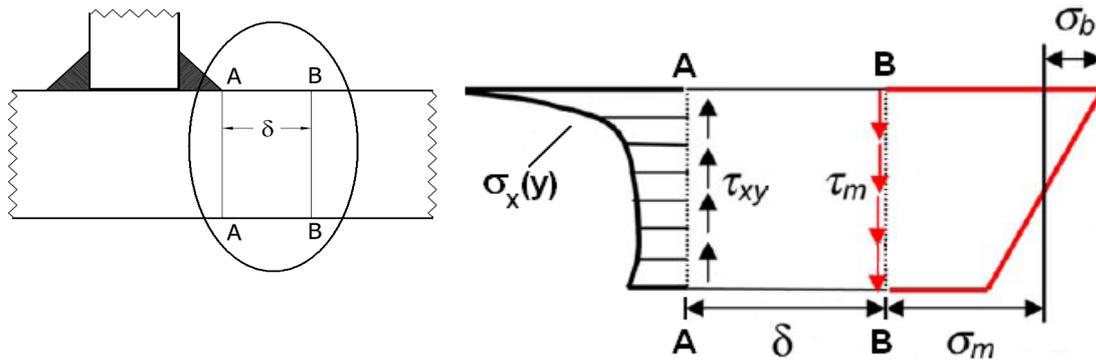


Figure 2-8 Linearization of stress distribution at the weld toe according to Battelle structural stress method [36].

As stated before, the Battelle structural stress approach was claimed to be mesh-insensitive. However, the comparison studies performed by researchers [37-39] showed that the mesh-insensitivity was demonstrated mostly in simple 2D structure details such as fillet welded lap joint. According to some studies on 3D structure details, the method was mesh sensitive and demanded even more care during the post processing by comparison with the stress extrapolation procedures. It is because of the other shear stress components are not included² which also influence choose of the distance δ . It is also reported that the nodal averaging is very important, especially in case of the coarse meshed FE models [40].

Another new concept developed for the purpose of determining structural stress based on assuming the computed stress value at a depth of 1mm below the surface at the weld toe in the direction of the expected crack path has been proposed by Xiao and Yamada [39]. The stress value at this point was assumed to represent the stress gradient over the plate thickness. This approach is verified by Xiao and Yamada for non-load-carrying fillet welds executed on both sides of transverse and longitudinal attachments. Later Noh et al. [41] have shown that the concept was also applicable to the fatigue assessment with respect to the weld toe failures of load-carrying fillet welds in cruciform joints considering partial and full penetration welds.

The stress at the point of 1mm can be directly read out by the stress results from finite element analyses. To read the stress in given point, the element size around the weld toe region should not exceed 1mm, leading to very finely meshed FE models which are limiting its practical application. However, this problem can be solved by using the sub-modelling technique. Any specific meshing rules have not been introduced by the authors.

A comparison study performed by W. Fricke and A. Kahl [37] showed that this method was considering the thickness effect (size effect) very well. The scatter of test results evaluated based on this method was smaller than for the conventional structural hot stress method and the Battelle structural stress method. However, the first order FE elements are recommended to be used with this method. The reason for this recommendation is that the mid-node in the second order elements causes a reduced stress at the lower edge of the notch element in the depth of 1 mm which was not consistent with the test results. In the first order elements, the mid-node does not exist and thus the reduction in the stress is limited. The results from the FE models

² Only τ_{xy} is included in the stress calculation procedure, Figure 2-8. The other shear stress components τ_{yz} and τ_{xz} are not included.

using the first order were consequently consistent the fatigue test results. A shortcoming with this method is that the method is not applicable for root failures.

The effort for creating the finite element models with solid elements on the plate edge details studied was insignificant. One reason is that the welds³ were created easily and the attached plate welded to the main plate edge was joined even though it was a fillet weld connection. The hot spot stress was determined by using the quadratic surface stress extrapolation. The standard deviation for all fatigue test points is 0.183 when performing a linear regression analysis with a free slope. The mean value of these data points was calculated to 128.7 MPa and the characteristic fatigue strength value to 99.5 MPa. With a fixed slope of 3, the characteristic value is calculated to 104.8 MPa with a standard deviation increasing to 0.189. The scatter obtained for the evaluated experimental data using the hot spot stress approach is smaller than the scatter from the nominal stress approach, since according to the definition of the hot spot stress, the calculated stress includes the geometrical effects of the details, being in this case the attached/gusset plates.

Eurocode 3 does not give any fatigue class recommendations for plate edge details when considering the hot spot stress while IIW recommends using two different fatigue curves dependent on the length of attached plates. According to this code, FAT100 should be used when the length of attached plates is equal or smaller than 100 mm, otherwise FAT90 should be used. The reason for that is the fact that when the attached plate is shorter, the welded joint is a non-load carrying joint and thus the weld is defined as a non-load-carrying weld which is categorised as FAT100. When the attached plate is longer, the welded joint is significantly influenced by the load and the weld becomes a load-carrying weld which is categorised as FAT90.

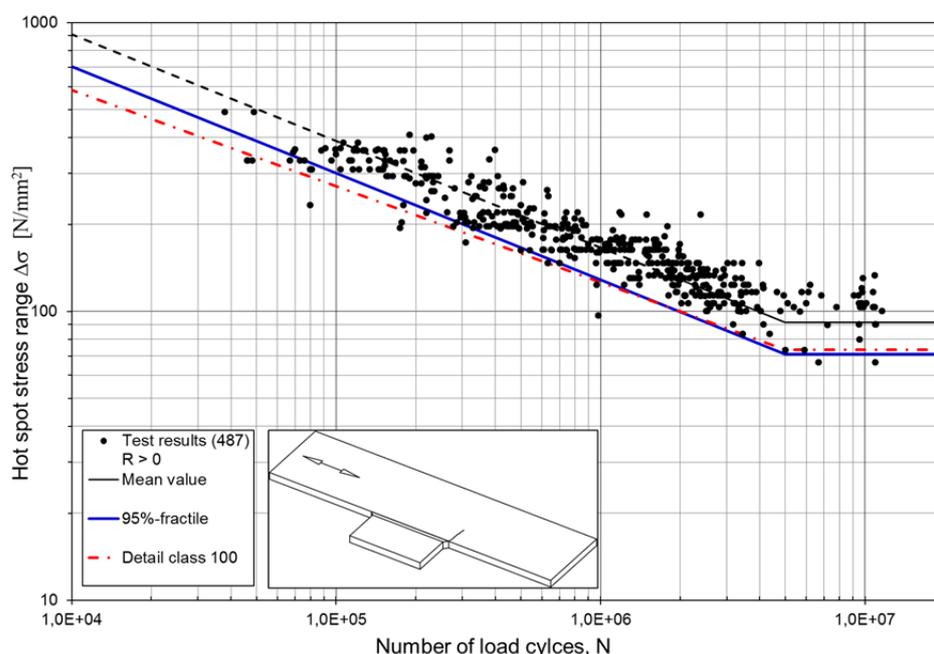


Figure 2-9 Fatigue test results for plate edge details based on hot spot stress method.

³ The reason for modelling the welds is that the results from the fatigue assessment methods are comparable and reliable by minimizing the variations in the finite element models. FE models with solid elements were used for both the hot spot stress and effective notch stress approach.

The results from the evaluations of the fatigue test data without considering the length of attached plates show that the fatigue category FAT100 seems to give a good representation of the fatigue strength of this particular detail. When the lengths are, however considered, this detail should be categorized as recommended in the IIW; for the shorter plate lengths FAT100 should be used and for the plate lengths longer than 100 mm FAT90 should be used.

Table 2-3 Statistical evaluation of fatigue test points.

Evaluation method		No. of Specimens	St. dev.	$\Delta\sigma_{\text{mean}}$ [N/mm ²]	$\Delta\sigma_c$ [N/mm ²]
Hot spot stress	All specimens	487	0.189	133.1	104.8
	$L \leq 100$	428	0.184	134.2	106.3
	$L > 100$	59	0.211	126	95.2

2.3 Effective notch stress approach

Stress raisers or notches emanating from geometrical discontinuities such holes, joints and defects from welds in structural components are rather common and cannot be avoided. The fatigue strength of welded joints is heavily depended on their notch properties giving higher stress concentrations which leads to lower fatigue life [42]. The notch stress in welded joints is the total local stress caused by both the component geometry and the local stress raiser, i.e. the weld itself.

The effective notch stress approach is mainly based on the computed highest elastic stress at the critical points, i.e. crack initiation points. This method was proposed by Radaj [6] who took account of stress averaging in the micro-support theory according to Neuber Rule with a fictitious radius of 1mm for plate thicknesses of 5 mm and above [21]. The reference notch radius, as illustrated in Figure 2-10, is calculated assuming the worst case conditions ($\rho=0$) for welded joints. Of course, in reality the real notch radius varies widely. When the micro-support length (ρ^*) is considered to 0.4 mm with the constraint factor (s) of 2.5 for steel members, the final rounding radius of notches becomes 1mm in this reference radius calculation. For smaller plate thicknesses, Zhang [43] has proposed the use of a fictitious radius of 0.05 mm, which is based on the relationship between the stress-intensity factor and the notch stress [44-46].

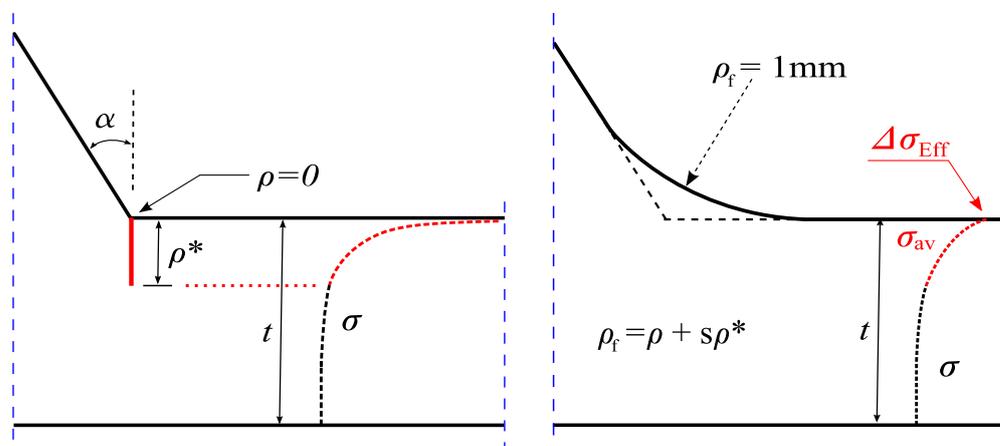


Figure 2-10 Neuber's micro-support concept in welded joint.

For fatigue analysis of welded joints when using the effective notch stress method, the geometric details around the region of stress concentration should have a sufficient element density in order to capture the maximum stress at the point of stress concentration. The major principal for this method is that the detail geometry around anticipated crack initiation regions is to be modelled and meshed with sufficient accuracy which can be obtained generally by 3D solid element models. However, 2D plane element based finite element models can be used for the cases in which the loading and geometry are simple enough to be represented in 2D model. The effective notch stress approach is included in the IIW recommendations as an alternative fatigue life assessment method with the recommendations for finite element modelling and the fatigue S-N curve to be used.

The plate edge welded details collected from the literature were also studied using the effective notch stress method following the recommendations given in IIW. Sonsino [45] suggests that a fatigue design curve of FAT225 should be used when calculating the effective notch stress based on the maximum principal stress, while a fatigue design curve of FAT200 should be used when considering von Mises stress. However, the maximum principal stress is recommended in the case of multiaxial stresses and ductile materials such as structural steels, while the von Mises stress criterion is used for brittle materials such as cast irons [6].

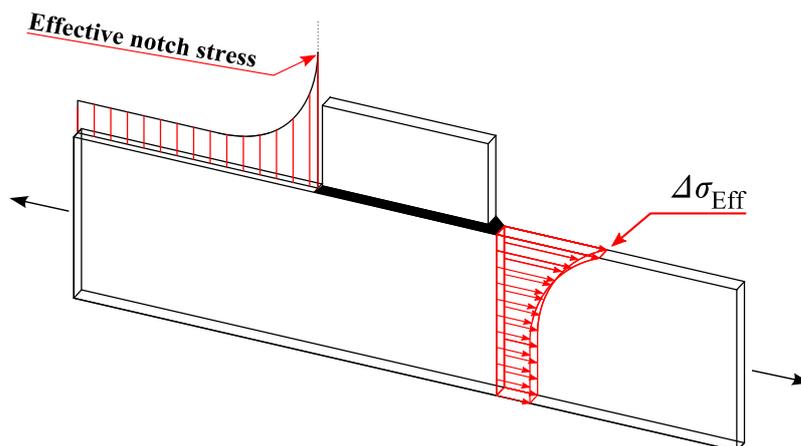


Figure 2-11 Effective notch stress definition at the weld toe in plate edge joint.

The effective notch stresses at the weld toe for the studied test specimens were computed using the sub-modelling technique since a very fine meshed region around the critical points (as shown in Figure 2-12) were required to capture the maximum elastic stress, see Figure 2-11. The sub-modelling is generally performed to transfer the displacements when defining node-based sub-regions or to transfer the stresses at the integration points when defining surface-based sub-regions from the coarsely meshed global model to the refined meshed local model. The sub-modelling technique can allow connecting more than one sub-model to each other as a serial/chain connection.

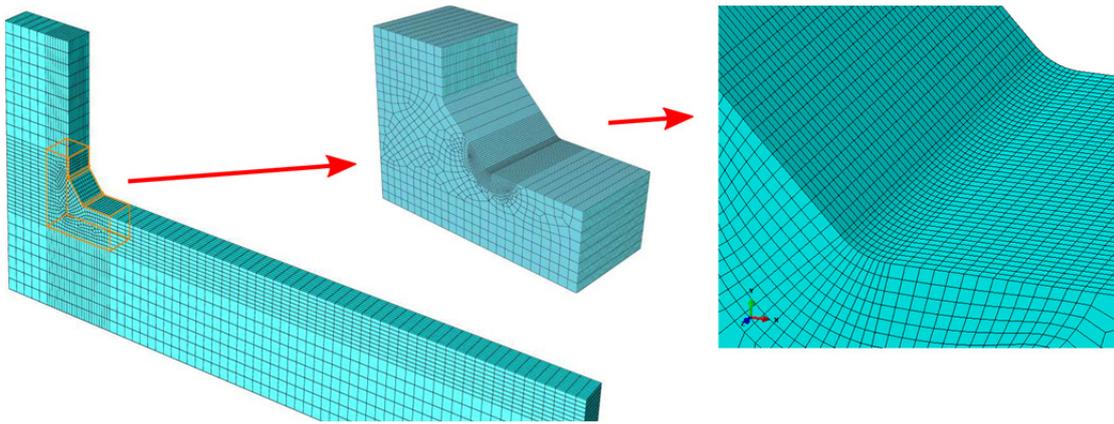


Figure 2-12 Global model and submodel for investigated plate edge joints.

The results for evaluating the fatigue test data of the plate edge details based on the effective notch stresses at the weld toe are plotted and presented in Figure 2-13. Linear regression analysis is used to compare the results with the recommended fatigue design curve. The mean and characteristic fatigue strength values when considering a slope of 3 are 312.5 and 236 MPa respectively. The standard deviation for the 487 experimental data points is 0.222 which seems to be rather high. One reason for the large scatter may be the variation in welding techniques, weld quality, and the type and size of local defect. This reason reveals on the other hand the effect of the weld in notch stress calculations since the effective notch stress method is based on rounding the sharp notch (weld toe in this case) to avoid the stress averaging over the short length of the notch region. There is yet another reason that might cause this unexpected scatter. The presence of residual stresses due to welding might also have an effect since the effective notch stress method takes into account the effect of the welds. Residual stresses are a well-known factor that can have a significant influence on the fatigue strength of welded joints, depending on their magnitude, sign and distribution [47, 48]. However, the recommended S-N curve of FAT225 for fatigue evaluation of the fatigue test data with the effective notch stress approach appears to give a good representation.

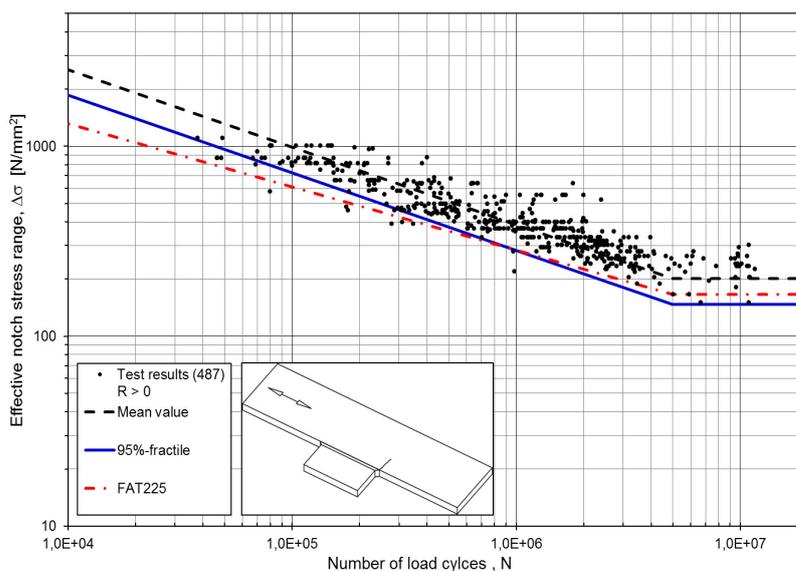


Figure 2-13 Fatigue test results for plate edge details based on effective notch stress method.

The results based on these three failure assessment approaches are compared in Table 2-4. As shown in this table, the smallest scatter for evaluating the fatigue test data points is obtained from the hot spot stress approach. For only the purpose of examining the effect of the length of attached plates in the calculated stresses when using the effective notch stress approach, the welded details were divided in groups, same as in the hot spot stress approach. As shown in Table 2-4, the effective notch stress method yielded almost same result when considering the length of the attached plates.

Table 2-4 Results for plate edge details using three fatigue failure assessments.

Evaluation method		No. of Specimens	St. dev.	$\Delta\sigma_{\text{mean}}$ [N/mm ²]	$\Delta\sigma_c$ [N/mm ²]
Nominal stress	All specimens	487	0.223	80.0	60.3
	$100 \leq L$	428	0.198	82.2	64.0
	$100 < L \leq 200$	42	0.240	67.2	47.0
	$200 < L \leq 300$	17	0.230	65.2	47.7
Hot spot stress	All specimens	487	0.189	133.1	104.8
	$L \leq 100$	428	0.184	134.2	106.3
	$L > 100$	59	0.211	126	95.2
Effective notch stress	All specimens	487	0.222	312.5	236
	$L \leq 100$	428	0.221	313.6	236.8
	$L > 100$	59	0.225	305.3	226.6

Based on the literature studies and evaluation works performed in this research thesis, the advantages and disadvantages of the fatigue life assessment methods can be summarized as in Table 2-5.

Table 2-5 Advantages and disadvantages of fatigue life assessment methods.

<i>Advantages</i>	<i>Disadvantages</i>
<i>Nominal stress approach</i>	
Simple calculations Well-defined and well-known Most common and widely used Available experimental data Available parametric formula Available fatigue classes in design codes Suitable for weld root and toe cracking	Fatigue detail category dependency Limitation for misalignment and macro-geometric changes Less accuracy in complex structures Thickness effect not included
<i>Hot spot stress approach</i>	
Fewer S-N curves needed The use of existing stress analysis Acceptable accuracy Less FE modelling effort Macro geometric effect included Utilized for tubular structures many years, well-known	Dependent on element size Dependent on element arrangement Different stress determination procedures Thickness effect not included Limited to weld toe cracking
<i>Effective notch stress approach</i>	
Thickness effect included in calculations Not affected by the stress direction Suitable for weld roots and toes cracking A single S-N curve	Applicable only with FEA Dependent on mesh density Dependent on radius size Effort for modelling – time consuming Larger models

3 Weld modelling techniques

In this chapter, the most frequently used weld modelling techniques are presented. Since the effective notch stress approach consider the notch stress at the weld root and toe, it is obvious that the welds are included in FE models. When using the hot spot stress the welds do not need to be modelled in simple shell element models in which the stress distribution is not significantly influenced by the local stiffness of joint even though the hot spot stress at fatigue critical points is determined by the surface stress extrapolation using the reference points which are located close to the welds. However, the welds should be modelled in cases where the stresses are affected by bending stress or when it is not easy to distinguish the non-linear stress caused by notch at the weld toe from stress concentration effects emanating from geometrical irregularities, such as welded joints with cut-out hole. In these cases the stiffness of the welded section should be taken into consideration and the welds can be modelled using various weld modelling techniques.

In solid element models the welds are usually modelled since the geometry and stiffness of the welds can be easily modelled using solid elements while in shell elements models, modelling of the welds require some modelling effort. In shell element models the stress value at welded regions can be dependent on the weld modelling technique. Recently several weld modelling techniques were developed to decrease the modelling work effort and also to increase the accuracy of representing the stiffness of welds [49-51]. The most frequently used weld modelling techniques⁴ are presented here.

3.1 Weld modelling using oblique shell elements

In shell element models, the welds in a welded joint can be represented using oblique shell elements as recommended by Niemi [5]. Both the stiffness and geometry of the welds can be correctly represented by utilizing this weld modelling technique. The attached plate should be joined to the main plate in the intersection as shown in Figure 3-1. The length of inclined shell elements can be chosen as shown in this figure. The thickness of oblique shell elements can be defined same as the throat thickness of welds.

⁴ These weld modelling techniques were also used in Paper I.

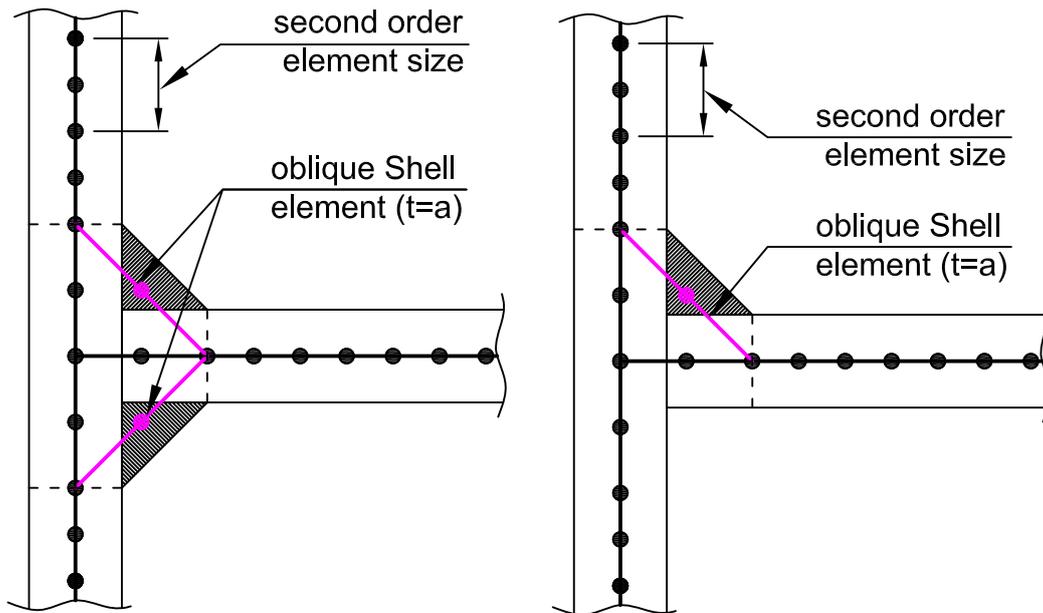


Figure 3-1 Weld modelling using oblique shell elements [5].

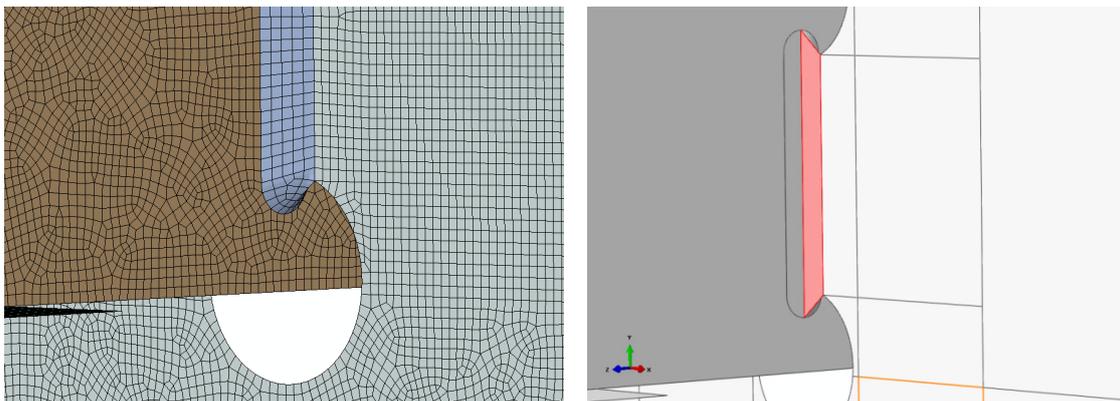


Figure 3-2 Weld modelling using oblique shell elements by joining attached plates to the parent plate in a common node.

As mentioned earlier this technique offers an opportunity to present both the stiffness and geometry of welds. This does not mean that the stress from these weld elements may be used for design calculations for example designing the joint against weld root cracking. To obtain a reliable stress result value to be used in root crack calculations the stiffness and geometry of welds play a very important roll and must be modelled correctly, not approximately. This technique is therefore more suitable and applicable for weld toe fatigue failures.

3.2 Weld modelling using rigid links

Weld modelling technique using rigid links was suggested by Fayard et al. [52]. The purpose of developing this technique was to compute hot spot stress at the weld toes. According to this technique the weld toe stress can be directly read out at the elements' centre of gravity which implies that there is no need for any surface stress extrapolation when determining the hot spot stress at weld toes.

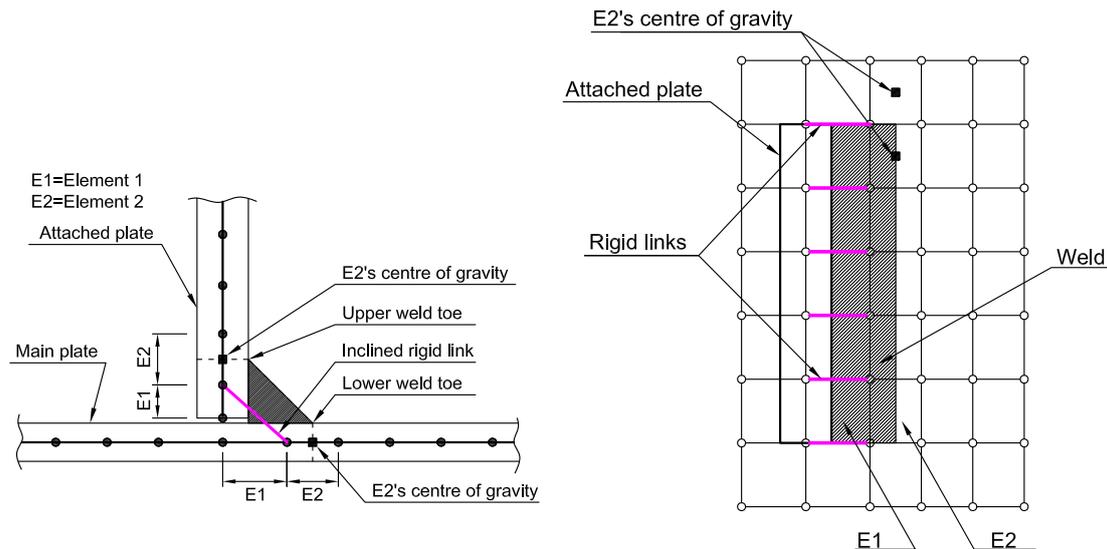


Figure 3-3 Single-side weld modelling with rigid links proposed by Fayard et. al [52].

The basis of this technique is to model the local rigidity of welded joints caused by the weld. This rigidity can be modelled linking the two adjacent shell elements using rigid links defined by pairs of nodes and located along the whole weld length. The lengths of elements, E1 and E2 as shown in Figure 3-3, should be chosen as correctly as possible to represent the local rigidity and thus obtain a reliable stress value. The common node for element E1 and E2 is used to link these elements by rigid links. It is important to notice that the plates at the intersection are not connected in the joint. Also the use of 4-node shell elements is recommended for this technique. An example of using rigid links is shown in Figure 3-4.

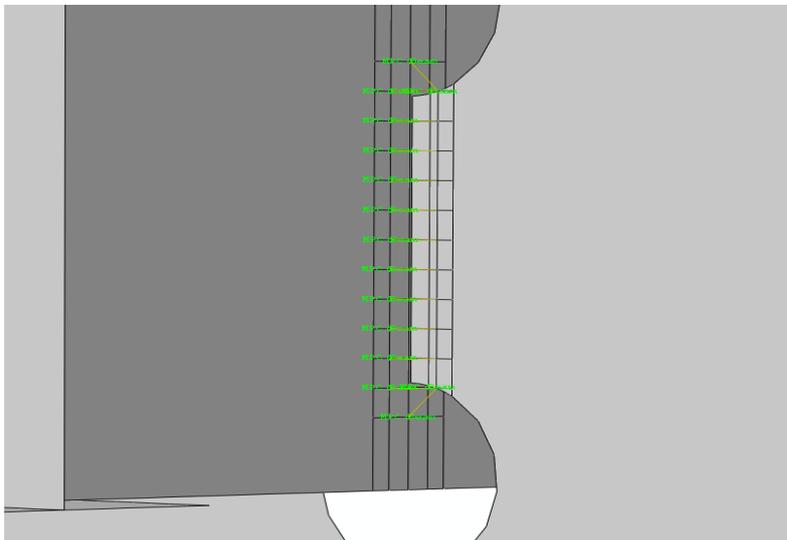


Figure 3-4 Weld modelling using rigid links.

3.3 Weld modelling using increased thickness

In order to represent the stiffness of the welds in welded joints, Niemi [5] suggested using shell elements with increased thickness in the intersection region of welded joints. This method is based on two important geometry configurations; increased

thickness and size/length of finite elements. Niemi mentioned only the intersection region of the weld without recommending thickness and size that should be used in the modelling.

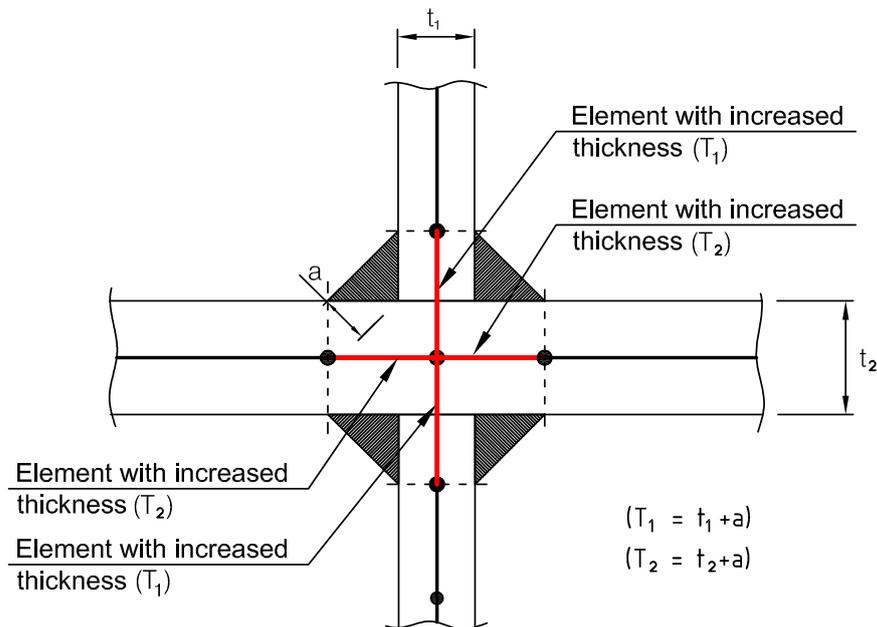


Figure 3-5 Modelling welds using shell elements with increased thickness [49].

Eriksson et al. [49] suggested two rows of shell elements with increased thickness, e.g. increased thickness elements both in the attached plate and the parent plate when considering a double sided filled weld, see Figure 3-5. The proportion of the shell elements with increased thickness at cruciform joints is shown in Figure 3-5. For cover plate connections when modelling the welds it is suggested that rigid elements can be used to join the attached plate to the parent plate while shell elements with increased thickness can be used in the parent plate using the recommended length as shown in Figure 3-6.

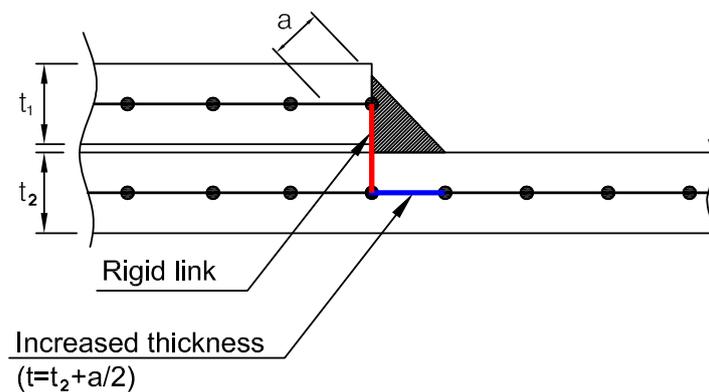


Figure 3-6 Modelling cover plate weld using shell elements with increased thickness and rigid links [49].

3.4 Weld ends modelling

In some cases the geometry and shape of welds in a joint may have larger influence than their stiffness. One example is fatigue cracking at weld toes at the end of welds.

In this case the welds can be modelled only at their ends where fatigue cracks initiate and propagate and thus the stress distributions at these points are of interest. Shell elements can be used for this purpose keeping the thickness of the weld ends same as the thickness of the welded plate. This technique proposed and applied in Paper I [28] is shown in Figure 3-7.

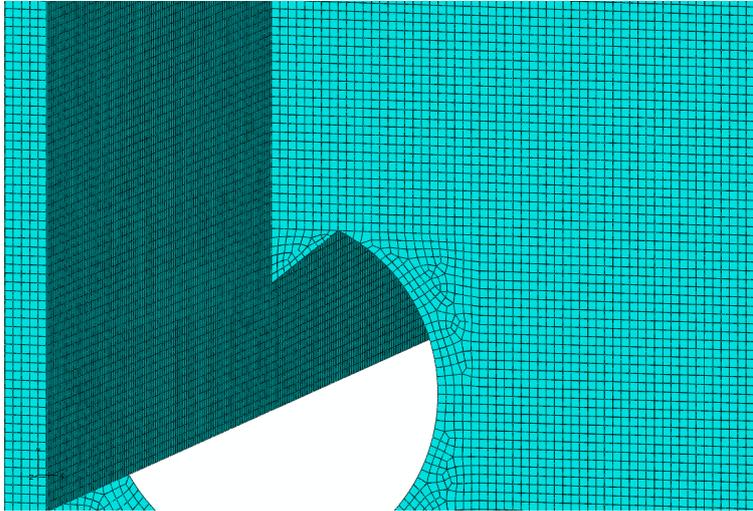


Figure 3-7 Weld ends modelling using shell elements.

In this example the fatigue cracks initiated at the weld toe in the transversal plate which was welded to the longitudinal plate. Since there is a cut-out hole at the end of the weld, the stress distribution was affected by both the hole and weld end so that the shape of the weld end could be changed by introducing a weld end as shown in this figure. Taking advantage of having a smooth transition from the cut-out hole to the longitudinal plate the stress caused by the singularity decreased drastically. A comparative study for various welds modelling techniques inclusive above mentioned technique can be found in Paper I [28].

3.5 Weld modelling using solid elements

Modelling welds with deformable solid elements both in solid and shell element models is used widely because of its simplicity in modelling work and its accuracy in results since the stiffness of welds can be modelled accurately. In solid element models, the geometry and stiffness of the welds in a welded joint can easily be represented by using solid elements, see Figure 3-8.

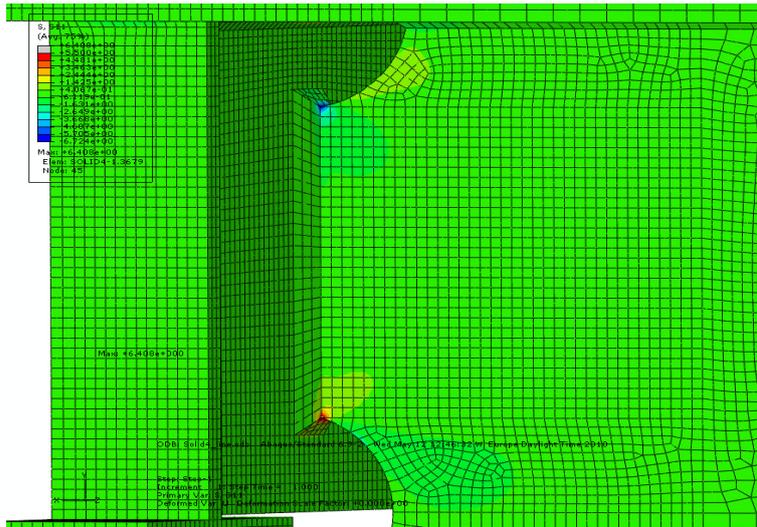


Figure 3-8 Modelling of the welds with solid elements.

When modelling the welds with solid elements in shell element models a special technique is necessary to connect these two different types of elements. The reason for that is the fact that solid elements have three degrees of freedom in each node while shell elements have five degrees of freedom in each node. The bending moments from shell elements need to be transferred to solid elements. There are a couple techniques available to perform it. One method when connecting the solid elements to the shell elements is using Multi Point Constraint (MPC) equations. This method requires generating MPC equations to transfer rotation from shell elements to solid elements which involve time consuming and work effort. However this procedure can be done by FE software automatically.

4 Application of the fatigue assessment methods

In this chapter, a brief summary and the major output of the appended papers are presented. Also some unmentioned outputs in the journal papers are discussed here.

4.1 Modelling and fatigue life assessment of orthotropic bridge deck details using FEM – Paper I

Orthotropic steel bridge decks have been used in both Sweden and all over the world for many years taking advantages of their load-carrying capacity in proportion to their weight. Orthotropic steel bridges have both complex geometry and complex loading configurations producing complicated bridge deck behaviour which is difficult to analyse, design, predict, optimise and control in design phase. The effects of the loading and geometrical conditions, i.e. decks components which are interacting, need to be considered accurately in the stress calculations. Fatigue cracks have been observed in various details of the existing orthotropic steel bridges throughout the world [1-4]. One reason for the observed fatigue cracks except that of their complex geometrical and loading configurations may be assuming a simple beam theory along with the nominal stress method which normally are used for the fatigue design of these details fails in many cases to accurately predict the load effects on these complex details. Defining substantially more detailed and accurate information about the stress state of orthotropic steel deck bridges is therefore extremely laborious without utilizing sophisticated numerical modelling techniques such as a finite element analysis. The utilization of finite element analyses involves more accurate stress estimation, covering both global and local effects at welded joints that are prone to fatigue. Fatigue evaluation techniques for steel bridges with complex details should therefore be based on accurate stress calculations, using the FEM. However, using finite element analysis in the design and analysis of complex structures to compute the finite element based stresses at fatigue critical details requires a good knowledge of the application of the fatigue assessment methods and modelling technique.

In Paper I, the application of the most common fatigue life assessment methods using the FEM is demonstrated on an orthotropic bridge detail. The detail is a welded rib-to-cross-girder connection with cut-out holes. In addition to the structural hot spot stresses which were evaluated both experimentally and numerically using different stress determination procedures, the effective notch stress approach and the nominal stress approach were used to evaluate the fatigue life of the detail.

The easiest way to calculate the fatigue strength of the investigated fatigue critical points as presented in Paper I is using the nominal stress method. The nominal stress at the mid-section considering the net/reduced section due to the cut-out hole of the web of the cross girder was calculated following recommendations from EC3. According to the design code, the equivalent stress – the resultant stress of the normal stress and shear stress – should be used as the governing stress for the fatigue strength capacity of the welded joints. Following these recommendations the calculated nominal stress evaluated by the allowable stress value did not yield appropriate results. When the distribution of shear stresses was examined closely over the net cross-section of the web of the cross girder in the finite element model of the tested specimen, it was obvious that the load from the rib plate was transferred to the web plate of the cross girder locally. The web plate area that was connected to the rib plate

was carrying almost the entire shear force, causing concentrated shear stresses in this region of the web as shown in Figure 4-1. The test specimen is here loaded with a total load of 400 kN. Almost 90% of the load is carried through shear by the part of the web between the two cut-outs.

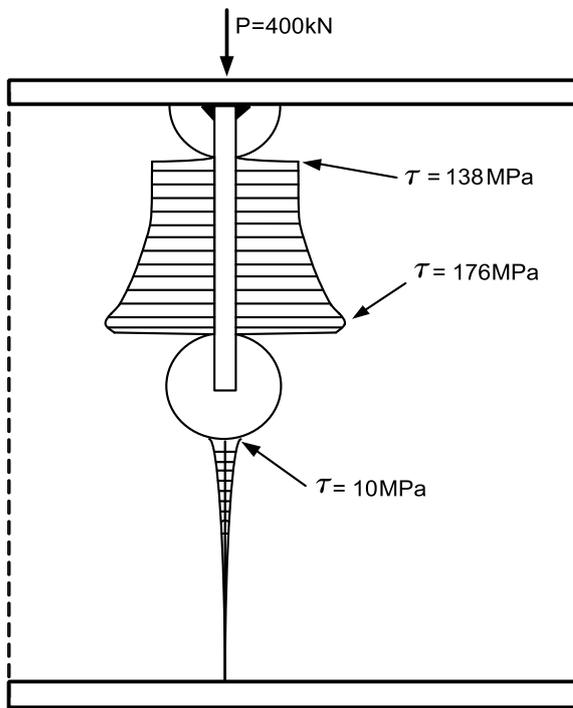


Figure 4-1 Shear stress distribution at the welded section.

If only this part of the web is considered to carry the shear force, the equivalent nominal stress will naturally be higher. It was shown that, in this case, the test result for the specimens is more consistent with the proposed S-N curve (C56) in EC3, as shown in Figure 4-2. A more clear definition for the cross-section in which the stresses will be calculated should therefore be outlined in EC3.

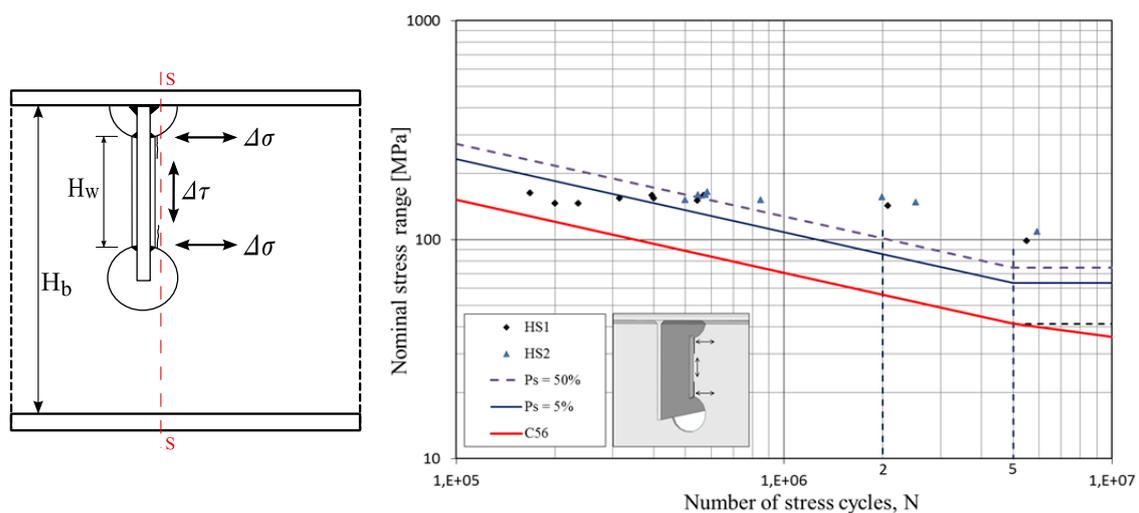


Figure 4-2 S-N diagram using equivalent nominal stress considering shear stress distribution only over the welded section (H_w).

For evaluating the fatigue life of the test specimens according to the structural hot spot stress approach, the evaluation procedure to be followed is more advanced and the finite element modelling requires extra care especially at the region of concern. Of course, there are several ways to model the test specimens, both using solid and shell elements. In the case of shell element modelling, the most important and crucial question was modelling the welds in the studied section even though the method - according to its definition - takes into account of the effect of the geometrical configurations, not the effect of the weld itself in the stress calculations. Shell element models without modelling the welds yielded unrealistic stress values and therefore the most frequently used weld modelling techniques as discussed in Chapter 3 were examined in this study. Here only the weld modelling technique using oblique shell elements is compared with the result from the fine element model in which the welds are not modelled. The result are also compared to that obtained from the solid element model, see Figure 4-3. As shown in this figure, this weld modelling technique yields an accurate estimation of the stress in the hot spots in comparison to the static test result and the solid element model.

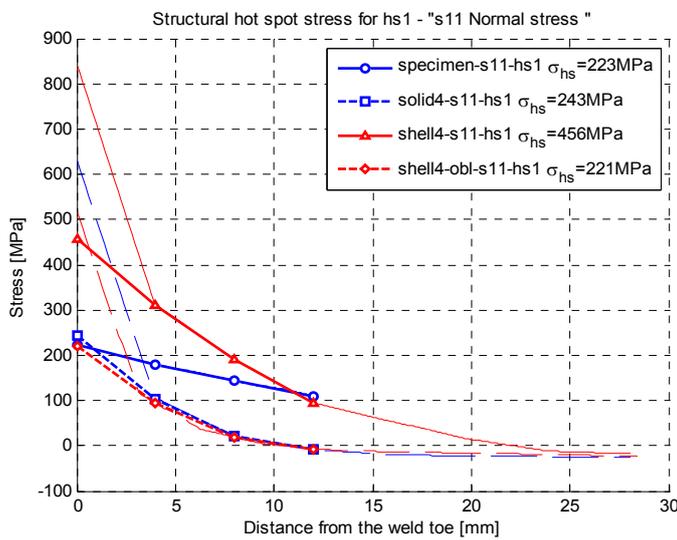


Figure 4-3 Stress distribution in front of the weld toe and hot spot stresses determined by quadratic surface stress extrapolation.

The results from the structural hot spot stress based evaluation of the fatigue life of the test specimens are in in good agreement with the recommended design curve of C90 as shown in Figure 4-4.

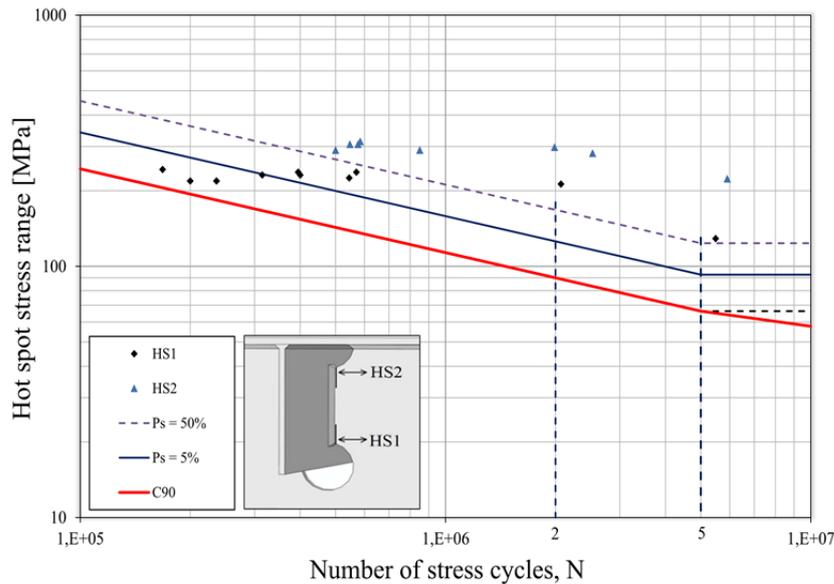


Figure 4-4 Fatigue test results based on hot spot stress approach.

Evaluating the fatigue life of the test specimens according to the effective notch stress can be performed only by means of finite element model. Since very finely meshed models around the critical points are required, the submodelling technique was utilized to determine the effective notch stress at the weld toe. The fatigue life of the test specimens was estimated using the effective notch stress method and the results are plotted in Figure 4-5 using a linear regression analysis with a slope of 3 to compare with the recommended fatigue design curve. As shown in Figure 4-5, the results are above the recommended S-N curve, indicating that the method yields highly conservative results. The recommend design curve is on the safe side. The detail could be categorised as FAT300. This is also confirmed by Park and Miki [28], who investigated the applicability of the notch stress method by studying some existing fatigue tests on details of different types. The authors showed that the results were above the S-N curve of FAT300. According to the effective notch stress method, the welds are recommended to be modelled assuming the worst case scenario which can cause underestimated fatigue life and thus the design stress might not be captured as correctly as possible. On the other hand, the hot spot stress does not take into account the welds in the stress calculations which might be a benefit for the estimation of the fatigue life of welded joints. However, more detailed investigations on this welded detail are needed before a firm conclusion can be drawn in this respect.

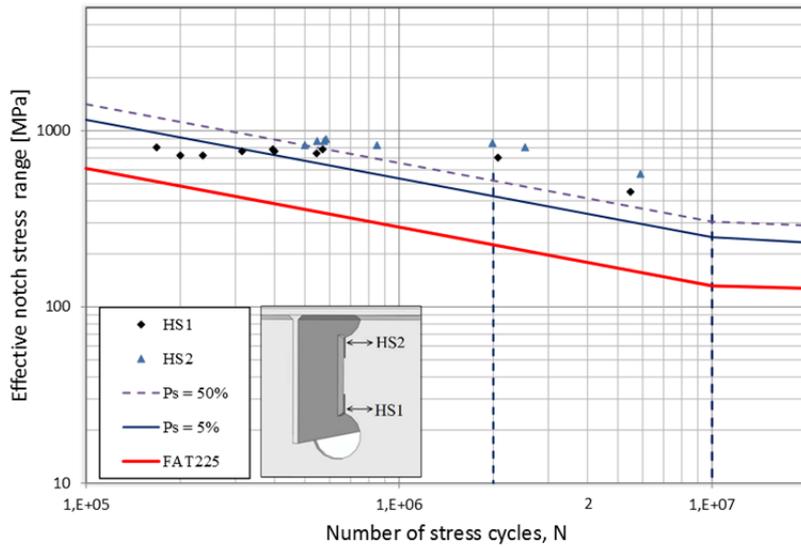
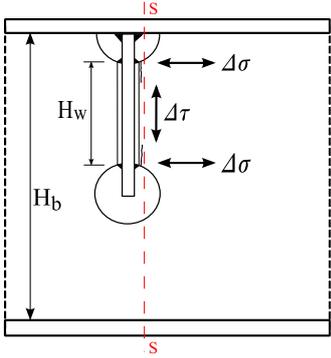
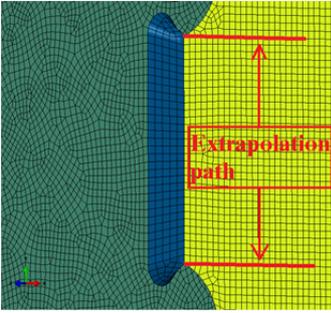
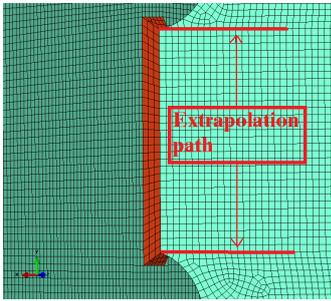
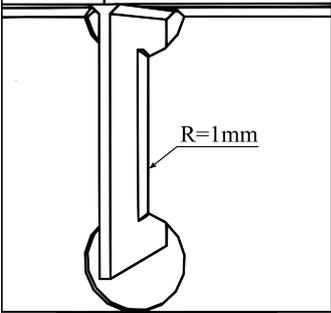


Figure 4-5 Fatigue test results based on the effective notch stress method.

Based upon the results obtained in this study, the recommendations for the application of the three fatigue failure methods for orthotropic bridge deck details are summarized in Table 4-1.

Table 4-1 Recommendations for orthotropic bridge deck details with open ribs.

Method	Structural detail	Description	Requirements
Nominal stress C56		<p>Connection of continuous longitudinal rib to cross girder.</p> $\Delta\sigma = \frac{\Delta M_s}{W_{net,s}}$ <p>Use H_b in cross-section calculations.</p> $\Delta\tau = \frac{\Delta V_s}{A_{w,net,s}}$ <p>Use H_w in cross-section calculations as following: $A_{w,net,s} = H_w \cdot t$</p>	<p>Assessment based on an equivalent stress range, $\Delta\sigma_{eq}$, combining the shear stress range and normal stress range in the web of the cross girder:</p> $\Delta\sigma_{eq} = \frac{1}{2} \left(\Delta\sigma + \sqrt{\Delta\sigma^2 + 4\Delta\tau^2} \right)$
Hot spot stress C90		<p>Connection of continuous longitudinal rib to cross girder.</p> <p>Linear or quadratic stress extrapolation technique can be used to determine the hot spot stress at the weld toes.</p>	<p>Finite element model with 8-node shell elements.</p> <p>The welds should be modelled by using oblique shell elements including the web plate.</p>
		<p>Connection of continuous longitudinal rib to cross girder.</p> <p>Linear or quadratic extrapolation technique can be used to determine the hot spot stress at the weld toes.</p>	<p>Finite element model with solid elements.</p> <p>The welds should be created with flank angles of 45° in FE models.</p>
<p>for quadratic surface stress extrapolation (max. element ≤ 4mm)</p> $\sigma_{HSS} = 3 \cdot \sigma_{4mm} - 3 \cdot \sigma_{8mm} + \sigma_{12mm}$ <p>for linear surface stress extrapolation (max. element ≤ 10mm)</p> $\sigma_{HSS} = 1.5 \cdot \sigma_{5mm} - 0.5 \cdot \sigma_{15mm}$			
Effective notch stress C225		<p>Connection of continuous longitudinal rib to cross girder.</p> <p>Max. Principal stress perpendicular to the weld toe should be used.</p>	<p>The recommended radius of 1mm should be applied along the weld line.</p> <p>Max. size of second order Hex. elements to be used around the hole: $r/4$.</p> <p>Max. size of second order Tex. elements to be used around the hole: $r/6$</p>

4.2 A comparative study on different fatigue failure assessments of welded details – Paper II

The aim of work performed in this part of the study is to investigate the accuracy and benefits of applying more advanced method when assessing the fatigue strength of commonly used welded details in steel and composite bridges. These methods from simplicity to complexity are the nominal stress, the hot spot stress and the effective notch stress method.

The first method is the nominal stress method. This method has been used for the fatigue analysis of steel structures from early on [53, 54]. The second method is the hot spot stress method for which a fictitious stress at a fatigue critical point, the so-called hot spot point, is calculated. This stress is considered to be representative for the fatigue strength of welded details [29, 21, 5]. The calculated hot spot stress at the weld toe is then used together with the recommended S-N-curve to estimate the fatigue life of the investigated detail. The third method, the effective notch stress method, proposed by Radaj [55] is even more advanced. Apart from taking the geometrical changes into account, as with the hot spot stress method, the effective notch stress method also takes the effects of the weld itself into account. The method is based on stress averaging with the Neuber's micro-support theory with a reference radius of 1 mm in plate thickness of 5 mm and above [56, 57]. For smaller plate thicknesses, Zhang [58] has proposed the use of a reference radius of 0.05 mm, which is based on the relationship between the stress intensity factor and the notch stress. It is worth mentioning here that the local stress concentrations are highly dependent on the weld profile in physical models. Therefore very fine mesh is usually required in critical regions in numerical analysis [59].

The fatigue experiment data of five frequently used welded details has been collected from the literature to confirm the performance of the three most frequently used fatigue assessment methods. These details are presented below together with a description of how the evaluation procedure with regard to the fatigue assessment methods has been performed. The results for each detail using these methods are then presented and discussed. The following five welded details have been selected to conduct the study.

- Plate edge details
- Overlapped joints
- Longitudinal attachments
- Cope hole details
- Cover plate details

A large amount of test results were available in the literature. But only those tests where all the information about the specimen like the width, length, thickness, weld size, material data, etc. were available have been selected for re-analysis. This is in order to be able to create well-defined finite element models of the specimens and calculate the relevant stresses accurately. Totally 1500 fatigue test results have been re-analysed.

The stress at the critical points used in the fatigue life calculations according to the three methods is computed for each test series. For the sake of consistency, only 3D solid elements were used in the created finite element models following the IIW

recommendations. Also in all finite element models, the welds were modelled and second order solid elements were used for that purpose. For the determination of the hot spot stress at the weld toe of the investigated details, the quadratic surface stress extrapolation technique recommended by IIW was used. As mentioned earlier, since the determination of the effective notch stress requires a very fine meshed model around the critical point to capture the maximum elastic stress, the sub-modelling technique was used to compute the effective notch stresses.

The fatigue tests collected from the literature contained only the tests performed under constant amplitude fatigue loading. To exclude the beneficial effects of compression stress caused by fatigue loading, the fatigue test specimens subjected to only stress ratios of $R > 0$ were considered. The numbers of cycles to failure are plotted against the computed stresses in a logarithmic scale. The fatigue test results considering the fatigue failure methods were plotted by using linear regression analysis by which the characteristic fatigue strength, the slope of the curve, the standard deviation, etc. can be determined. Finally, the result from the evaluation procedures is compared with the recommended S-N curves given in Eurocode 3 and IIW.

General conclusions

The standard deviations obtained from the three different methods are approximately of the same magnitude, which was unexpected. Since the refined and advanced methods take into account the stress raising effects, it was expected to that these methods would produce smaller scatter. However, variations in welding technique, weld quality and possible size effects may all have contributed to some scatter in test results which is confirmed by the scatter obtained from the hot spot stress method. The scatter from this method for example was the smallest one due to the fact that the method ignores the weld effects in the stress calculations. Despite that the scatter obtained from the evaluation procedures is approximately same, the results for estimating of the fatigue strength of the welded details when using the advanced failure methods especially the hot spot stress method are in better agreement with the fatigue test results in comparison to the nominal stress method.

Another common conclusion for the studied welded details is that the fatigue category of FAT225 recommended by the IIW for the effective notch stress method appears to give reasonable agreement with the fatigue test results even though for some details fatigue strength category of FAT300 can be used.

Plate edge details

The length of the attached plates has a significant effect on the fatigue strength of welded plate edge joints. The fatigue strength of the joints will decrease as the length of the plate increases. This is however not recognized in Eurocode 3 where the fatigue strength of 40 MPa is assigned to this detail irrespective of the length of the attached plate. This recommendation appears to be rather conservative considering the results from the current evaluation.

IIW recommends using fatigue strength of 90 and 100 MPa depending on the length of the attached plates for the hot spot stress method while in Eurocode 3, there is no recommendation given. According to the definition of the method, only one S-N curve should be sufficient for this detail. The reason for the two S-N curves is that the attached plate might become more load-carrying with increased length.

Overlapped joints

A distinct difference in fatigue strengths could be seen for this detail depending on the failure location. The fatigue strength was higher when the fatigue failure occurs in the main plate. This difference is also recognized in both the Eurocode and in the IIW.

The Eurocode and IIW recommend using fatigue strength of 90 MPa when using the hot spot stress method. Based on the current results this seems to be inappropriate for cracking in the main plate. It provides however a better estimate for cracking in the cover plate.

Longitudinal attachment

The fatigue strength for this type of detail is a function of the length of the attached plates. This has been recognized in both Eurocode 3 and IIW. The results from this investigation showed that Eurocode 3 provides a good representation of the fatigue strength of this detail. However, the result for the 50 mm length of the attached plates appears to be non-conservative. The IIW recommendations for the failure in the main plate with the present test results are more consistent with the test results, except the attached plate length of 200 mm.

Based on the present results, fatigue class of C90 should be more consistent with the test results instead of the recommended fatigue strength curve of C100 when using the hot spot stress method.

Cope-hole details

For cope-hole details shear stress has quite an adverse effect on the fatigue strength. This effect has been recognized by the IIW recommendations where the fatigue strength of this detail is a function of the ratio of shear (τ) to normal (σ) stress. In Eurocode 3 however, one C-class is assigned irrespective of the τ_a/σ_m -ratio.

Based on the result from this study, it can be seen that FAT100 recommended by IIW for non-load carrying welds for the hot spot stress method is not consistent with the test results. However, if the results from detail 4D (see Table 2-9 in Paper II) which undergoes high τ_a/σ_m ratio are excluded, FAT100 appears to be a reasonable representation.

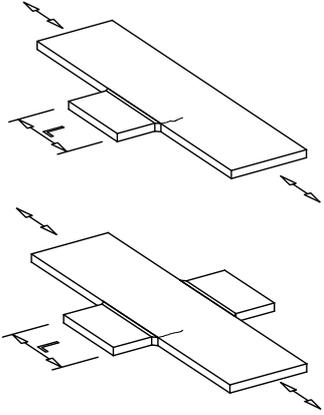
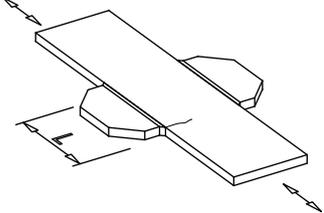
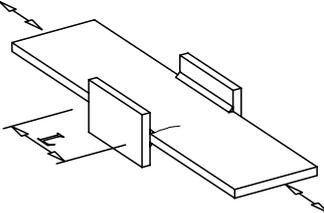
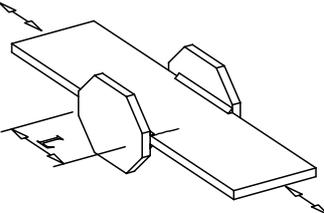
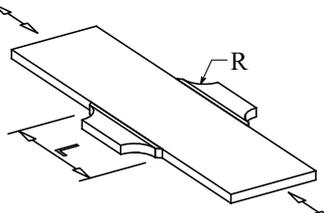
Cover plate details

For this detail, the fatigue strength is dependent on the ratio between the thicknesses of the cover plate to that of the main plate. It increases as this ratio decreases. This effect has been recognized by both Eurocode 3 and IIW recommendations. The results in this study showed that the recommendations given in Eurocode 3 is more consistent with suggesting either of two values, for the ratio above or below 1. In IIW there are several intervals given. The results from the evaluation of the fatigue test also indicate that the fatigue strength is independent of the shape of the weld end.

The recommended fatigue strength of 100 MPa in EC3 and IIW for the hot spot stress method appears to give reasonable agreement with the results from the current evaluation.

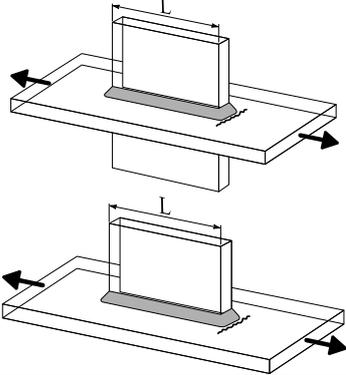
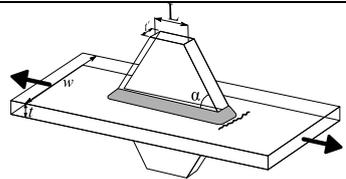
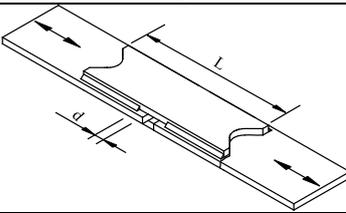
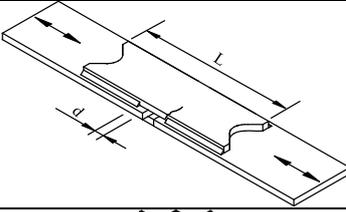
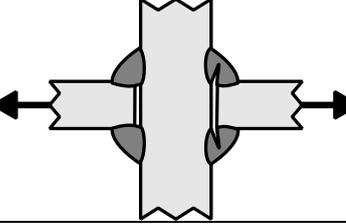
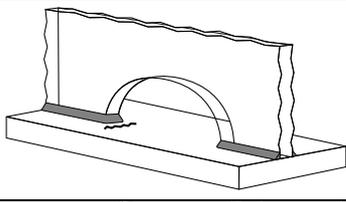
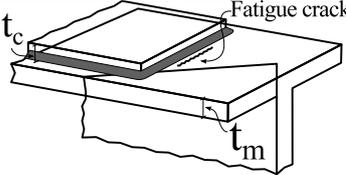
Based upon the results obtained in this study, the following recommendations as shown in Table 4-2 and Table 4-3 regarding to the different fatigue life assessment methods can be presented.

Table 4-2 Recommended fatigue strength class for different type of plate edge joints.

Structural detail	Fatigue life assessment method				
	Nominal stress		Hot spot stress		Effective notch stress
	$L \leq 100$	C63	$L \leq 100$	C100	
	$100 < L \leq 200$	C50	$100 < L$	C90	
	$200 < L \leq 300$	C50			
	$L \leq 100$	C71	$L \leq 100$	C100	
	$300 < L$	C56	$100 < L$	C90	
	$100 < L$	C63*	C100		
	$100 < L$	C50**	C100		
	$\frac{1}{6} \leq \frac{R}{L} \leq \frac{1}{3}$	C63	C100		

*Without round weld end, **with round weld end

Table 4-3 Recommended fatigue strength class for various welded joints.

Structural detail	Fatigue life assessment method			
	Nominal stress		Hot spot stress	Effective notch stress
	$L \leq 150$	C71	C90	C300
	$150 < L$	C56		
	$150 < L$	C71	C80	
	$\alpha < 45^\circ$ $\alpha > 45^\circ$			
	$100 < L \leq 120$ All t	C56	C80	
	$120 < L$ All t	C56		
	C45 All configurations		C100	
	C36		N/A	
	Correction factor for $\tau_a/\sigma_m \geq 0.2$	C71	Correction factor for $\tau_a/\sigma_m < 0.2$ C90	
	$t_c/t_m < 1$ $t_m \leq 20$	C56	C100	
	$t_c/t_m \geq 1$ $t_m \leq 20$	C50		

5 Conclusions

5.1 General conclusions

The conclusions based on the work performed in this study are divided into two parts. In the first part, the conclusions and recommendations for the fatigue assessment of orthotropic bridge deck details are given. In the second part, the conclusions for the studied welded details for the three fatigue assessment methods are presented.

The application of the investigated fatigue life assessment methods on an orthotropic bridge details showed that the application of local approaches for the estimation of fatigue life of these complex details, yields more accurate results. When using the nominal stress method, special attention should, however, be paid to the distribution of shear stress over the welded section. Based on this investigation, the following recommendations for the application of the fatigue assessment methods and finite element modelling techniques can be presented:

- The nominal stress method provides good agreement with the test results only when the shear stress distribution over the welded section and the normal stress distribution over the girder section are considered correctly. A more clear definition for critical cross-sections where the stress calculations would be performed needs therefore be outlined in Eurocode 3.
- When using the structural hot spot stress approach, it is essential to correctly represent the welds in complex details with cut-out holes. For the studied welded joint, fine meshed solid element models yield more representative stress ranges at the hot spot points. The use of solid element models including the welds to evaluate the structural hot spot stresses for welded details with cut-out holes is therefore recommended. For models incorporating shell elements, it is important to represent the welds in complex welded joints, not only in term of stiffness (thickness) but also with regards to shape (geometry). The study shows that this can be achieved in the best way by using oblique shell elements.
- The straight stress evaluation path yielded more reliable results and should be used to determine the structural hot spot stresses. The structural hot spot stresses calculated without any extrapolation (i.e. using the 0.5t stress derivation procedure) also yield good results in comparison with the results calculated using the surface stress extrapolation procedures.
- The Battelle structural stress method produces a good result only for HS1 (hot spot point 1), while the method underestimates the stress concentration at HS2 (hot spot point 2). This discrepancy at hot spot point 2 needs to be examined in more details.
- The 1mm stress method produces accurate results for both investigated hot spot points. However, the method requires fine meshed FE models.
- Using smaller tetrahedral solid elements facilitates the modelling work and the differences between the results when using hexahedral and tetrahedral elements are very small. However, the modelling work when applying the effective notch stress approach requires much more effort than the work involved in using the structural hot spot stress approach.
- Based on the experience obtained from the modelling effort in this study, the effective notch stress method appears to be more suitable for evaluating the components of small structures such as trucks, cars and machineries. The

structural hot spot stress approach as applied from 1960s to until now is more applicable for larger structures such as offshore, ships and bridges in which the effect of the weld in the stress calculations is almost unimportant.

- Despite the hot spot stress method is a mesh-sensitive method when using the FEM the accuracy of results can be verified by the measured strains if it is available. In complex welded details, it is essential that the accuracy of the fatigue life estimation method should be verified by the measured strains in fatigue critical points. The essential of using strain gauges in complex welded details on fatigue tests are substantiated in Paper I. The measured strains at hot spot point 2 were lower than the measures strains at hot spot point 1, which was opposite results obtained from the FE analysis.

The conclusions for the studied welded details for the three fatigue assessment methods can be drawn as following:

- The standard deviations obtained from the three different methods are very similar, which was unexpected. Since the refined and advanced methods take into account the stress raising effects, it was expected to that these methods would produce smaller scatter. However, variations in welding technique, weld quality and possible size effects are all expected to contribute to some scatter in fatigue test results. The scatter of the test results when evaluated with the hot spot stress method was the smallest one due to the fact that the method includes the macro geometrical effects and ignores the weld effects in the stress calculations. However, despite the fact that the scatter obtained from the evaluation procedures is approximately same, the results for estimating of the fatigue strength of the welded details when using the advanced failure methods especially the hot spot stress method are in better agreement with the fatigue test results when compared to the conventional nominal stress method.
- The results from estimating all fatigue test points for the welded plate edge joints based on the hot spot stress method showed that a single fatigue design curve of C100 can be used irrespective of the length of the attached plates. However, when the length of the attached plates is considered, the results showed that the length of attached plates has a clear effect on the fatigue strength of these welded details. This is due to the fact that the longer attached plates are the more they act as part of the flange/main plate and thus becomes load-carrying to some extent. Considering the results obtained for this detail in this study, the hot spot stress based fatigue S-N curve of C90 can be used for plated edge details with the length of attached plates longer than 100 mm and C100 for plated edge details with the length of attached plates of 100 mm or shorter.
- Based on the results obtained in this study, generally the hot spot stress based fatigue S-N curve of C90 can be used for details with load-carrying welds and C100 for details with non-load-carrying welds except some cases as discussed earlier and presented in Paper II.
- Another important conclusion for the studied welded details is that as a lower bound fatigue strength of FAT225 recommended by the IIW for the effective notch stress method appears to give reasonable agreement with the fatigue test results even though for some welded details fatigue strength category of FAT300 can be used.

5.2 Outlook for future research

The results from the presented study showed that an accurate estimation of the fatigue strength of welded details can be independent of the method to be utilized. It is therefore more research needed to confirm the accuracy of the methods on other welded details.

The results from the investigated details showed that some welded details might be classified as C300 when using the effective notch stress method. More detailed investigations on these welded details are needed to draw a firm conclusion or to give such a recommendation.

As mentioned in earlier, 1mm stress method takes into account the thickness effect very well even though the method requires finely meshed models around the critical regions. This method can be also applied the studied welded details in Paper II and also other welded details to verify the accuracy of the fatigue assessment methods and the thickness correction factor

In complex details, more accurate estimation can be obtained applying crack propagation analysis based fracture mechanics. The orthotropic bridge deck welded details can be analysed using this approach.

As mentioned in the previous chapter, the Battelle structural stress method yield a good result only for HS, while the method underestimated the stress concentration at HS2. This discrepancy at hot spot point 2 should be examined to the applicability of the methods for complex details in fatigue life analysis.

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