RESIDUAL STRESS ANALYSIS AND FATIGUE ASSESSMENT OF WELDED STEEL STRUCTURES

A Thesis Submitted

In partial fulfillment for the award of the degree of

Master of technology

In

Production Engineering

SUBMITTED BY

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(2K20/PIE/02)

UNDER THE GUIDANCE OF

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May 2022

CANDIDATE'S DECLARATION

I, AKSHAY SHARMA, hereby certify that the work which is being presented in this thesis entitled "RESIDUAL STRESS ANALYSIS AND FATIGUE ASSESSMENT OF WELDED STEEL STRUCTURES" being submitted by me is an authentic record of my own work carried out under the supervision of Dr. M.S. Niranjan Associate Professor, Department of Mechanical Engineering, Delhi Technological University, Delhi.

The matter presented in this thesis has not been submitted in any other University/Institute for the award of M.Tech Degree.

AKSHAY SHARMA

(2K20/PIE/02)

CERTIFICATE

I, AKSHAY SHARMA, hereby certify that the work which is being presented in this thesis entitled "RESIDUAL STRESS ANALYSIS AND FATIGUE ASSESSMENT OF WELDED STEEL STRUCTURES" in the partial fulfillment of requirement for the award of degree of Masters of Technology in Production Engineering submitted in the Department of Mechanical Engineering, Delhi Technological University, Delhi is an authentic record of my own work carried out during a period from July 2021 to May 2022, under the supervision of Dr. M. S. Niranjan Associate Professor, Department of Mechanical Engineering, Delhi Technological University, Delhi.

The matter presented in this thesis has not been submitted in any other University/Institute for the award of M.Tech Degree.

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ACKNOWLEDGEMENT

It is a matter of great pleasure for me to present my dissertation report on "RESIDUAL STRESS ANALYSIS AND FATIGUE ASSESSMENT OF WELDED STEEL STRUCTURES". First and foremost, I am profoundly grateful to my guide Dr. M. S. Niranjan Associate Professor, Mechanical Engineering Department for their expert guidance and continuous encouragement during all stages of thesis. I feel lucky to get an opportunity to work with them. Not only understanding the subject, but also interpreting the results drawn thereon from the graphs was very thought provoking. I am thankful to the kindness and generosity shown by them towards me, as it helped me morally complete the project before actually starting it.

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Finally, and most important, I would like to thank my family members for their help, encouragement and prayers through all these months. I dedicate my work to them.

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ABSTRACT

The S-N curves with their related fatigue classes are used for fatigue design and analysis on steel and composite bridge structures utilizing nominal stress approach. It's possible that this approach will overestimate the impact of loads on structural components because there are so many different structural elements and loading scenarios to consider these days. When the nominal stress can't be simulated due to geometry or loading complexity, or when there isn't a classified detail to compare it to design codes, hot spot was established to properly assess the influence of loads on the fatigue strength of welded steel structures. The benefits of this method's long history of use in fatigue design and analysis are yet to be realized by steel and composite structures.

The study utilizes finite element approach for calculation of design stresses, for fatigue life estimation. First of all a comparative experimental study is done between global and local stresses so as to give insight why local approach would be beneficial. Thereafter using different weld modelling techniques a finite element analysis for local life assessment methods such as hot spot stress approach, for complex steel structure is performed to verify its applicability.

From the experimental comparative study, the variation between the results of global and local life assessment methods was not very much which was unexpected, but still the results showed that the local stress life assessment approach was more suitable for study. For FEA solid weld models yielded more realistic results, but some discrepancy was found in hot spot 2 which needed further investigation.

Keywords: hot spot stress approach, finite element method, nominal stress approach, welded steel structures.

Chapter 1

1. Introduction

Complicated and progressive local damage is caused by a variety of reasons such as the quantity and frequency of loads that create fluctuating stress, environmental factors, geometric complexity, defects in material, and discontinuities. There are many factors that contribute to fatigue failure. It is difficult to precisely evaluate the effects of load on the fatigue strength of structural elements due to the complexity and irregularity of steel structures. It's difficult to anticipate the stress effects on welded details on big steel structures with intricate properties, such as orthotropic bridge decks.It is possible to better predict the implications of a failure if the geometry and/or loading conditions are taken into account. [1] For a wide range of bridge types and characteristics, a fatigue analysis found fatigue damage cases. Weldments in steel structures may be assessed using innovative methods that produce an accurately computed fatigue design stress for use in load testing.

For fatigue design and analysis, utilizing the finite element approach allows for a more precise assessment of the impacts of the loads on the researched details. A bridge's shape and loading circumstances, as previously mentioned, contribute to the bridge's complicated deck behaviour. Stress states in steel and composite bridge constructions are hard to determine with any certainty without utilizing finite element method. An effective finite element model must not be compromised for time in the process of modelling. The anticipated stress accuracy can be reduced by simplifying the finite element models, which could lead to an over or underestimation of fatigue life. Volume element-based models are often accepted to be the most accurate representations of the real thing because of their ability to accurately recreate the geometry and to accurately represent the stiffness. When using well-built finite element models, it is not always evident how to accurately quantify and extract stresses for a specific fatigue assessment method. Since the stresses collected by improved techniques are generally located in a location with significant strain gradients, known as stress singularities, the FEA results may be particularly sensitive to finite element modelling methodologies.

The resultant strains might be rather varied, based on the nature and size of the elements. The development of local stress approaches such as the hot spot stress method, the effective notch stress method, and crack propagation analysis utilizing fracture mechanics has been made possible by the use of the finite element methodology in steel structural fatigue engineering. Many new uses for these approaches have evolved in the previous few decades. Stress impacts (i.e. stresses) can be quantified in complicated detail with more precision using refined and local stress concepts that take into account the effects of multiple stress producing sources. When it comes to the design and analysis of tubular structures for fatigue, the hot spot stress method has not been frequently used in bridges.[2]. Several ideas for fatigue assessment methods have been provided in various design codes due to the significant influence that modelling methodology has on the obtained findings. But many complicated bridge aspects, such as orthotropic deck details, are not addressed by fatigue design codes and standards' modelling and stress calculation suggestions. For the implementation of the hot-spot stress approach, Eurocode 3 [3] gives only a table of detail categories and no recommendation on how to model or determine hot spot stress.

Chapter 2

Literature Review

All of these elements have a part in fatigue failure, which is a complex and ongoing kind of local damage induced by a variety of factors. There are many factors that contribute to fatigue failure. It is difficult to precisely evaluate the effects of load on the fatigue strength of structural elements due to the complexity and irregularity of steel structures.

It is feasible to examine these consequences more accurately using a refined or local failure assessment technique that takes into consideration the geometry and/or loading conditions.

The use of the finite element technique in fatigue design of steel structures led to the development of local stress ideas such as the hot spot stress approach, effective notch stress approach, and crack propagation analysis using fracture mechanics.

Hobbacher et al. discovered that when using the nominal stress method, the main component's geometrical irregularities (such as cut holes and bends/curves) must be taken into account when performing fatigue stress calculations, even though the welded connection has no effect on the local stress distribution.

Welding details that are subjected to hot spot stress can be analysed with reduced S–N curves by Niemi and colleagues. Only weld toe fatigue failures can benefit from this technique. Fatigue stress may be assessed at ‘‘hot spot’‘areas using this method.

Modelling, extrapolation, and the types of hot spot locations are not covered by Eurocode 3's structural hot spot stress procedures. This is an alternative method for evaluating fatigue.

A fictional radius of one millimeter was Radaj's idea for applying the Neuber Rule's micro-support theory to plates having a thickness of five millimeters or more for effective notch stress approach.

Because of the relationship between the stress-intensity factor and the notch stress, Zhang et al. advised a fictional radius of 0.05 millimeters for measuring notch stress effectively.

When determining the effective notch stress from the maximum primary stress, Sonsino et al. suggest using a FAT225 fatigue design curve, and FAT200 when utilising von Mises stress. In the case of brittle materials like cast iron, the von Mises stress criteria is utilised, while the maximum main stress is suggested for multiaxial stresses and ductile materials like structural steels.

Fayard et al. proposed a weld modelling approach using rigid links. The stress in the weld toes may be estimated with the use of this method. An crucial component of this technique is to model how welded connections behave in terms of local stiffness

2.1 Research Gap

On the basis of literature review the following research gaps have been identified:

- Local life assessment methods such as hot spot stress lacks research in regard to complex steel structures.
- Research on finite element analysis for local life assessment methods for complex structures is scarce.

2.2 Objectives of the work

- To perform a comparative study between global and local life assessment methods.
- To study different weld modelling techniques used for modelling welded structures.
- Using local life assessment methods to accurately compute load effects in a complicated steel structure.
- To apply finite element analysis on a complex steel structure for local stress life assessment and demonstrate its application.

1.3 Methodology

- The first step was to analyse the current guidelines and design codes for fatigue evaluation methodologies in the literature. There were no proposals for enhanced life evaluation methodologies in Eurocode 3.
- Second, a database of fatigue testing was compiled from published literature for a selection of chosen welded details.
- Three-dimensional finite-element models were built and analysed for the fatigue study of welded steel structures in order to determine the optimal meshing quality. The evaluation findings were compared to IIW and Eurocode fatigue strength S-N curves where they were available.
- Test results were utilised to evaluate the accuracy of results obtained using various fatigue life assessment methods for welded details studied.

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2.4 Limitations

As-welded joints are the only type of welded joints that were examined in this study. This study does not include treated welded joints or high-strength steels. Excluding compression stress's positive effects, only specimens with stress ratios higher than zero are gathered for fatigue testing. The data used in this investigation includes the results of fatigue tests performed under constant amplitude fatigue loading.

Only the weld toe showed failure in the fatigue tests performed utilising life assessment methods.

According to the IIW and Eurocode 3 criteria for design stresses and suggested fatigue strengths, the fatigue test specimens in this study were modelled using finite elements.

1.4 Outline of the thesis

Chapter 2 introduces the various approaches for assessing fatigue. This chapter briefly focuses on various methods. A welding detail is evaluated to demonstrate the methods' utility and dependability. The conclusions are confirmed by the findings of fatigue tests in the literature.

Weld modelling approaches that are widely used in this study are covered in Chapter 3.

All of the case studies in the appendices are summarised in Chapter 4. Here you'll find advice on anything from modelling framework to fatigue strength categories.

Chapter 5 is the concluding chapter in which the findings obtained from the evaluations are given. There are also suggestions for further studies.

Chapter 3

Experimental Methodology for various assessment methods

Steel structures subjected to fatigue stress can be assessed for their fatigue life in a variety of ways. For steel constructions, strains, stresses, and stress intensity parameters are commonly used to predict life expectancy. You can use one of four common fatigue life evaluation methods to estimate steel structures like bridges and ships. Global and local are the two broad groups into which they belong. The global approach is the simplest and most widely utilised method, as its name implies. A range of local approaches, including as the hot spot stress method, effective notch stress method, and linear elastic fracture mechanics, may be used to investigate crack propagation.The S-N curve classification is used by all three ways to estimate overall life, while fracture mechanics principles are used by the fourth approach to measure crack development independently of any S-N curve. As a starting point, these approaches utilise the linear elastic theory or numerical methods like as FEM or BEM. However, this study does not include the fracture propagation method.

There must be a thorough understanding of the FEM's concepts and the fatigue assessment methodologies in order to apply it effectively for calculating design stress information needed for fatigue life calculations. FEA stresses are highly dependent on the finite element modelling approach because of the strong strain gradients, or stress singularities, in the area where stresses are estimated using FEA [4-6]. Useful stress parameters for fatigue assessments are shown in Figure 1.

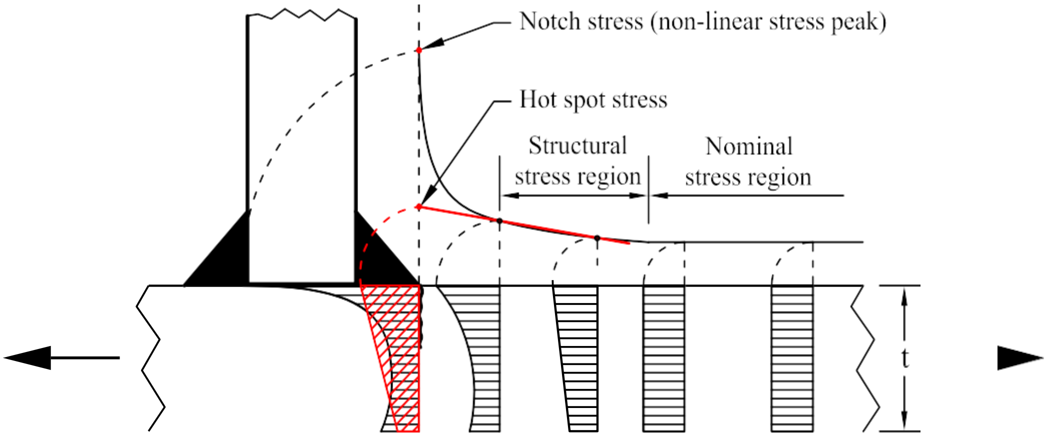


Figure: 2-1 Distribution of stress over the thickness of the plate and along the surface of the weld.[5]

The aim of this chapter is to explain how fatigue testing procedures that are typically utilised may be applied to a particular welded detail.

Using fatigue-loaded structures like gusset plates on bridge beams (see Figure 2-2), the differences between two types of plate edge welded joints may be shown. [7-19] This joint has been subjected to a series of fatigue tests to ensure that the methods are functioning correctly. Material used is grade A corten mild steel. Table 2-1 shows the variance in dimensions and the amount of experiment data. An evaluation of the acquired fatigue test results was conducted using stress calculations based on fatigue life assessment methodologies for the researched details.

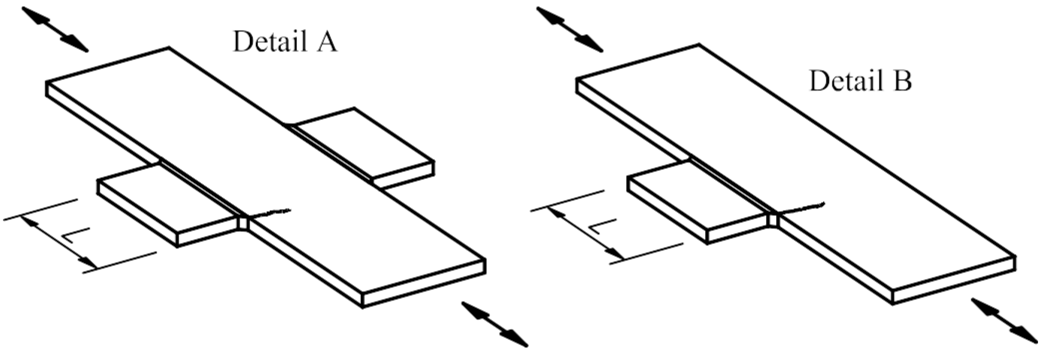


Figure 2-2 Plate edge details.

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	24	10-14	80-120	10-14	50-400
Detail B	7	10-14	90-110	10-12	50-450

The most significant factor affecting steel structural fatigue strength is fatigue loading [20]. Failure loading of structural components occurs when applied loads fluctuate, such as pressure variations, vibration, temperature fluctuations and wave load. This leads to fluctuating or repeated stress. Figure 2-3 shows the relevance of stress range and stress ratio in estimating fatigue damage. Fatigue loading can be divided into two categories: constant amplitude (CAFL) and variable amplitude (VAFL). There were only CAFL-based fatigue tests gathered from the scientific literature.Stress ratio R > 0 was used in the fatigue tests to eliminate the favourable benefits of compression stress.

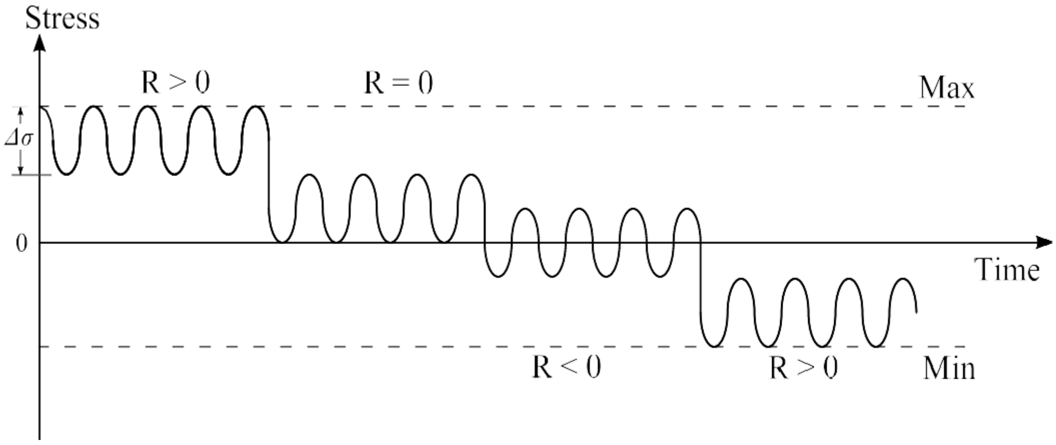


Figure: 2-3 Different forms of constant amplitude fatigue loads[5].

3.1Nominal stress approach

The fatigue life of steel structures is typically evaluated using the nominal stress approach. These results are based on an average stress calculated from measurements taken at various points in the cross section under discussion. In stress calculations, welds and connecting plates have an impact on local stresses that are not included. Welded connections are ignored in fatigue stress calculations, but geometrical configurations or flaws in a primary component must be considered in the context of the fatigue design. Stress distribution in a fabric's cross section can be greatly affected by geometric configurations and abnormalities such as cutout perforations, discontinuity of cross-section or curve/bend in a beam.

Nominal stress is used to classify fatigue in most design guidelines and recommendations. The nominal stress technique is no longer applicable if a nominal stress cannot be determined or if a design category is available for a more complicated geometries. It is important to develop new method to estimate a product's fatigue life.

The force divided by the section area can be used to estimate plate edge stress in accordance with the linear elastic beam theory (see Figure 2-4 for an instance). Nominal stress techniques need the use of S-N curves or fatigue classes specified in design standards. Despite the fact that plate length has a major impact on the amount of stress concentrations at the plate end, i.e. at formation of weld cracks, Eurocode 3 recommends that this feature be allocated to the C40 detail category.

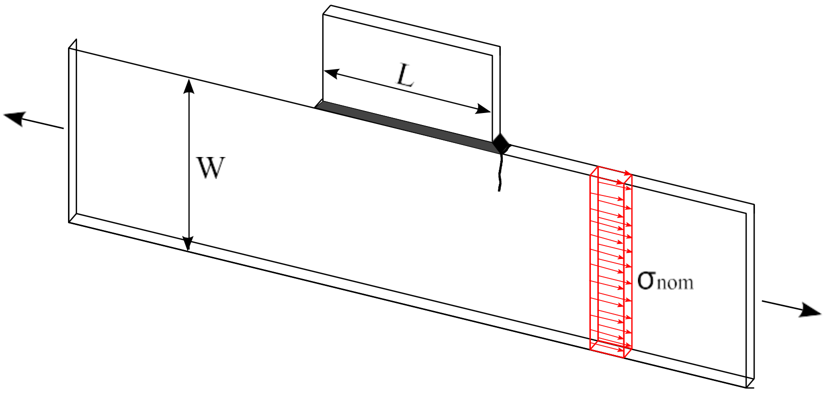


Figure 2-4 For a plate edge joint, the nominal stress is defined[5].

The analysis of fatigue test results based on the nominal stress range is shown in Figure 2-5. On executing a linear regression analysis with a free slope, the standard deviation for all of the experiment's data points is 0.211. The average value of 55.3 MPa is well below the mean value of 75.8 MPa. Average pressure is 75.8 MPa, and the typical level is 60.3 MPa, according to an increase in the standard deviation of 0.223. It appears that the recommended fatigue class is conservative, according to this evaluation study.

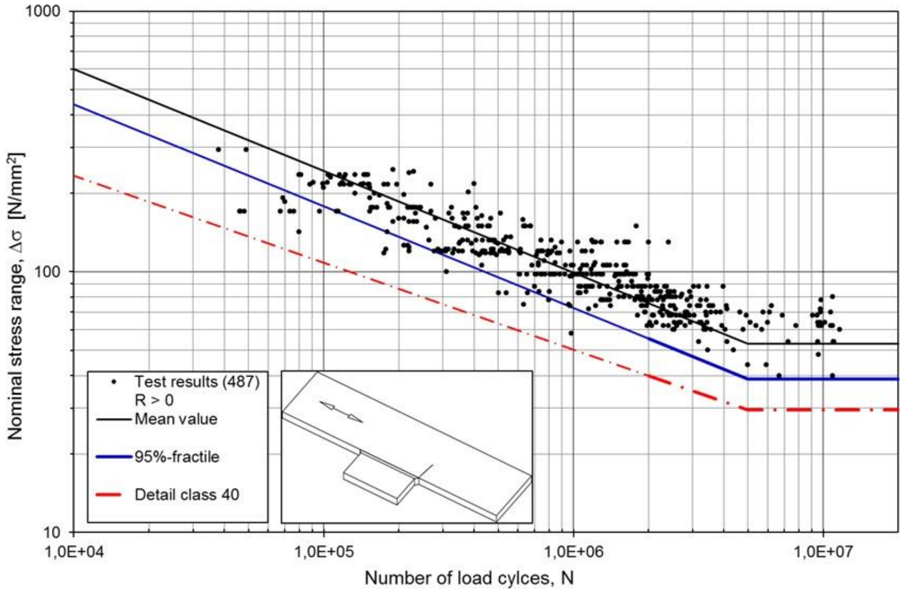


Figure 2-5 Fatigue test results for plate edge details based on nominal stress method.

The results of fatigue tests were investigated utilizing the nominal stress technique in order to highlight the discrepancies in the strength of plate attachments. Table 2-1 summarises the findings of the research. When using the nominal stress technique to evaluate fatigue life, the length of the connecting plates might be considered. The fatigue strength recommendations curve is quite conservative for lengths under 100 mm.

Table 2-2 Statistical evaluation of fatigue test points.

Evaluation method		**No. of specimens**	**St. dev.**	**$\Delta\sigma_{mean}$** [N/mm2]	**$\Delta\sigma_C$** [N/mm2]
Nominal stress	All specimens	31	0.223	80.0	60.3
	$L \leq 100$	18	0.198	82.2	64.0
	$100 < L \leq 200$	9	0.240	67.2	47.0
	$200 < L \leq 300$	4	0.230	65.2	47.7

3.2Hot-spot stress approach

The fatigue strength of welded structures can be evaluated using the hot-spot stress approach when the nominal stress cannot be calculated due to geometry or loading concerns. Pressure vessels and welded tube couplings have been designed using this method since the 1960s. It was then utilised to successfully weld plated structures using the approach. [5, 6, 22, 23] spring to mind. The implementation of a hot spot stress technique to evaluate the fatigue life of welded complex structures is becoming more widespread. The hot spot stress approach, which is used to account for fatigue stresses, only considers the weld joint. This approach reduces the amount of S–N curves necessary to calculate the fatigue life of welded components. However, weld toe fatigue failures are only covered by this method. According to Niemi and Fricke , it is possible to assess fatigue stress by employing the ‘‘hot spot‘‘ positions[5, 25, 26, 27]. IIW rules now provide an alternate method for assessing fatigue life, which incorporates two new fatigue critical hot zones. The total membrane and bending stress can be used to approximate these two hot spots (a and c) in the thickness direction, but the stress distribution at the point ʻʻbʻʻ must be evaluated along its edge. The computed stress at a site such as this is referred to as a ʻʻhot spot stressʻʻ or a ʻʻstructural hot spot stress,ʻʻ depending on context.

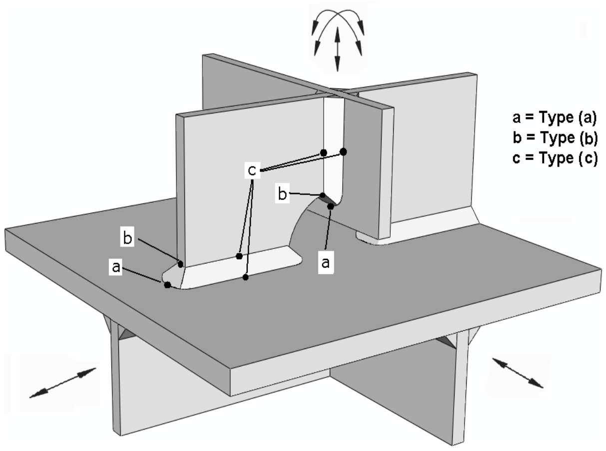


Figure 2-6 Three types of fatigue critical hot spot point at the weld toes [28].

The structural hot-spot stress approach is increasingly being utilised to evaluate the fatigue life of steelwelded structures, and the method's application has grown dramatically since it was originally utilized for fatigue analysis using finite element modelling (FEM). Because structural hot spots are often discovered in places with substantial strain gradients, i.e. stress singularities, FEA findings are mesh sensitive. The results may vary significantly depending on the kind and amount of components utilised, as well as the method used to extract the hot spot stress values. To get a stress value that can be connected to the detail's fatigue strength, stress assessment techniques are necessary. The IIW includes a complete set of rules and processes for applying structural hot spot stress, including reference points, size and element type[21]. As an alternate technique of measuring fatigue life, Eurocode 3 [3] contains the idea. The code, however, provides no advice or instructions on how to apply the hot spot stress approach, including modelling and extrapolation methods, as well as the sorts of hot spot sites, save from a few structural elements and a fatigue curve.

The precise position of structural hotspots could be determined using FEA data. To get the structural hot-spot stress at the toes of weld, Figure 2-7 depicts a linear surface stress extrapolation using two reference sites. The alternative method, quadratic surface stress extrapolation, determines the structural hot-spot stress using three reference points. Fricke [29] recommends using a factor of 1.12 to estimate the hot spot tension at the weld toe. [30].

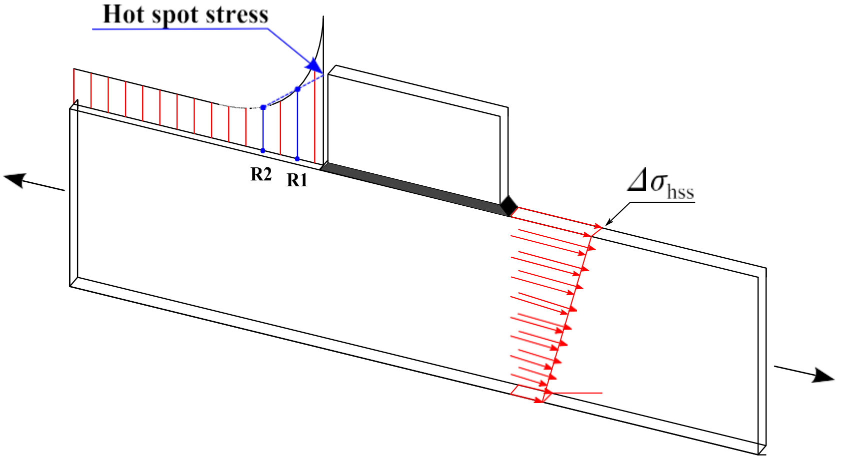


Figure 2-7: In a plate edge joint, a hot spot stress is defined at the weld toe[5].

Structural hot-spot stress analysis relies on meshes, which have a fundamental flaw.For surface stress measurements to be appropriate components, finite element models must be constructed and produced in compliance with the guidelines. For example, FE models in the pre-processing phase must be generated based on post-processing requirements. For the most parts, it's a moment process to model in FE. Because it can only detect weld toe cracks, the hot-spot stress approach has a limitation[31, 32].

In order to conduct hot spot stress investigations on fatigue of welded structures, models are usually built by assuming an ideal structural geometry that excludes misalignments and faults. To account for misalignments in fatigue design calculations, stress amplification factors accessible in various design rules and regulations or abnormalities input into models can be utilized.

An alternate, ‘‘mesh-insensitive’‘ technique of detecting hot-spot stress has been developed by researchers. To better correlate fatigue findings from varied sizes and connection types into a single hot-spot stress S–N curve, Battelle Institute researchers lead by Dong developed the linearized structural stress distribution approach [33-35]. The Battelle structural stress approach shown in Figure2-8, for example, uses FEA data and basic structural mechanics concepts like force-moment balance in sections throughout the thickness of the plate to forecast structural stresses at the weld toe. The structural stress at the weld toe may be estimated at a short distance, δ1, from the weld toe and described as the superposition of membrane and bending components due to equivalent stress conditions on the reference planes.. The membrane and bending stresses must be included in Eq.1 for calculating the linearized equilibrium stress at the weld toe.

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

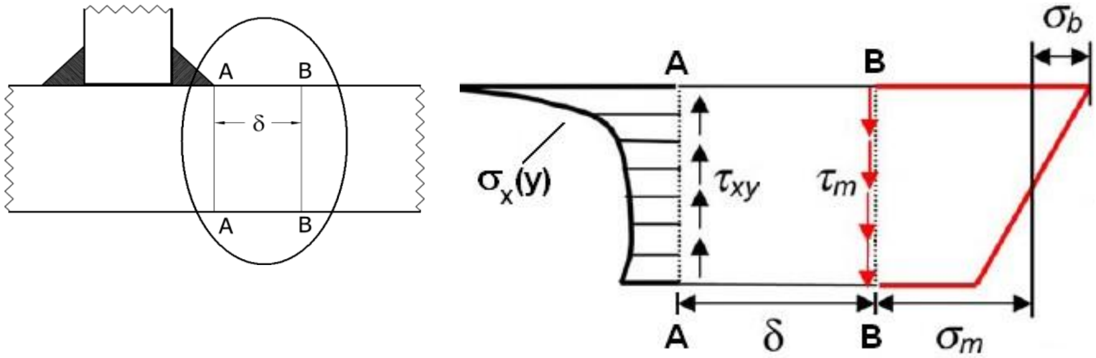


Figure 2-8 Linearization of stress distribution at the weld toe according to Battelle structural stress method [36].

The Battelle structural stress method, as previously indicated, was said to be mesh insensitive. Fillet welded lap joints were shown to be the most susceptible to mesh-insensitivity, according to researchers [37, 39]. Research on 3D structural details has indicated that the technique is mesh-sensitive and requires substantially more rigorous post-processing than stress extrapolation, which has been widely used in the industry. The lack of other shear stress components2 has an impact on the choice of distance. In the case of coarse-mesh FE models, nodal averaging is critical, according to studies. [40].

Structural stresses may be estimated if the stress value measured at the weld toe is one mm below the surface and oriented in the direction of expected crack propagation.This number was designed to indicate the stress gradient over the thickness of the plate. These welds have been tested on both transverse and longitudinal attachments using this method. In cruciform joints, however, Noh et al. [41] demonstrated that the idea may also be utilised to analyse the fatigue of load-carrying fillet welds. Weld toe failure mechanisms include partial and total penetration at these joints.

Stress findings from finite element analysis may be used to directly determine the stress at the point of 1mm. Elements must be no larger than 1mm in diameter in order to accurately measure stress at a given location. This results in extremely finely meshed FE models, which limit their practical applicability. Sub-modeling, on the other hand, may be the answer to this problem. The authors have not provided any meshing instructions.

The thickness impact (size effect) was taken into account by W. Fricke and A. Kahl in a comparative study [37]. Compared to the Battelle structural stress technique or the conventional structural hot stress method, this approach has a lower standard deviation of test results. However, with this strategy, it is suggested that the first order FE components be utilised. Due to the mid-node in second-order elements, the bottom edge of the notch element was found to have less stress than expected in the depth of 1 mm, which was contrary to test results. Stress can only be reduced to a limited extent because of the lack of a mid-node in first order elements.

The fatigue test findings were in line with the results of the first order FE models. This approach has certain drawbacks, such as the fact that it does not work for root failures.

Few resources were required to create the solid elements for plate edge features examined in finite element models. In spite of the fillet weld connection, it's plausible that the welds3 were simply made and then attached to the main plate edge. Quadratic surface stress extrapolation was used to estimate the hot spot stress. When utilizing a linear regression analysis with free slope, the standard deviation for all fatigue test points is 0.183.These data points have an overall strength of 128.7 MPa and a typical fatigue strength of this material is 99.5 MPA, as shown in figure A slope of 3 and a standard deviation of 0.189 yield a typical pressure of 104.8 MPa. To account for the geometrical effects of the attached/gusset plates, we used a technique called hot spot stress to calculate an estimated stress that has a lower scatter than if we had used a nominal stress estimate.

IAW suggests using two unique fatigue curves based on the length of linked plates when dealing with hot spot stress in Eurocode 3 despite not having a fatigue class for plate edge details. The FAT100 connector should be used when the length of the connected plates is 100 mm or less; the FAT90 connection should be used when the connected plates are more than 100 mm in length. Due to this fact, FAT100 joints are really only found when the connected plates are shorter. It is a load-carrying weld that is FAT90 when a longer plate is added.

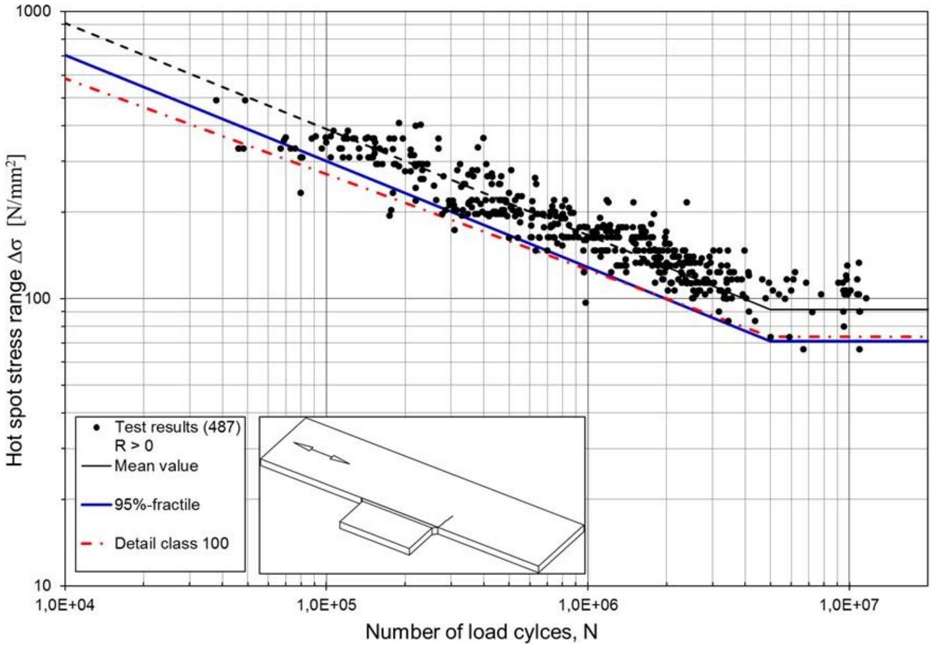


Figure 2-9 Fatigue test results for plate edge details based on hot spot stress method.

FAT100 appears to be a good match for this detail's fatigue strength based on the interpretation of fatigue test data without regard to the length of the connected plates. FAT100 and FAT90 should be used for shorter plate lengths, respectively, according to the requirements of the IIW, whereas FAT90 should be used for larger plate lengths greater than or equal to 100 mm.

Table 2-3 Statistical evaluation of fatigue test points.

Evaluation method		**No. of Specimens**	**St. dev.**	$\Delta\sigma_{mean}$ [N/mm^2]	$\Delta\sigma_C$ [N/mm^2]
Hot spot stress	All specimens	31	0.189	133.1	104.8
	$L \leq 100$	18	0.184	134.2	106.3
	$L > 100$	13	0.211	126	95.2

3.3 Effective notch stress approach

Geometric discontinuities in structural components, such as holes, joints, and faults from welds, can cause stress raisers or notches. To reduce fatigue strength, the notch characteristics produce higher stress concentrations in the weld joint. Component geometry and the local stress increase, a weld, combine to produce a nostril stress in weld joints.

The effective notch stress technique is heavily reliant on this method, which is based on the calculated greatest elastic stress at critical regions such as crack initiation points. In order to account for stress averaging in the micro-support theory for plate thicknesses more than 5 mm, Radaj [6] recommended using a fake radius of 1 mm using the Neuber Rule [21]. The reference notch radius shown in figure 2-10 was calculated using worst-case welding joint conditions (ρ=0). This notch radius may be significantly different from the one seen above. Limitation factors of 2.5 and micro-support length (ρ*) of 0.04 mm are used for steel members in order to establish the ultimate rounding radius for notches. Zhang [43] proposes a fictional radius of 0.05 mm for thin plates based on the stress-intensity factor and the notch stress relationship [44-46].

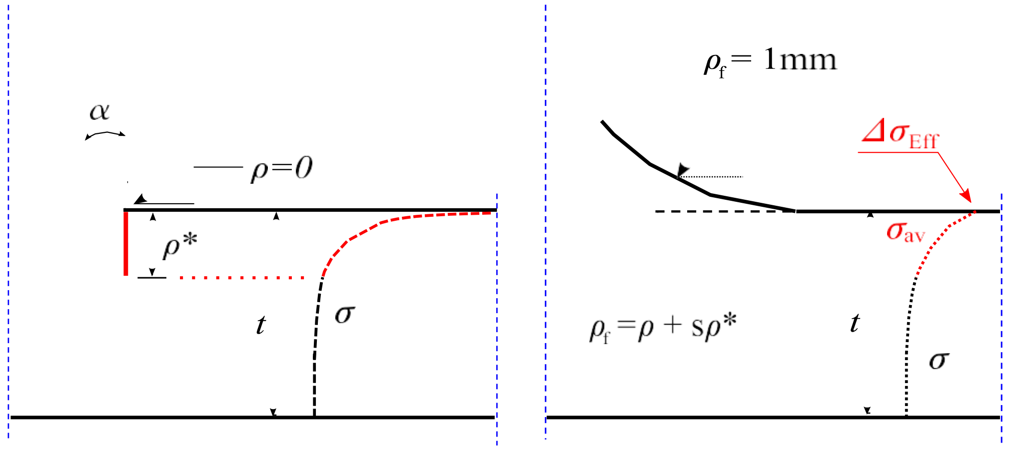


Figure 2-10 Neuber's welded joint micro-support concept [21].

An efficient notch stress approach for fatigue analysis of weld joints calls for a high enough element density in geometric features surrounding the stress concentration zone to capture the highest stress there. As a basic aspect, this approach requires a 3D solid element model to accurately describe and mesh the precise geometry around predicted crack start regions. 2D plane element models based on plane elements may be utilised when loading and geometry are simple enough to be represented in a 2D model.The IIW guidelines for fatigue life assessment utilise effective notch stress as an alternative to finite element modelling and the S-N curve..

In accordance with IIW's guidelines, the effective notch stress technique was used to examine the plate edge welded details that were obtained from the literature. The FAT225 fatigue design curve is recommended for effective stress estimates based on the greatest main stress, while the FAT200 should be used for von Mises stresses. [45] Cast iron should be subjected to the von Mises stress criterion whereas multiaxial stresses and ductile materials like structural steel should be subject to the maximum main stress.[6].

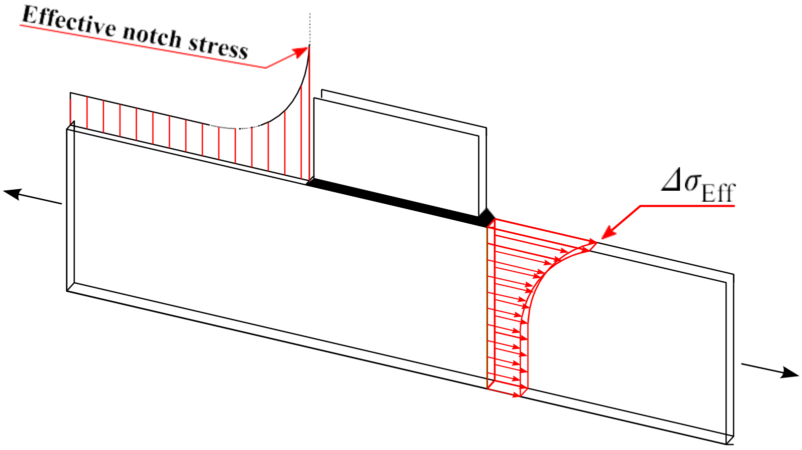


Figure 2-11: Effective notch stress definition in the plate edge joint at the weld toe[5].

The weld toe effective notch stresses had to be computed for the test specimens in question using a very fine meshed zone encompassing the crucial areas (as indicated in Figure 2-12). Many times sub-modeling is used to transfer displacements and stresses among coarsely meshed model simulations and finer meshed local models in order to define node basis sub regions or surface base sub regions. It is also possible to use sub-modeling to discover integration sites when building a surface-based sub-region.Allows serial/chain connections between sub-models.

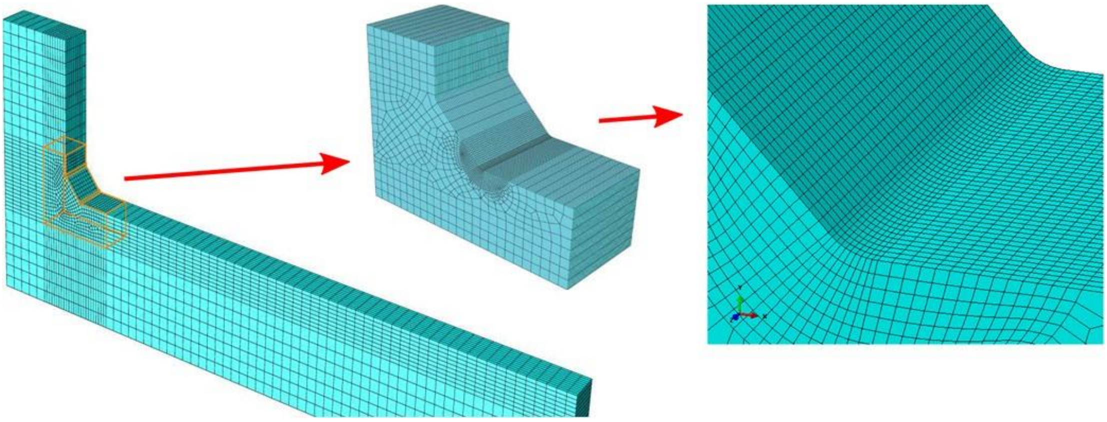


Figure 2-12 Global model and submodel for investigated plate edge joints.

FIGURE 2-13 shows the results of plate edge details fatigue tests based on effective weld toe stress notch stress. The fatigue design curve is compared to the actual findings using linear regression analysis. Fatigue values of 312.5 and 236 MPa were recorded on Slope 3. The 487 experimental data points have a standard deviation of 0.222, which appears to be excessive. A possible reason for the wide range of results is the wide range of welding processes, welding quality, and local flaws. Because the notch stress approach relies on rounding the sharp notch to avoid stress averaging throughout the short notch area, welding the weld toe can impact stress estimates for notch stress. Another possible explanation for this sudden dispersion is at work. If residual stresses from welding are present, the effective notch stress approach may need to be adjusted to take these into account. The size, sign, and distribution of residual stress may have a massive effect on the fatigue strength of welded joints [47, 48]. The effective notch stress technique for analysing fatigue test data is a close estimate of the S-N curve using the S-N curve proposed by FAT225.

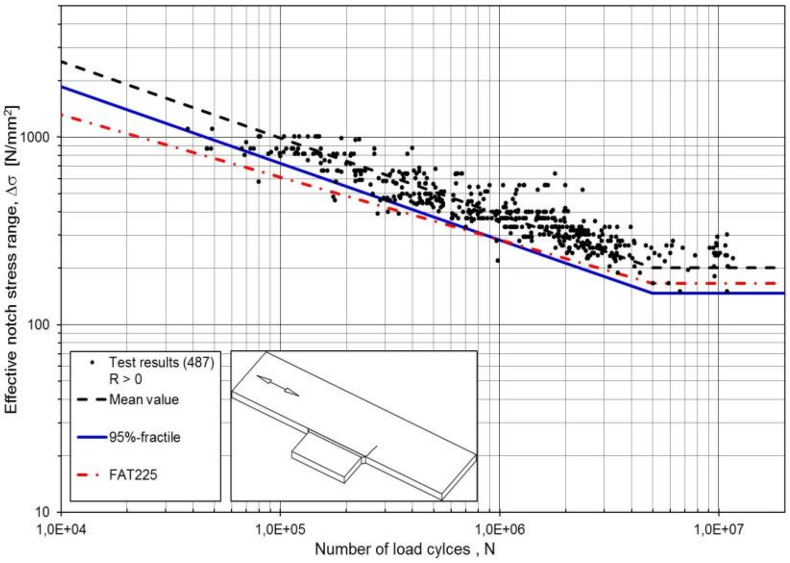
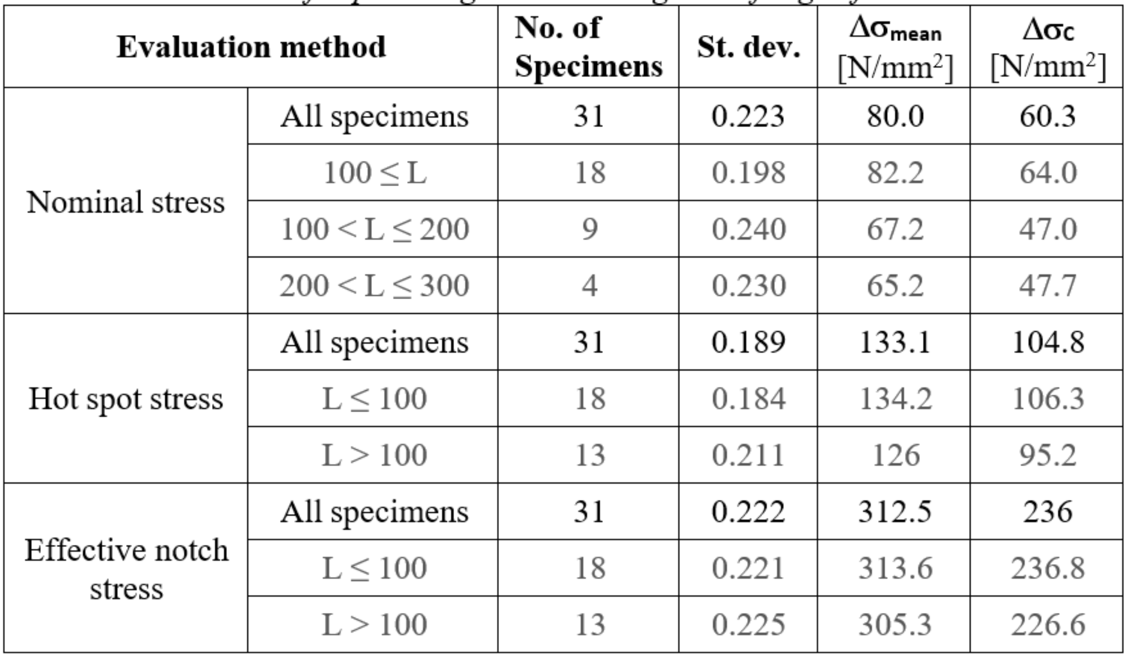


Figure 2-13 Fatigue test results for plate edge details based on effective notch stress method.

Results from these three types of failure assessment approaches are shown side-by-side in Table 2-4. Using the hot spot stress technique yields the most reliable fatigue test results in this table. As in the hot spot stress approach, the welded details were split into groups for the aim of analysing the effect of plate length on computed stresses while using effective notch stress strategy. Table 2-4 shows that the efficient notch stress strategy yielded nearly identical results to the conventional method in terms of the length of the connected plates.

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



Evaluation method		**No. of Specimens**	**St. dev.**	$\Delta\sigma_{mean}$ [N/mm^2]	$\Delta\sigma_C$ [N/mm^2]
Nominal stress	All specimens	31	0.223	80.0	60.3
	100 ≤ L	18	0.198	82.2	64.0
	100 < L ≤ 200	9	0.240	67.2	47.0
	200 < L ≤ 300	4	0.230	65.2	47.7
Hot spot stress	All specimens	31	0.189	133.1	104.8
	L ≤ 100	18	0.184	134.2	106.3
	L > 100	13	0.211	126	95.2
Effective notch stress	All specimens	31	0.222	312.5	236
	L ≤ 100	18	0.221	313.6	236.8
	L > 100	13	0.225	305.3	226.6

Based on literature research and assessments conducted for this thesis, Table 2-5 summarises the advantages and downsides of fatigue life assessment methodologies.

Table 2-5 Pros and Cons of different fatigue life assessment methods.

Pros	***Cons***
Nominal stressApproach	
Calculation in simpler. Accurately characterised The most extensively used and commonplace Feedback from previous studies Parametric formula widely accessible Fatigue classes that may be used in design codes For cracking of the weld root and toe	There is a strong link between fatigue and the category. Macro-geometric alterations and misalignment are not allowed. Reduced accuracy in intricate structures Not included is the thickness effect.
Hot spot stressApproach	
Smaller number of S-n curves are needed. Existing stress analysis can be used. Accuracy is acceptable. Less finite element modelling resources Included is a macro-geometrical effect. Tubular structures have historically relied on this material, that is well.	Depends on the size of the element Depending on the arrangement of the elements Various methods for assessing stress Not included is the thickness effect. Welding toe cracking is the only cause.
Effective notch stressApproach	
Calculations take into account the effect of thickness The stress direction has no impact on this. Suitable for cracking of the weld roots and toes a single S-N graph	FEA is required for this application. Mesh density is a factor. Radius size has an effect on this. Modeling effort takes a lot of time. Models that are bigger in scale

Chapter 4
TECHNIQUES FOR WELD MODELLING

Most commonly used welding modelling techniques are discussed in this chapter. FE models incorporate weld root and toe stress because to the notch stress technique. Instead of using hot spot stress to model welding, local joint stiffness can have no effect on stress distribution. A surface stress extrapolation method, on the other hand, uses reference points near welds to determine hot spot stress in fatigue sensitive areas. There are times when welds should be simulated, such as when welds are subjected to bending loads or stress concentration produced by geometric flaws, such as cut-out holes in the weld joint. When modelling these welds using different weld modelling methodologies, the stiffness of the welded component should be considered.

Modeling welds in shell element models is more difficult than in solid element models because solid elements may be more easily modelled. Depending on the weld modelling approach, the stress value in welded sections might vary in shell element models. Many new weld modelling approaches have been developed in recent years to reduce the modelling time and improve the accuracy of describing welds [49, 51]. Here are some of the most often used weld modelling techniques4.

4.1Using oblique shell elements to model welds

Oblique shell elements can be used to model a welded joint's welds [5]. This weld modelling technique is capable of properly capturing the stiffness and geometry of the weld. As indicated in Figure 3-1, the connecting plate should be connected to the main plate at the junction. You have a choice in the length of the inclined shell components, as seen in this diagram. The throat thickness of welds may be used to measure the thickness of oblique shell elements.

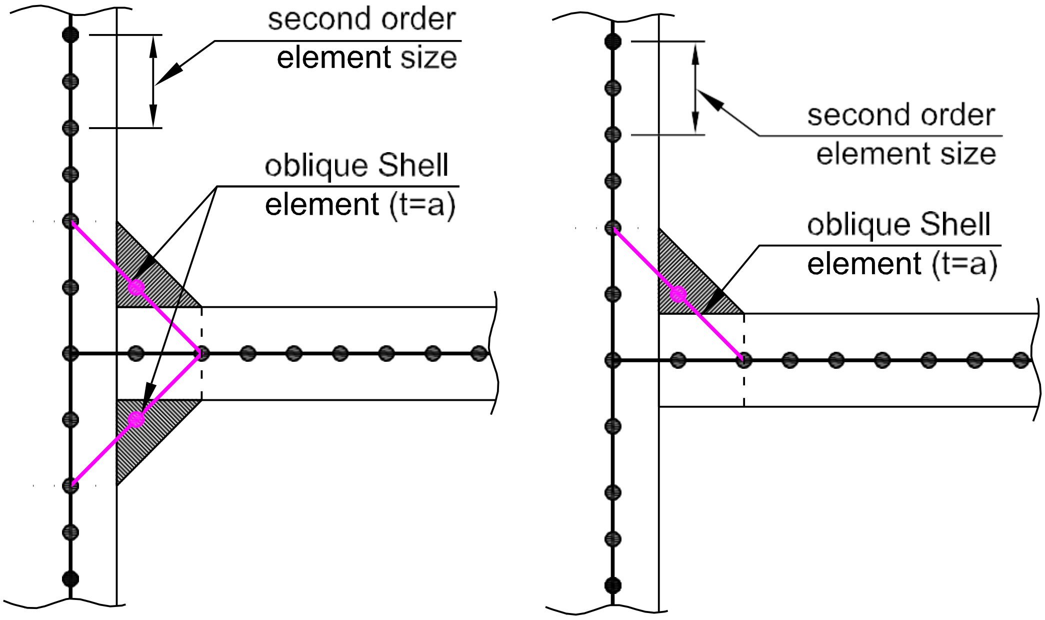


Figure 3-1 Weld modelling using oblique shell elements [5].

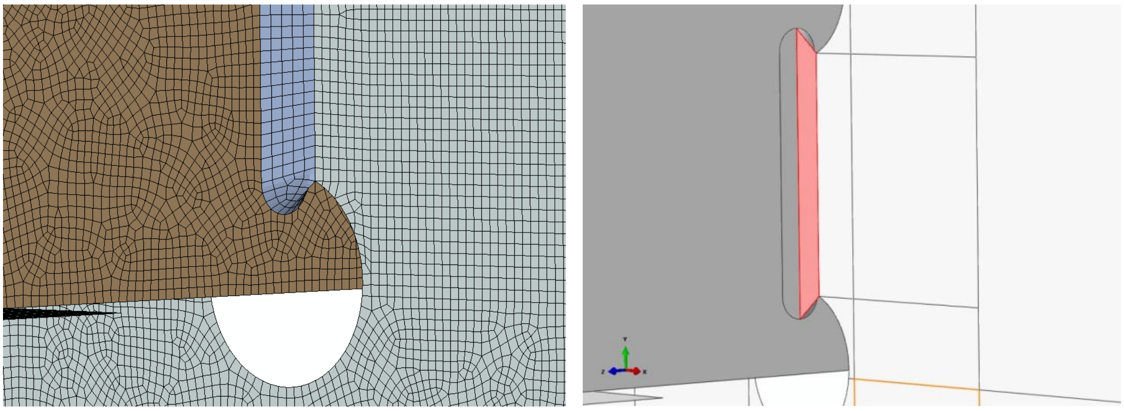


Figure 3-2 Weld modelling using oblique shell elements by joining attached plates to the parent plate in a common node.

As previously indicated, this approach allows the stiffness and geometry of welds to be shown. For example, when designing a joint to prevent cracking at the weld root, tension from these weld parts could be utilised. Weld stiffness and geometry are critical factors in obtaining accurate stress result values for use in root crack computations, and they must be accurately modelled rather than approximated. As a consequence, this method is more suited to treating weld toe fatigue failures.

4.2Using rigid links to model welds

Fayard et al. [52] proposed a weld modelling approach using rigid links. [53]. The stress in the weld toes may be estimated with the use of this method. Because of this strategy, the hot spot stress at the weld toes may be immediately read out at the center of gravity of the elements, do dispensing with the need for surface stress extrapolation.

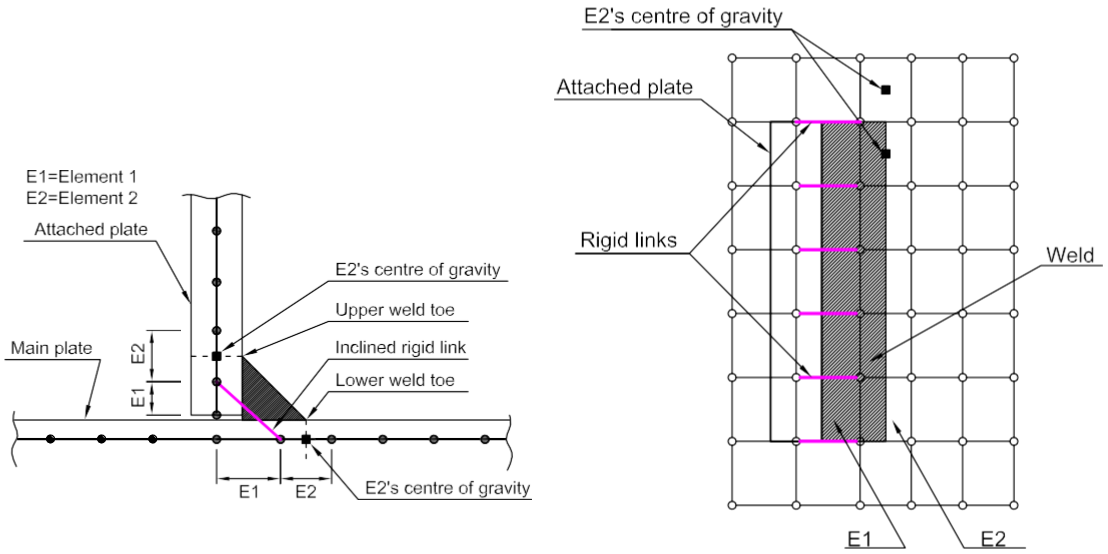


Figure 3-3 Single-side weld modelling with rigid links proposed by Fayard et. al [52].

An crucial component of this technique is to model how welded connections behave in terms of local stiffness. As the weld proceeds, pairs of nodes form hard connections between neighbouring shell components and run along the weld. If the lengths of E1 and E2 in Figure 3-3 are appropriately selected, they may be used to estimate anxiety levels directly. Rigid links connect elements E1 and E2 through their common node. There are two plates at the junction that aren't connected at the joints. For this strategy, 4-node shell components are also suggested. Figure 3-4 illustrates the use of stiff connections.

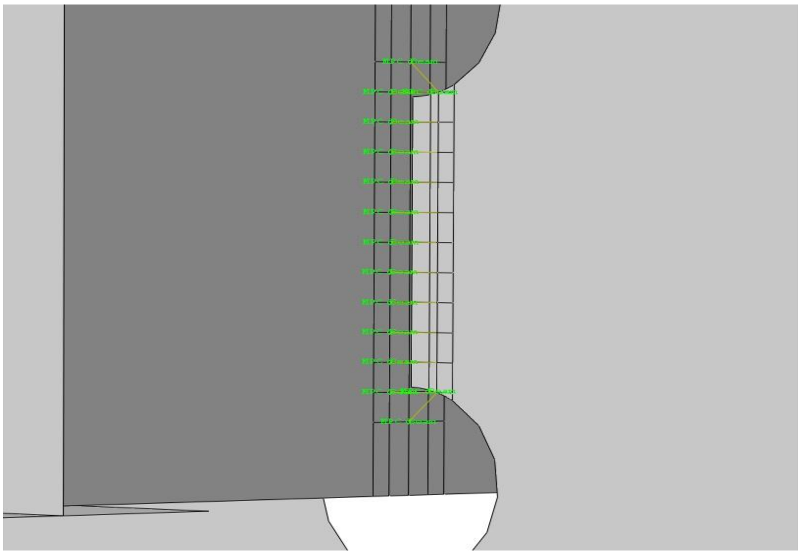


Figure 3-4 Weld modelling using rigid links.

4.3Weld modelling using increased thickness

Niemi [5] proposed employing shell components with increasing thickness to reflect the stiffness of the welds of welded connections in order to accurately describe their characteristics. Increased thickness and length of finite components are two essential geometric configurations in this strategy. There was no indication of thickness or dimension that should be used in the modelling of the weld by Niemi.

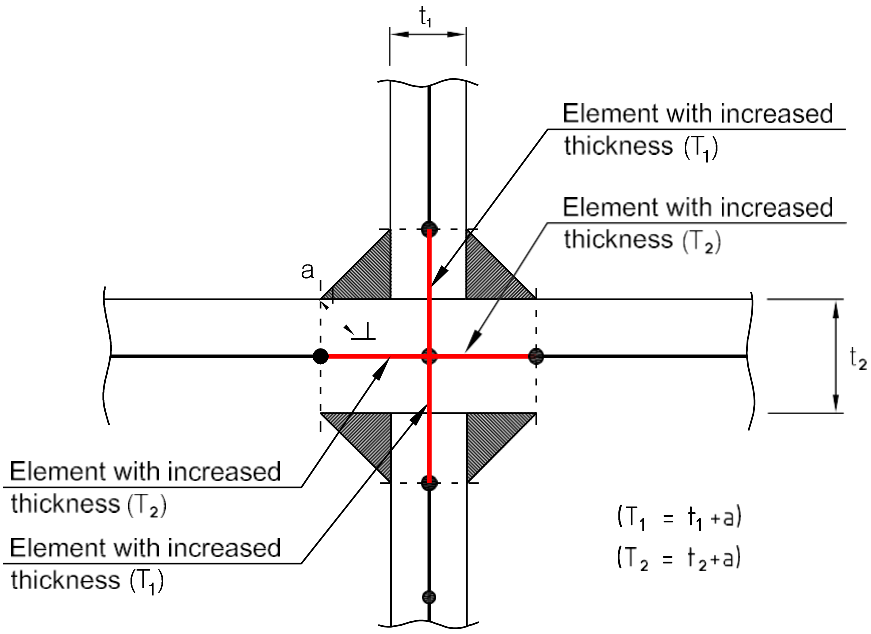


Figure 3-5 Modelling welds using shell elements with increased thickness [49].

Eriksson et al. [49] advocated two rows of shell components with increasing thickness, such as increased thickness elements in the connected plate and the parent plate.The cruciform joint surface area shell element % is shown in Figure 3-5. Weld connections between cover plates may be depicted using a combination of rigid elements to link a discrete piece of metal to the parent plate and shell components with greater thickness to join the parent plate.

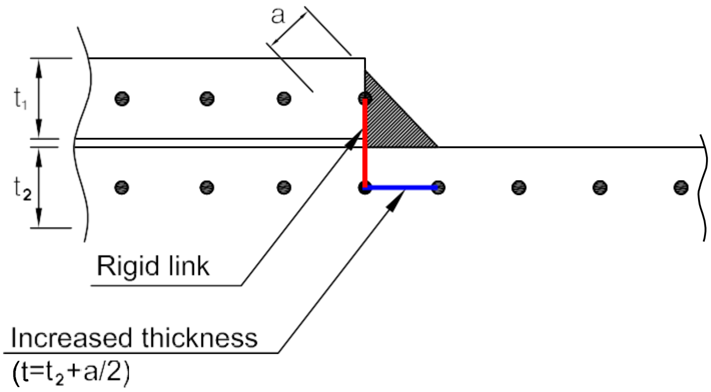


Figure 3-6 Modelling cover plate weld using shell elements with increased thickness and rigid links [49].

4.4Weld ends modelling

There may be more influence on the stiffness of a joint due to the shape and form of the welds than the material source. At the conclusion of a weld, fatigue cracking is a frequent issue.

Weld ends, where fatigue fractures develop and spread, must be modelled in this scenario because the stress distributions at these points are of special relevance. These shell components may be used as long as the thickness of the weld end is equal to the thickness of the weld plate. Figure 3-7 depicts this method, which was proposed and used in a case study [28].

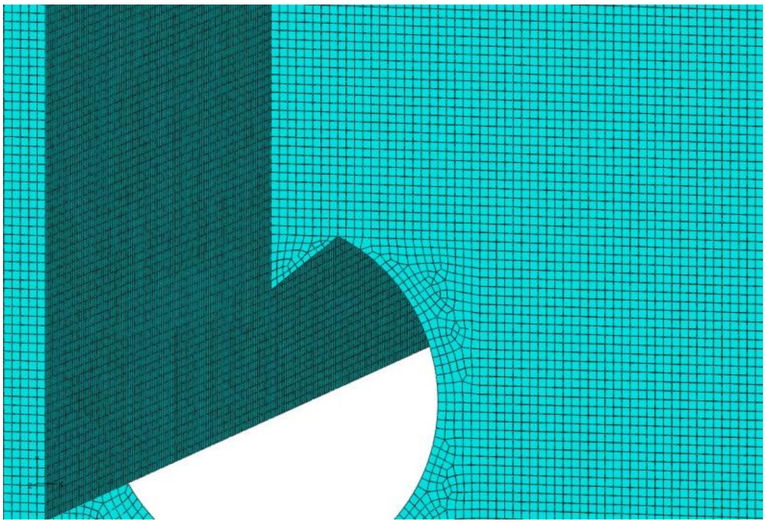


Figure 3-7 Weld ends modelling using shell elements.

After fusing the longitudinal plate's weld toe to the longitudinal plate, fatigue fractures formed in the weld toe. Because of the weld's form, a cut-out hole at the end altered the stress distribution. A weld end, as depicted in the figure, was built in order to alter the weld end's shape. When the cutting hole transitioned seamlessly to the longitudinal plate, the stress was reduced substantially. Weld modelling strategies were tested in a case study, including the method described above. [28].

4.5Using solid elements for weld modelling

It is widely used because it is simple to model and reliable in its results, and because weld stiffness can be accurately predicted. A welded junction's shape and stiffness may be simply represented in solid element models, as shown in Figure 3-8.

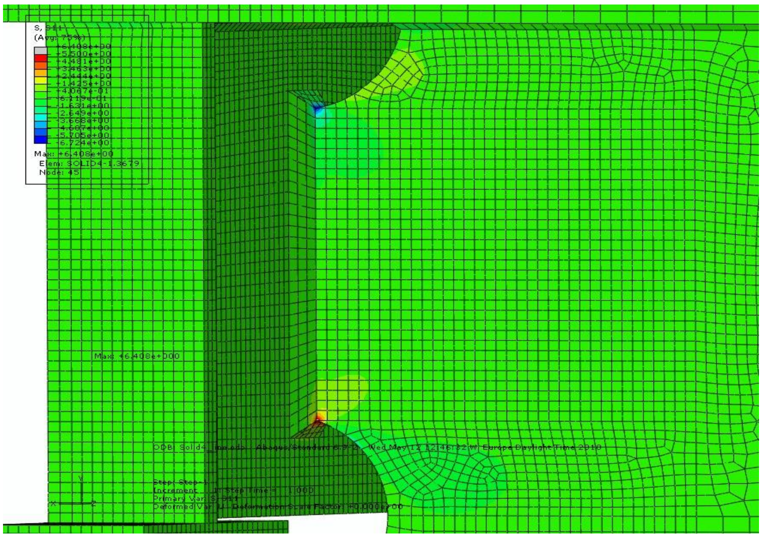


Figure 3-8 Modelling of the welds with solid elements.

Welds in shell element models must be modelled using a particular approach to join the two types of elements. Node degrees of freedom in solids are three, while node degrees of freedom in shells are five. There must be an exchange of bending moments among solid and shell elements Perform it in a number of ways, if necessary. Shell elements can be integrated with solid components utilising Multi Point Constraint (MPC) formulae. It takes time and effort to generate MPC equations in order to transfer rotation from the shell parts to the solid components using this technique. FE software, on the other hand, may carry out this operation completely automatically.

Chapter 5
Application of the fatigue assessment methods

5.1 Using FEM to model and estimate the fatigue life of orthotropic bridge deck details

All across the world, orthotropic steel bridge decking has been used for many years because of its high load-bearing capability in relation to its low weight. Engineers have a difficult time with orthotropic steel bridges in the design phase due to their complex geometry and complex loading systems. Calculations of stress must take into account the interplay of deck components under various loading and geometrical circumstances. Different orthotropic steel bridge features all across the globe have been found to exhibit fatigue cracks [1-4]. Other than the complicated geometrical and loading configurations, one explanation for the observed fatigue cracks might be because the nominal stress approach and basic beam theory often employed for fatigue design fail to effectively forecast the load effects on these intricate features in many circumstances. When it came to the stress status of orthotropic steel deck bridges, modern numerical modelling approaches like finite element analysis are required. Welding joints that are prone to fatigue can be more accurately strained using finite element analysis. Precise stress estimates based on the finite element modelling are critical when analysing steel bridge fatigue. Finite element stress calculations at fatigue-critical features in structural design and analysis require, however, a thorough understanding of fatigue assessment methodologies and modelling approaches in order to be successful in this effort.

Modeling an orthotropic bridge detail in FEM demonstrates the most common methods of assessing fatigue life. An opening in the weld that connects a cross-girder with one of its corner This detail's fatigue life and structural hot spot stresses were evaluated to use a stress notch methodology, as well as other stress evaluation methodologies.

The nominal stress approach may be used to quickly assess the fatigue strength of the fatigue critical locations investigated in this research. According to European Union guidelines, the cut-out hole in the cross-girder web must be taken into account when estimating the nominal midsection stress. The sum of normal and shear stresses determines the fatigue strength of welded joints. As a result of these regulations, the intended results were not attained. In the finite element model of the tested specimen, the load from the rib plate was transmitted to the web plate of the cross girder. Due to the substantial shear stress in this section of the web, the web plate area connected to the rib plate received virtually all of the shear force. 1. The test specimens are subjected to 400 kN of stress throughout the experiment. Between the two cut-outs, 90 percent or more of the shear stress is transmitted through the web.

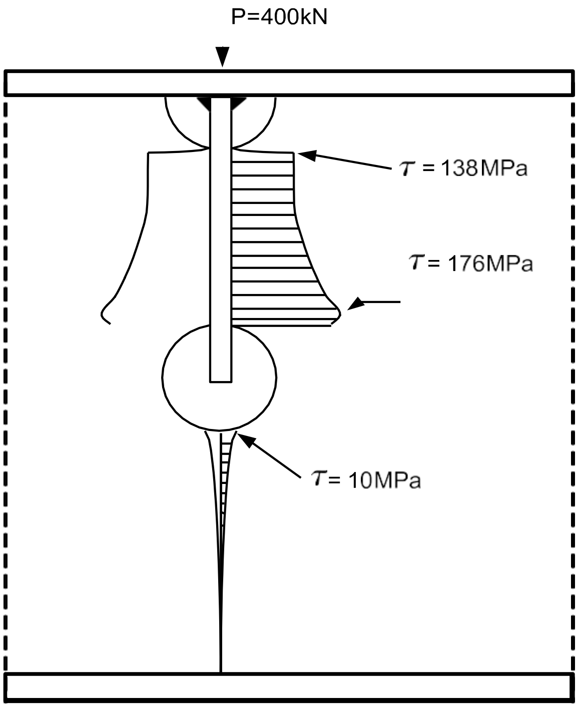


Figure 4-1 The distribution of shear stress in the welded section.

The comparable nominal stress will be higher if only this part of the web is regarded to be able to withstand the shear force. It can be seen in this image (Fig. 4-2) that the specimen test findings are more in line with the S-N curve (C56) from EC3.Therefore, EC3 should provide a more precise specification of the bridge area used to compute the stress.

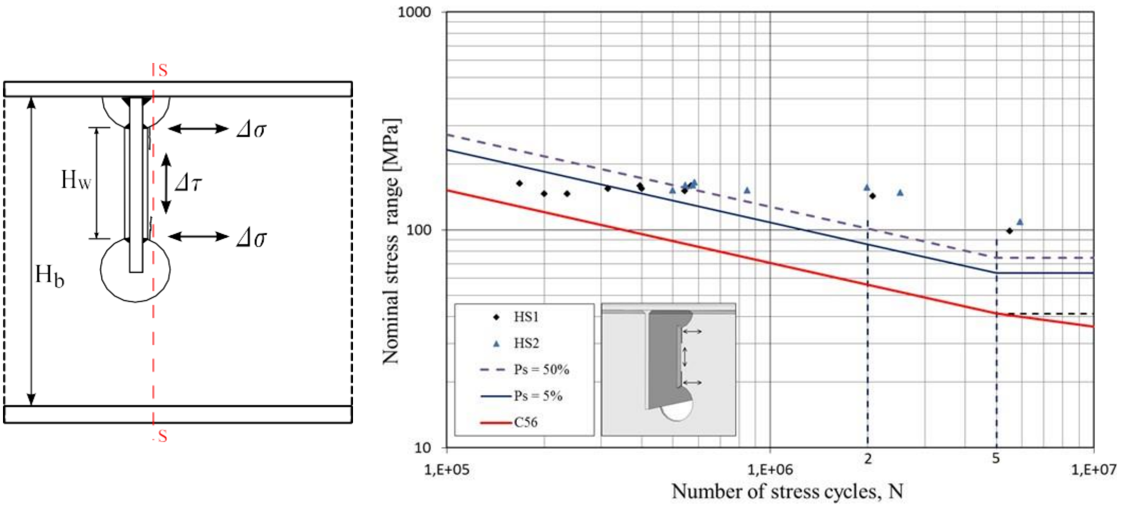


Figure 4-2 S-N diagram using equivalent nominal stress considering shear stress distribution only over the welded section (H_w).

Detailed finite element modelling in the domain of structural hot spot stress is necessary to determine fatigue life. A wide variety of solid and shell element models may be used to simulate the test specimens. While shell element modelling primarily considers geometrical configurations, not welds, when it comes to stress calculations, the most important and critical concern was how to simulate the welds in the analysed section. Because shell element models without modelling welds gave inaccurate stress estimates, this study analysed the most extensively used weld modelling methods described in Chapter 3. Oblique shell element weld modelling is solely compared to the fine element model here, which does not simulate welds. Figure 4-3 shows a comparison of these results with those from the solid element model. When compared to the static test result and a solid element model, this weld modelling technique may provide an accurate assessment of stress in the hot areas.

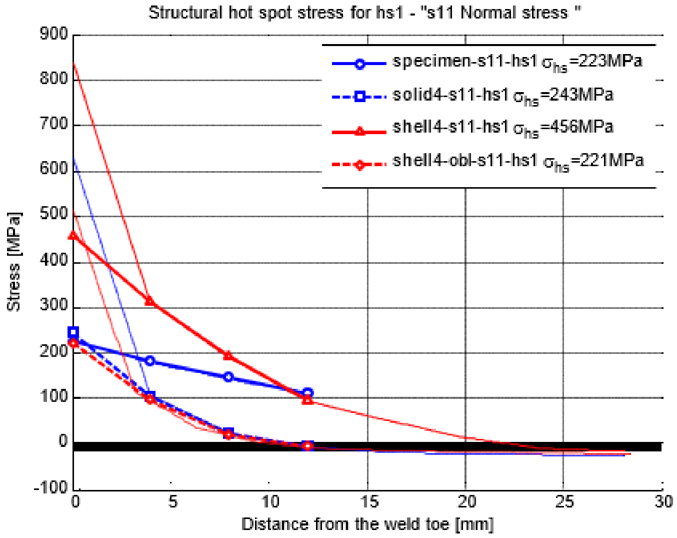


Figure 4-3 Stress distribution in front of the weld toe and hot spot stresses determined by quadratic surface stress extrapolation.

The fatigue life of the test specimens is demonstrated to be in excellent agreement with the suggested design curve of C90 in Figure 4-4, based on structural hot spot stress.

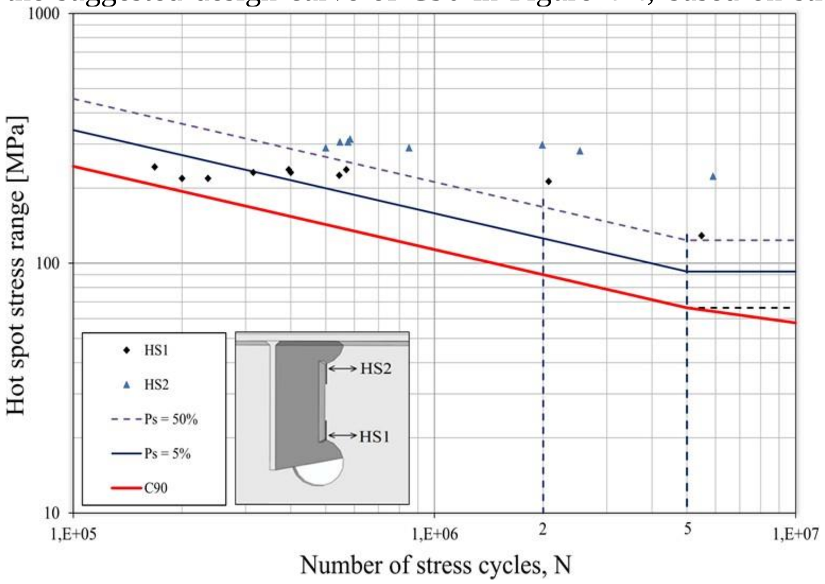


Figure 4-4 Results of fatigue tests based on the hot spot stress approach.

Based on the effective notch stress, only a finite element model can be used to determine the fatigue life of test specimens. As part of the submodeling method, the effective notch stress at the weld toe was calculated using extremely finely meshed models at critical areas. To compare the effective notch stress values reported in Figures 4-5 to the fatigue design curve, we used linear regression analysis with a slope of 3. In light of the facts, Figure 4-5 shows how cautious the approach is. The design curve that has been presented is on the conservative side of the spectrum. ‘‘The optimum option was determined to be a cautious curve’‘. This level of detail might be described using FAT300. As Park and Miki [28] show, the notch stress approach may be applied by looking at various current fatigue tests on various kinds of details. The data were shown to go beyond the S-N curve of FAT300 by the authors. Welds should be computed assuming the worst-case scenario, which may result in an underestimation of fatigue life and a distortion of the design stress. In estimating the fatigue life of welds, hot spot stress does not include welds in the stress calculations, which may be an advantage. However, further in-depth investigation into this aspect of the welding process is needed before a definitive conclusion can be reached.

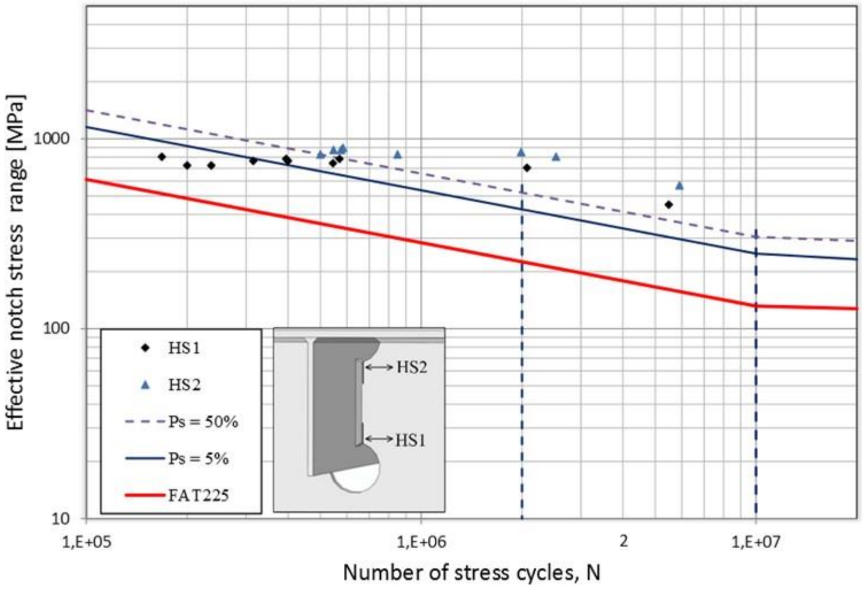


Figure 4-5 Results of fatigue tests based on the effective notch approach

Conclusions

General conclusions

There are two aspects to the findings that result from this investigation. Three methods of assessing fatigue in welded details are discussed in greater depth in part 1. The results and suggestions for evaluating orthotropic bridge deck detail fatigue are reported in part 2.

Three fatigue evaluation approaches can be used to make conclusions about the analyzed welded details.:

- Standard deviations found by the three distinct approaches are extremely similar which was not expected. In order to reduce dispersion, the refined and improved approaches were supposed to account for the stress-inducing impacts. There may be some variation in fatigue test results due to changes in welding procedure, welding quality, and maybe size effects.
- The test results from hot spot had the lowest possible degree of variability because of the method's inclusion of macro geometrical parameters and exclusion of weld effects. When it comes to measuring fatigue intensity, the hot spot stress technique, is more accurate than the traditional nominal stress strategy.
- The welded plate edge joints can use a single fatigue design curve of C100, independent of plate length, based on the results of the hot spot stress approach.
- In terms of fatigue strength, these welded details' fatigue resistance was found to be strongly affected when considering the length of the linked plates. In part, this is due to flange/main plate attachments becoming longer, which makes them load-carrying in some way.
- For plate edge details with connected plates longer than 100 mm, a hot spot stress-based fatigue S-N curve C90 may be used; however, for plate edge details with attached plates less than 100 mm, the S-N curve C100 for plate edge details with attached plates shorter than 100 mm should be utilized.
- For the effective notch stress approach, the IIW's FAT225 lower bound fatigue strength appears to produce satisfactory agreement with fatigue test findings, despite the fact that the FAT300 fatigue strength category can be employed to some welded details.

According to this study, local techniques to calculating the fatigue life of intricate orthotropic bridge characteristics are more accurate than global approaches. A specific focus should be placed on how shear stresses are distributed across the welded section when employing the nominal stress approach.. It is possible to make recommendations for using fatigue assessment methodologies and finite element modelling techniques after doing this investigation:

- Shear stress distributions over welded sections and normal stresses over bridging sections must be adequately analyzed before nominal approach can be used correctly. Stress calculations in Eurocode 3 require a clearer definition of the critical cross-sections.
- Welds in complicated features with cut-out holes must be adequately reflected for structural hot spot stress analysis. For the examined welded connection, fine mesh solid element models give more realistic stress ranges at hot spot locations.Solid element models with welds should be used to analyse structural hot spot stresses

in welded details with cut-out holes.

- Welds in complicated welded connections must be represented in terms of stiffness (thickness), as well as form, in models that include shell parts (geometry). Oblique shell components are shown to be the most effective approach to do this, according to the findings of the study.
- Straight stress evaluation provides more reliable data for determining structural hot spot stresses. In the absence of any extrapolation, the structural hot spot stresses predicted using the 0.5t stress derivation technique (using surface stress extrapolation procedures) provide comparable results.
- While the approach accurately measures stresses at HS1 (the first hot spot site), it grossly underestimates stress concentrations at HS2 (the second hot spot point) . Hot spot point 2 has a discrepancy that needs more investigation
- In the case of both hot spot spots, the 1mm stress approach yields reliable findings. However, fine mesh FE models are required.
- Smaller tetrahedral solid components make modelling easier, and the differences between hexahedral and tetrahedral outcomes are quite tiny. When adopting effective notch stress, however, the amount of effort required to model is significantly more than the effort required to model the structural hot spot stress technique.
- The accuracy of the hot spot stress technique can be checked by using strain measurements in a FEM, even if this approach is mesh-sensitive.Stress measurements at fatigue critical places are required in complicated welded details to ensure that fatigue life estimation methods are accurate.
- Strain gauges in intricate welded details have been shown to have a massive effect on fatigue test results in study. According to the FE analysis, the strains measured at hot spot point 2 were lower than the strains observed at hot spot point 1.

Outlook for future research

Welded detail fatigue strength may be accurately estimated using any approach, as evidenced by the findings of the study reported here. Other research is needed to verify the correctness of the techniques in respect to additional welding details.

When the effective notch stress technique was used to analyse the researched details, it was discovered that some welded features may be categorised as C300. To reach a definite judgement or advocate such a course of action, further inquiry is required on these welding details.

Although the approach demands tight meshing around the crucial zones, the thickness impact is taken into consideration extremely effectively by the 1mm stress method. This method may be used to validate the fatigue evaluation procedures and thickness correction factors used in Paper II and other welded details.

An accurate prediction of complex properties can be made using crack propagation analysis, which utilizes the principles of fracture mechanics. This technique can be used to study the welding details of orthotropic bridge decking..

We saw in the last chapter that using the Battelle structural stress technique only worked well for HS and underestimated stresses for HS2. There should be more research into the possible applications of this mismatch in fatigue life analysis if it is discovered at hot spot point 2.