THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Fatigue evaluation of welded details –
using the finite element method

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Cover:
The cover picture shows the FE models used for crack propagation analyses

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To my parents
and my son Kerem

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ABSTRACT

The fatigue evaluation of welded details is generally based on the notion of nominal stress, using the classified S-N curves with corresponding fatigue classes for typical details. An approach of this kind should be used with extra caution to ensure that the load effects for components are accurately captured, because an ever-increasing number of welded details are resulting in a limited number of possible treatable design cases.

The fatigue of welded structures is a somewhat complex and progressive form of local damage which can be evaluated more accurately using local failure approaches, such as the hot-spot and effective notch stress methods. Methods based on fracture mechanics can also be applied in cases where fatigue cracks are detected or can be assumed to exist. A large number of welded details with complex geometry and load conditions that are known to be critical with respect to fatigue can be found in welded steel structures. Estimating more detailed and accurate information on the stress state of these details is very difficult without using finite element analysis. On the other hand, the result obtained from finite element analysis can be highly sensitive to the modelling technique, as the stresses obtained from the local failure approaches are often in an area of high strain gradients, i.e. stress singularities.

In the first part of this thesis, the fatigue evaluation of welded details using the finite element method was studied to evaluate the applicability and reliability of the local failure approaches for details that are typical in steel and composite bridges. In order to obtain a better understanding of these methods in terms of implementation and limitation, both "simple" and complex welded details were studied using various finite element models.

In the second part of this thesis, the fatigue evaluation of welded details in existing steel structures was investigated in order to examine the fracture resistance of fatigue-cracked welded details and to obtain more reliable inspection periods for the cracked structures. The effectiveness, accuracy and applicability of the crack-propagation analysis based on the linear-elastic fracture mechanics for distortion-induced fatigue cracking in bridge structures, were investigated by performing several crack-propagation analyses.

The results obtained in this thesis show that the local failure approaches provide better fatigue life estimations in comparison with the conventional methods, even though these approaches require more effort for modelling. In addition, the fatigue assessment of critical details susceptible to distortional cracking can be performed more accurately using the local failure approaches. This type of detail should not be estimated using the conventional nominal stress based methods due to the highly localised deformation whose effect cannot be captured by these methods. On the other hand, the crack-propagation analyses showed that the crack growth rate decreases as the crack length is extended, due to relaxation, as the web gap becomes more flexible because of the extended crack. The fracture mechanics-based methods can be utilised in order accurately to determine the required inspection period and retrofitting technique.

Keywords: Hot-spot stress method, effective notch stress method, welded details, fracture mechanics, the finite element method

Utmattningsutvärdering av svetsade detaljer med finita elementmetoden

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SAMMANFATTNING

Utmattningsutvärdering baseras generellt på metoden med nominella spänningar kombinerat med angivna hållfasthetskurvor för vanliga svetsförbandsdetaljer. En sådan konventionell utvärderingsmetod bör tillämpas med extra försiktighet för att säkerställa att lasteffekterna i förbandet noggrant inkluderas, eftersom det ständigt ökande antalet svetsförbandsdetaljer har lett till att begränsat antal detaljer blir möjliga för utvärdering.

Utmattningssprickor i svetsade konstruktioner är en ganska komplex och progressiv form av lokala skador, som eventuellt kan utvärderas noggrannare med ”lokala” analysmetoder såsom hot-spot metoden och effektiv-notch metoden samt brottmekaniska metoder. Tillämpning av finita elementmetoden på utmattningsanalyser innebär mer noggranna spänningsberäkningar på svetsade detaljer, som inkluderar både globala och lokala effekter. Ett stort antal svetsförband med komplex geometri och lastförhållanden, som är kritiska med avseende på utmattningskapaciteten, kan förekomma i svetsade stålkonstruktioner. En mer detaljerad och noggrann framräkning av spänningstillståndet hos dessa komplexa detaljer är mycket svår att utföra utan användning av finita elementanalyser. Resultaten från sådana analyser påverkas dock av modelleringstekniken, eftersom de spänningar som erhållits från de lokala analysmetoderna i själva verket avser ett område med höga spänningsgradienter, dvs. singulariteter.

I första delen av föreliggande avhandling har utmattningshållfastheten för svetsade detaljer studerats för att bedöma tillämpbarheten och tillförlitligheten hos de lokala analysmetoderna. För att kunna uppnå en bättre förståelse av dessa metoder vad gäller genomförande och begränsningar, har både enkla och komplexa svetsförbandsdetaljer studerats genom att tillämpa olika finita elementmodeller.

I andra delen av avhandlingen har utmattningskapaciteten hos svetsförband med sprickor i befintliga broar studerats för att uppskatta restlivslängd och för att ta fram mer tillförlitliga inspektionsintervall för broar med utmattningssprickor. Effektiviteten, noggrannheten och tillämpbarheten hos metoder för utvärdering av restlivslängden har studerats genom att utföra olika brottmekaniska analyser för ett svetsförband med deformationsinducerade utmattningssprickor hos en brokonstruktion.

Resultaten från denna studie visar att de lokala analysmetoderna leder till noggrannare utmattningsutvärdering i jämförelse med den konventionella metoden även om dessa metoder är mer tidskrävande. Livslängden hos förbandsdetaljer som påverkas av deformationsinducerade sprickor kan även utvärderas mer noggrant med de lokala analysmetoderna. Däremot visar resultatet från de brottmekaniska analyserna för förbandsdetaljer med sprickor att spricktillväxthastigheten minskar med ökad spricklängd på grund av minskad deformation. Utmattningssprickors tillväxtskede och återstående livslängd för spruckna och reparerade svetsförbandsdetaljer kan uppskattas noggrant med hjälp av brottmekaniska metoder.

Nyckelord: Hot-spot metoden, effektiv-notch metoden, svetsförbandsdetalj, brottmekanik, finita elementmetoden

LIST OF PUBLICATIONS

This thesis is based on the work contained in the following papers:

Paper I

Aygül, M., Bokesjö, M., Heshmati, M., and Al-Emrani, M. (2013). "A comparative study of different fatigue failure assessments of welded bridge details." *International Journal of Fatigue*, 49(0), 62-72.

Paper II

Aygül, M., Al-Emrani, M., and Urushadze, S. (2012). "Modelling and fatigue life assessment of orthotropic bridge deck details using FEM." *International Journal of Fatigue*, 40(0), 129-142.

Paper III

Aygül, M., Al-Emrani, M., and Lukic, M. (2013). "Fatigue evaluation of welded bridge details prone to distortional cracking by local approaches." Submitted to *Revue Construction Métallique*.

Paper IV

Aygül, M., Al-Emrani, M., Barsoum, Z., and Leander, J. (2013). "Investigation of distortion-induced fatigue cracked welded details using 3D crack propagation analysis." Submitted to *International Journal of Fatigue*.

Paper V

Aygül, M., Al-Emrani, M., Barsoum, Z., and Leander, J. (2013). "An investigation of distortion-induced fatigue cracking under variable amplitude loading using 3D crack propagation analysis." Submitted to *International Journal of Fatigue*.

THE AUTHOR’S CONTRIBUTIONS TO JOINTLY PUBLISHED PAPERS

The contribution of the author of this doctoral thesis to the appended papers is described here.

I. Participated for the main part of the planning and writing of the paper

II. Responsible for the planning and writing of the paper
Shared responsibility in the planning of the experiments

III. Responsible for the planning and writing of the paper

IV. Responsible for the planning and writing of the paper
The field measurement data is supplied by the co-authors who have contributed to the paper with comments and revisions

V. Responsible for the planning and writing of the paper
The field measurement data is supplied by the co-authors who have contributed to the paper with comments and revisions

ADDITIONAL PUBLICATIONS BY THE AUTHOR

Journal paper

Leander, J., Aygül, M., and Norlin, B. (2013). "Refined fatigue assessment of joints with welded in-plane attachments by LEFM." *International Journal of Fatigue*, 56(0), 25-32.

Conference paper

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*. City: AWST-10/63: Istanbul, Turkey, pp. 261-268.

Licentiate thesis

Aygül, M. (2012). Fatigue Analysis of Welded Structures Using the Finite Element Method. Licentiate thesis. Lic. 2012:04. Department of Civil and Environmental Engineering, Chalmers University of Technology, Gothenburg, Sweden.

Report

Al-Emrani, M. and Aygül, M. (2013) Fatigue design of steel and composite bridges – A guideline *(A guideline for bridge engineers)*

Contents

Preface

The research work presented in this thesis had been carried out from 2009 to 2013 at the Department of Civil and Environmental Engineering, Division of Structural Engineering, Steel and Timber Structures at Chalmers University of Technology in Gothenburg, Sweden. The research work between 2009 and 2011 was carried out within part of the BriFaG research project "Bridge Fatigue Guidance – Meeting Sustainable Design and Assessment". This project was financed by the European Commission – Research Fund for Coal and Steel. The research work carried out between 2011 and 2012 was financed by the Swedish Transport Administration, Trafikverket. All this funding is gratefully acknowledged for making it possible for me to accomplish the presented research work.

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Mustafa Aygül

Gothenburg, December 2013

Notation

Abbreviations

3D	Three dimensional
ABS	American bureau of shipping
AWS	American welding society
BEM	Boundary element method
BS	British standard
CAFL	Constant amplitude fatigue loading
DNV	Det norska veritas
EC	Eurocode
FE	Finite element
FEA	Finite element analysis
FEM	Finite element method
FPSOs	Floating Production, Storage and Offloading units
Franc3D	Fracture analysis code (3-Dimensional)
GEN	Generalized stress criterion
GL	Germanischer Lloyd
IIW	The international institute of welding
LEFM	Linear-elastic fracture mechanics
MTS	Maximum tensile/tangential stress
NDT	Non-destructive testing
S-N	Stress-number of cycles
SERR	Strain energy release rate
SIF	Stress intensity factor
St. dev.	Standard deviation
VAFL	Variable amplitude fatigue loading

Roman lower-case letters

a	Crack depth
a_0	Initial crack length
a_f	Final crack length
a_w	Weld thickness
a/c	Crack shape
c	Half crack length

d	Distance
m	Exponent for Paris law, fatigue strength curve slope
n	Exponent for thickness factor
t	Thickness
t_{ref}	Reference thickness
r	Radius

Roman upper-case letters

$A_{w, net,s}$	Net cross-sectional area of a welded joint
BH	Blind hole
C_0	Material parameter
da/dN	Crack growth rate
E	Modulus of elasticity
G	Strain energy release
H_b	Height of the web plate of a beam
H_w	Height of welded section
K	Stress intensity factor
K_{max}	Maximum stress intensity factor
K_{min}	Minimum stress intensity factor
K_{open}	Stress intensity factor level to open the crack surface
M	Bending moment
N	Number of cycles
N_C	Constant number of cycles for the fatigue strength curves
TH	Through hole
R	Stress ratio
$W_{net,s}$	Elastic modulus of the net cross-section of a beam

Greek lower-case letters

$\beta_{II, III}$	Mixed-mode factors
δ	Relative out-of-plane distortion
σ	Normal stress
σ_{bend}	Bending stress
σ_{eff}	Effective notch stress
σ_{hss}	Hot-spot stress

σ_{max}	Maximum principal stress
σ_{mem}	Membrane stress
σ_{min}	Minimum principal stress
σ_{nom}	Nominal stress
σ_{peak}	Non-linear peak (notch) stress
$\sigma_{r\theta}$	Crack-tip singular stress (in polar coordinates, r and θ)
σ_{str}	Structural stress
σ_{tot}	Total stress
$\sigma_{\theta\theta}$	Crack-tip singular stress, hoop/tangential stress (in polar coordinates, r and θ)
τ	Shear stress
$\tau_{r\theta}$	Crack-tip singular shear stress (in polar coordinates, r and θ)
υ	Poisson's ratio

Greek upper-case letters

Δ	Girder deflection
Δa	Crack increment
Δa_{median}	Crack increment specified for the crack front point with the median stress intensity factor range
$\Delta\theta$	Angle of crack direction
ΔK	Stress intensity factor range
ΔK_C	Stress intensity factor range for material toughness
ΔK_{Ed}	Stress intensity factor range for load effects
ΔK_{eff}	Effective stress intensity factor range (for mixed-modes)
ΔK_{eff}^{cc}	Effective stress intensity factor range (for crack closure)
ΔK_{median}	Median stress intensity factor range
ΔK_{Rd}	Stress intensity factor range for fractural resistance
ΔK_{th}	Threshold stress intensity factor range
$\Delta\sigma$	Stress range
$\Delta\sigma_C$	Characteristic fatigue strength of a S-N curve (at 2 million cycles)
$\Delta\sigma_{eff}$	Effective notch stress range
$\Delta\sigma_{eq}$	Equivalent stress range
$\Delta\sigma_{hss}$	Hot-spot stress range
$\Delta\sigma_{mean}$	Mean stress range
$\Delta\tau$	Shear stress range

1 Introduction

1.1 Background

In welded steel structures, fatigue damage is a complex and progressive form of local damage which is significantly influenced by many factors, such as the magnitude of the loads, geometric complexities, discontinuities, material imperfections, temperature and environment. This local damage may originate from micro-cracks which are either already incorporated into the components during manufacture or developed by loading effects during service life. The geometric complexities and irregularities, as well as load transfer conditions, in welded steel structures, which combine to produce complicated structural behaviour, can cause difficulties when it comes to correctly estimating the effects of these factors on the fatigue strength of structural components. The difficulty in producing an accurate evaluation of the fatigue strength of structural members increases even more when it comes to the welded details that are prone to distortion-induced fatigue cracking, which is not easy to determine in the design phase and whose behaviour is completely different in crack propagation. Load-induced fatigue cracking can result in local failure, exposing the structure to failure, while deformation-induced fatigue cracking does not imply that the structure is not safe and will collapse without any repairing or retrofitting. An accurate estimation of the load and geometric effects in complex welded details is decisive for the service life of structures and underlines the importance of using a “correct” fatigue assessment method in fatigue design.

A large number of welded details with complex geometry and loading conditions that are known to be critical with respect to fatigue can be found in steel and composite bridge structures. Estimating more detailed and accurate information about the stress state of these details is very difficult without using finite element analysis. The use of the finite element method is therefore becoming increasingly widespread and is preferred for the purpose of fatigue life assessment. The use of the finite element method in the fatigue design of steel structures has enabled the development of advanced local failure methods, such as the structural hot-spot stress approach, the effective notch stress approach and crack propagation analysis on the basis of fracture mechanics. The application range of these methods with finite element analysis has increased greatly in recent decades.

One important aspect of modelling is the ability to create a finite element model without compromising the accuracy of the model in comparison to the required effort. Simplifying finite element models may reduce the accuracy of the computed stress, which can result in over- or underestimated fatigue life, since the effects of various stress-raising sources, which could have a decisive impact on the fatigue strength of the complex welded details, may not be captured accurately. It is a well-known fact that volume element-based models produce the closest resemblance, as the geometry can easily be modelled and the stiffness can be represented more accurately. However, it is not always clear how the correct determination and extraction of the stresses for a particular fatigue assessment method should be performed, even when well-constructed finite element models are used. This is due to the fact that the result of finite element analysis can be highly sensitive to the finite element (FE) modelling technique, as the stresses obtained from FE models are often in an area of high strain gradients, i.e. stress singularities. The obtained stresses may differ substantially, depending on the type and size of elements. In order to obtain reasonably accurate results when using a FE analysis, several fatigue design regulations and codes of standards have been produced, with recommendations for FE modelling for use in fatigue assessment. EN 1993-1-9 (EN1993-1-9 2005) provides only very limited information on the application of the structural hot-spot stress approach: apart from a table of detail categories, no recommendations for modelling are given, while the International Institute of Welding (IIW 2008; IIW 2010) provides the most comprehensive rules and recommendations for the modelling and stress determination of many basic welded details using both the hot-spot stress and the effective notch stress approach. Generally, the recommendations for modelling and stress determination given in fatigue design codes and standards do not cover many complex welded bridge details, such as orthotropic bridge deck details and details that are susceptible to distortional fatigue cracking. Moreover, even though the hot-spot stress approach has been used in fatigue design and analysis in tubular structures, such as offshore and ship's structures, for several decades, the method has not been applied on a larger scale to steel and composite bridges. There is therefore a lack of guidance to engineers about how properly to model a structure in order to determine the stresses suited to fatigue calculations.

1.2 Research objectives

The principal objective of this thesis was to evaluate the applicability and reliability of the most common fatigue life assessment methods when using the finite element method for complex welded structures. In order to obtain a better understanding of the methods in terms of implementation and limitation, both simple and complex welded bridge details were studied. The fatigue life assessment methods that have been considered are the nominal stress, structural hot-spot stress and effective notch stress methods. A number of frequently used bridge details have been evaluated in order to compare the equivalence of these life assessment methods. Moreover, the crack-propagation approach based on linear-elastic fracture mechanics (LEFM) as a fracture mechanics method has been considered for the fatigue evaluation of welded details with cracks.

The thesis can be mainly divided into two parts with respect to the fatigue design of welded structures. The ***first part*** focuses on the ***fatigue evaluation of welded details,*** performed in the design phase. A database of the most common bridge details collected from the literature has been used to compare the equivalence between the fatigue lives estimated by the different fatigue assessment methods. Furthermore, the application of the structural hot-spot stress and effective notch stress methods to complex welded details has been studied using various finite element models. Within the scope of this part, the objectives were to:

- Investigate the equivalence between the stress values based on the fatigue assessment methods for a number of frequently used "simple" bridge details
- Examine the suitability of the structural hot-spot stress and effective notch stress methods for application to complex bridge details, such as welded joints with cut-out holes in orthotropic bridge decks and welded details susceptible to distortional fatigue cracking
- Provide guidelines for the finite element modelling of the studied welded details for the purpose of fatigue evaluation.

The ***second part*** deals with the ***fatigue evaluation of welded details*** in the presence of cracks in existing structures, in the service phase. The main purpose of this part is to examine the behaviour of distortion-induced fatigue cracking in welded details in an existing bridge and to obtain more reliable inspection periods for the bridge structure. Moreover, the effectiveness, accuracy and applicability of the crack-propagation analysis to distortion-induced fatigue cracking in bridge structures are investigated by performing a number of crack-propagation analyses.

In this part of the thesis, the distortion-induced fatigue cracks detected in a steel girder bridge, the Söderström Bridge, located in Stockholm, were studied using 3D crack-propagation analysis based on LEFM, considering both mode-I and mixed-mode conditions. Finite element analyses using "real" traffic loads from the strain measurements were first performed to verify the accuracy of the FE models. At a later stage, crack-propagation analyses were performed considering quasi-static, constant and variable amplitude fatigue loading. Since the crack growth direction has a great influence on the computed stress intensity factors, three common crack growth direction criteria were also investigated. Within the scope of this part, the objectives were therefore to:

- Examine the behaviour of crack propagation, i.e. the reduction in the crack growth rate with extended crack growth
- Estimate the residual fatigue life of the cracked welded details and obtain more reliable inspection periods for the bridge structure
- Study the effectiveness of the retrofitting technique on the welded details in the bridge structure
- Examine the applicability of crack-propagation analysis on complex welded details with cracks in large structures considering both constant and variable amplitude fatigue loading
- Confirm the accuracy of the studied crack growth direction criteria.

1.3 Scope and scientific approach

The two parts of the study presented in this thesis are mainly independent from one another, as the first part deals with fatigue evaluation in the design phase, while the second part deals with fatigue evaluation in the service phase. The scientific approach to the research task is therefore different for each part.

For the first part of this thesis, the scientific approach shown in Figure 1-1 was followed. The approach to achieving the aims of the research work was first to study the recommendations for the fatigue assessment methods available in the literature and in various design codes. Interest focused on EN 1993-1-9 (EN1993-1-9 2005), which has very limited or no recommendations for the advanced life assessment methods (local failure approaches), and the IIW (IIW 2008; IIW 2010), which has the most extensive rules and recommendations for modelling and stress determination for the most common welded details for both the hot-spot stress and the effective notch stress methods. Secondly, a database of fatigue tests on a number of selected welded details was created by collecting fatigue test data from the literature.

As shown in Figure 1-1, the second step in this part of the study was to establish global FE models in order to determine the fatigue-critical local details and to simulate the loads effects accurately. Depending on the size of the global FE model, different types of finite element were incorporated. In the final step in this part, a local analysis of the studied welded details based on the various fatigue assessment methods was performed. To establish an appropriate level of finite element modelling and in order to determine the optimal quality of meshing for the fatigue design analysis of welded steel structures, finite element models with different modelling techniques and meshing with various sizes and types of element were investigated. The results of the evaluation were compared with the related fatigue strength curves according to EN 1993-1-9 (EN1993-1-9 2005) and IIW (IIW 2008), when they were available. As mentioned earlier, the method based on fracture mechanics for the fatigue design of welded details was not used. This method is shown in Figure 1-1 only for the purpose of indicating that this type of method can be used in the design phase by considering a fictitious crack.

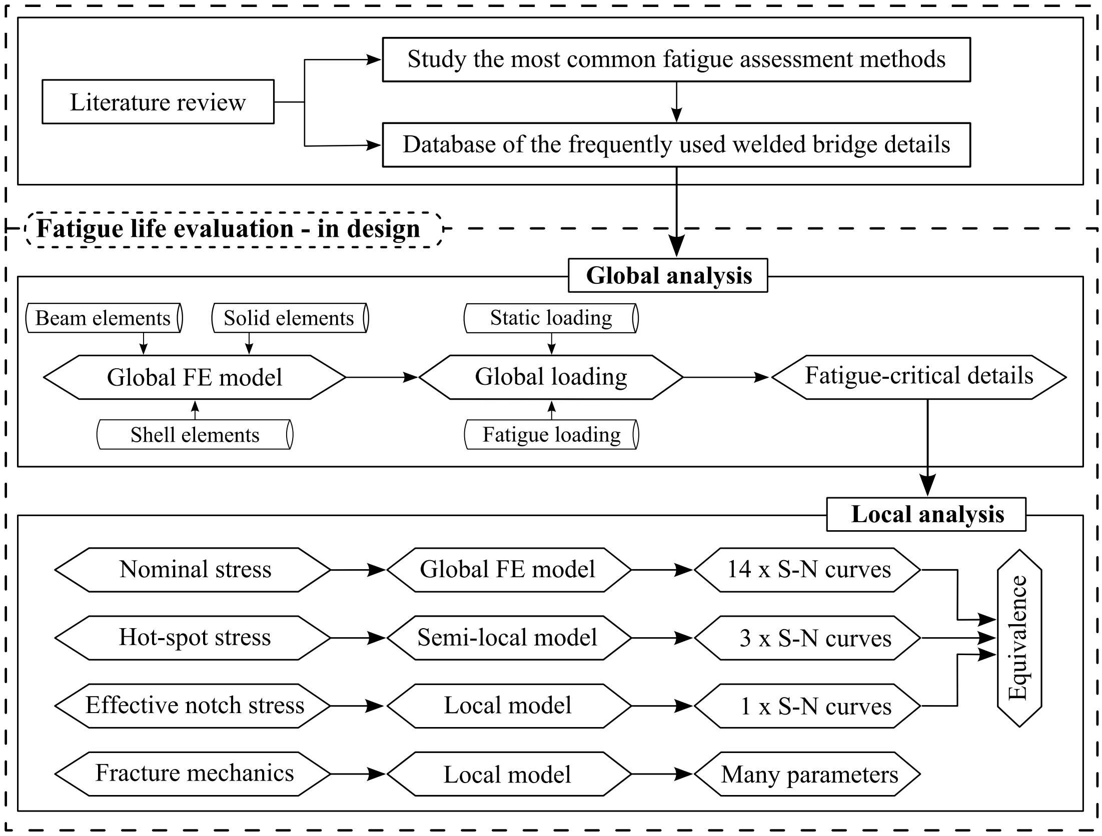


Figure 1-1 Scientific approach for the first part of the study presented in this thesis

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 of the different assessment methods were compared to answer the following questions:

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

For the second part of this thesis, the scientific approach as shown in Figure 1-2 was followed. The approach to achieving the aims of the research projects was to study a damaged railway bridge in which numerous cracks in the welded joints connecting the vertical web stiffeners to the web plate of the main girders were detected. The study began by examining the bridge structure and the detected cracks caused by out-of-plane distortion. Moreover, field measurements of the bridge during a period of two months were obtained. Secondly, global FE analyses of various 3D models with different levels of complexity were performed by incorporating different types of finite element such as beams, shells and solid elements. This step in the second part ended with model verification. In the final step in the second part, various crack-propagation analyses considering different parameters, such as loading – quasi-static, constant and variable amplitude fatigue loading –, crack direction criteria and failure modes were conducted. Moreover, the effect of the retrofitting technique for the welded details was examined.

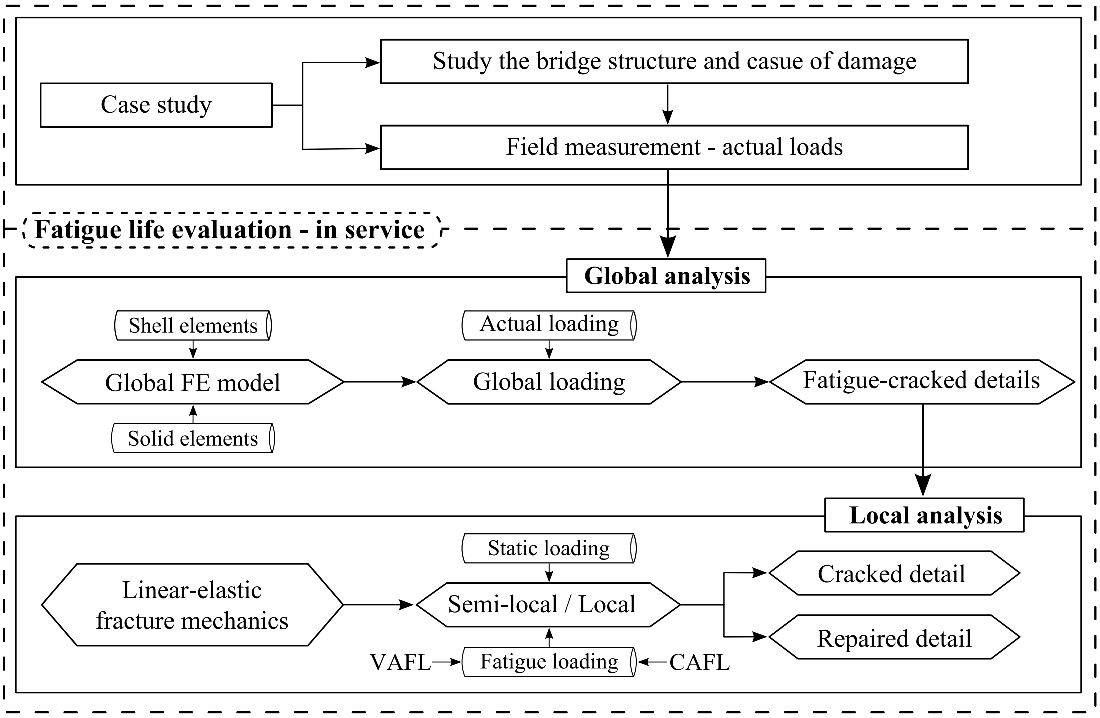


Figure 1-2 Scientific approach for the second part of the study presented in this thesis

Distortion-induced fatigue cracking, which is a common source of fatigue damage due to unforeseen local component behaviour, unintended or otherwise overlooked interaction between the bridge components, was investigated by LEFM with "real" bridge loads. The results of the crack-propagation analyses with different parameters were compared with one another to answer the following questions.

- Does the crack growth rate decrease with the extended crack growth in all crack growth directions?
- What is the accuracy of the estimated fatigue life based on the crack-propagation analyses in comparison with the service life of the detected cracks in the bridge?
- What is the effect of fracture mode conditions? Which fracture mode should be considered in crack propagation analysis?
- How large is the deviation between the crack-propagation analyses with constant and variable amplitude fatigue loading?
- Is the accuracy of the crack-propagation analyses affected by the crack growth direction criteria?

- Can the crack be prevented from propagating without any repairs?
- Is the retrofitting technique for the welded detail effective and sufficient to arrest the crack propagation?

1.4 Limitations

The welded joints studied in this thesis contain only as-welded types of joint. Post-weld-treated welded joints and high-strength steels are not included in this study. The fatigue test data evaluated in this thesis contain only fatigue tests performed under constant amplitude fatigue loading. The fatigue test data evaluated using the fatigue assessment methods contain only failure at the weld toe.

Interest focuses primarily on analytical procedures based on the fatigue evaluation of welded details using the finite element method.

Only high-cycle fatigue is considered in this thesis. Low-cycle fatigue is outside the scope of this thesis.

Using fracture mechanics methods for the fatigue assessment of steel structures in the design phase is not covered, but their use in the fatigue assessment of existing steel structures is included. The focal point of the crack-propagation analyses was to study the applicability and accuracy of 3D crack-propagation analysis in large structures.

1.5 Outline of the thesis

This thesis consists of five papers and an introductory part which gives the background, analyses and results for the subjects dealt with in the papers. Moreover, the results of two different crack-propagation analyses of the cracked welded detail for the repairing technique are presented. The chapters are organised chronologically according to the process used in the project.

Chapter 2 – Fatigue in welded structures: This chapter gives an introduction to fatigue in welded details. A brief description of the factors that affect the fatigue strength of welded details and are related to the subject is given in this chapter.

Chapter 3 – Fatigue evaluation methods: This chapter presents a short background to the fatigue assessment methods for evaluating welded details investigated in this thesis.

Chapter 4 – Fatigue evaluation using FEM – in design: In this chapter, the application of the fatigue assessment methods which are usually used in the design phase for both simple and complex details is presented. The scientific approach for the first part presented in the previous section is used in this chapter.

Chapter 5 – Fatigue evaluation using FEM – in service: This chapter gives a very brief summary of the case studies presented in the appended papers; both the outlined and unmentioned details and conclusions are presented. The scientific approach for the second part presented in the previous section is used in this chapter.

Chapter 6 – Conclusion: is the final chapter in which the conclusions based on the results of the evaluation work are presented. Suggestions for future research are also given.

2 Fatigue in welded structures

2.1 Introduction

In the design of steel structures, fatigue is an important and decisive limit state for structures subjected to fluctuating loads, such as bridges, cranes, offshore, ships and so on. Fatigue is a time-dependent damage and failure mechanism composed of a process of crack initiation and propagation. When a structural component is subjected to repeated cyclic loads, the process of crack initiation may start at stress amplitudes below the yield stress as a result of localised, irreversible plastic deformation generated by slip band movements (Schijve 2009). In the process of crack propagation, the crack formed in the crack initiation phase will start to grow if the crack driving force is larger than the crack growth resistance of the material. Finally, fatigue failure following initiation and propagation may occur with continued loading. Fatigue failure is therefore a process of damage accumulation, depending on the crack initiation and the accumulation of the damage during the crack propagation cycle by cycle during the service life. On the other hand, it is worth mentioning here that, although crack initiation and propagation follow one another, the mechanism is different in these two processes. The initiation process is heavily dependent on material properties and on irreversible plasticity, resulting in the formation of intrusions and extrusions, which requires cyclic shear stress, while the propagation process is mainly dependent on the tensile[1] stress.

Fatigue in welded structures is an even more complex physical process influenced by many quantities affecting the stress/strain field at the point of damage development. In welded structures, depending on the type and shape of the joint, localised high stress concentrations can occur at fatigue-critical locations due to abrupt changes in stiffness. Furthermore, welding introduces a number of geometric imperfections and defects in the weld itself. The fatigue life of welded structures is therefore mainly covered by crack propagation, as the crack initiation is extremely short and negligible, due to welding.

2.2 Factors influencing fatigue performance

The fatigue strength of steel structures is influenced by a large number of parameters, such as the type of load, structural details, material, surface and environment. However, some of these factors, such as material and surface, lose their importance and effects when it comes to the fatigue performance of welded structures. In this section, the two main factors, fatigue loading and structural details, which are the most important factors influencing the fatigue performance of welded steel structures (Fisher et al. 1974) and therefore have a decisive effect on the estimation of the fatigue life of welded structures and the work performed in thesis, are presented.

2.2.1 Fatigue loading

Fatigue loading, producing a history of cyclic stresses in structural members, can be defined as fluctuations in the applied loads, such as traffic loads, pressure changes, vibrations, temperature differences and wave loads. During their service life, large

[1] In the propagation phase, shear deformation is still driven.

welded structures are usually subjected to variable cyclic loading consisting of a somewhat complex load-time history. Not only are the stress ranges generated by these loads of varying amplitude, but other stress parameters that might affect the fatigue performance, such as mean stress values and the sequence of loading cycles, are also fairly stochastic. In order to deal with these complex loading situations, the variable amplitude stress ranges generated by the “real” loads are represented as one or more constant amplitude stress ranges, which are easier to handle in design calculations. This stress transformation can be performed by a stress cyclic counting method, such as the Rainflow or the Reservoir method. The stress and its parameters are illustrated in Figure 2-1 for both constant and variable amplitude fatigue loading.

The most important and primary parameter influencing fatigue life is the stress range ($\Delta\sigma$), where each stress cycle contributes to the damage accumulation in fatigue failure. Constant amplitude fatigue loading is defined as cyclic loading with constant amplitude and a constant mean load ($\Delta\sigma_m$) (Schijve 2009). The stress ratio (R) is the ratio of minimum to maximum stress indicating the effect of mean stress, which is a secondary parameter influencing fatigue life. The effect of mean stress is ignored in the fatigue design of welded components due to the presence of high residual stress from welding (Gurney 1968; Maddox 1975). The importance and effect of mean stress is, however, obvious in cases with stress-relieved welds and post-welding treatment (Nussbaumer et al. 2011).

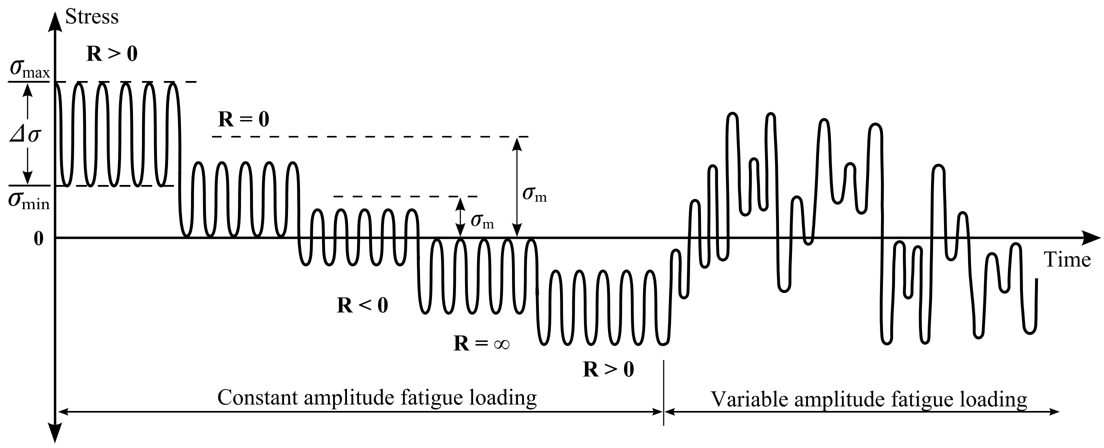


Figure 2-1 Stress parameters defined in fatigue loading

As pointed out earlier, fatigue damage and failure in welded structures occur at relatively low stress levels, below the yield stress of materials. The elastic behaviour is therefore suitable for use in the estimation of the fatigue stresses to be used in design.

2.2.2 Structural detail

The fatigue strength of a welded detail is directly dependent on the geometric configuration of the detail, crack location and dimension. The effects of stress concentration reducing or increasing the fatigue strength of welded details are influenced by the complexity, shape, thickness and discontinuities of the detail, such as notch roots and welds (Nussbaumer et al. 2011).

It is a known fact that sharp changes by attached members, holes and notches, i.e.

abrupt changes in stiffness, introduce changes in stress distribution producing stress-raising sources. The resistance of structural details to fatigue is therefore governed by the type of detail and its geometric properties. The geometric properties are also associated with the weld, which introduces notches and discontinuities causing further stress-raising sources and thereby locations for fatigue cracking. The main effects of welding on the fatigue strength of welded details are the shorter or negligible crack initiation period and, by introducing high residual tensile stress during welding, the material properties of steel in relation to the fatigue performance are negligible.

Another factor in a structural detail which influences the fatigue strength of welded details is the effect of plate thickness, resulting primarily in lower fatigue strength as the thickness increases. Gurney (Gurney 1968) pointed out, on the basis of experimental evidence and fracture mechanics analyses, that the effect of the plate thickness could be significant, with increased plate thickness with the same geometry subjected to the same magnitude of stress, i.e. the stress gradient effect. This means that the stress field around the weld toe is larger in thicker plates and the stress in the thickness direction at the weld toe will reduce more slowly than it does in thinner plate, an effect of the steepness of the stress gradient. Moreover, welding introduces high residual tensile stresses in the welded detail and the magnitude of introduced residual welding stress generally increases with increasing thickness.

In the fatigue design of welded structures, the deleterious effect of increased plate thickness on fatigue strength is taken into account by multiplying the fatigue strength with a thickness reduction factor[2]. Various standards and codes of fatigue design incorporate a thickness factor for thicker plates than the reference thickness which was chosen in the range between 16mm and 32mm when using the nominal stress or hot-spot stress method as a fatigue assessment method. The thickness correction factor that was first introduced into fatigue design rules appeared in the publication of the Department of Energy Guidance Notes in 1984 (Gurney 1995). In EN 1993-1-9, the thickness reduction factor for thicker plates is considered by using the following expression:

$$\Delta\sigma = \Delta\sigma_{nom,hss}\left(\frac{t_{ref}}{t}\right)^{n} \qquad \textit{Eq. 2-1}$$

where $\Delta\sigma_{nom,hss}$ is the computed stress of the joint plate according to the nominal or hot-spot stress method, t is the plate thickness, t_{ref} is the reference thickness[3] and n is the thickness exponent[4].

2.3 Fatigue strength curves – S-N curves

The fatigue life assessment of welded steel structures is commonly based on the two main methods; the classification method (also known as the S-N curve method) and

[2] The need to use a thickness reduction factor for the fatigue life evaluation is actually dependent on the fatigue assessment method that is used. This reduction factor does not need to be used for local assessment methods, such the effective notch stress method and the 1mm stress method, as the effect is included in the calculated stress, see next chapter.

[3] The reference thickness is 25mm in EN 1993-1-9, DNV and IIW, while this thickness is defined as 16mm in BS7608:1993.

[4] In general, the thickness exponent is not constant and is given in design codes depending on the type of joint.

the methods based on fracture mechanics. The classification method is principally based on the determination of the design stress in the fatigue-critical region by using a stress determination concept and comparing a relevant S-N curve to describe the fatigue life of the studied detail. This method is a standardised fatigue design method and is based on the assumption that the material behaviour of the whole structure, including the fatigue-critical locations in which cracks are expected to initiate, is elastic. The most common stress concepts utilised for determining the fatigue stress in fatigue-critical details will be presented in the next chapter.

The fatigue strength data for welded details are presented in the form of S-N curves (also called Wöhler curves) in a logarithmic relationship between the stress range ($\Delta\sigma$) and the number of stress cycles (N) to failure. This linear relationship in a logarithmic scale is expressed as follows:

$$\log(N) = \log(N_C) - m \cdot \log(\Delta\sigma) \qquad \textit{Eq. 2-2}$$

or

$$N = \frac{N_C}{\Delta\sigma^m} \qquad \textit{Eq. 2-3}$$

where m is the slope of the S-N curve.

S-N curves are mainly provided for a variety of structural details and are obtained from experimental stress-life data. Figure 2-2 shows the S-N curves recommended by EN 1993-1-9 (EN1993-1-9 2005). S-N curves, also called fatigue strength curves, are normally defined as their characteristic fatigue strength in N/mm^2 at two million stress cycles under constant amplitude fatigue loading. The S-N curves recommended by EN 1993-1-9 are obtained by evaluating the experimental data using the linear regression analysis based on a 75% confidence level of 95% probability of survival (EN1993-1-9 2005). The constant amplitude fatigue limit according to EN 1993-1-9 is assigned to five million stress cycles (see Figure 2-2), while in IIW (IIW 2008) this limit is 10 million stress cycles. In this thesis, fatigue strength curves according to EN 1993-1-9 are used when available for the nominal stress and hot-spot stress methods. For the effective notch stress method, however, the fatigue strength curves recommended by IIW are used.

For constant amplitude fatigue loading, the infinite fatigue life obtained for the stress ranges is below the constant amplitude fatigue limit, while, for variable amplitude fatigue loading, the stress ranges below the cut-off limit yield infinite fatigue life. It should be remembered that variable amplitude loading actually means constant amplitude loading with varying stress ranges.

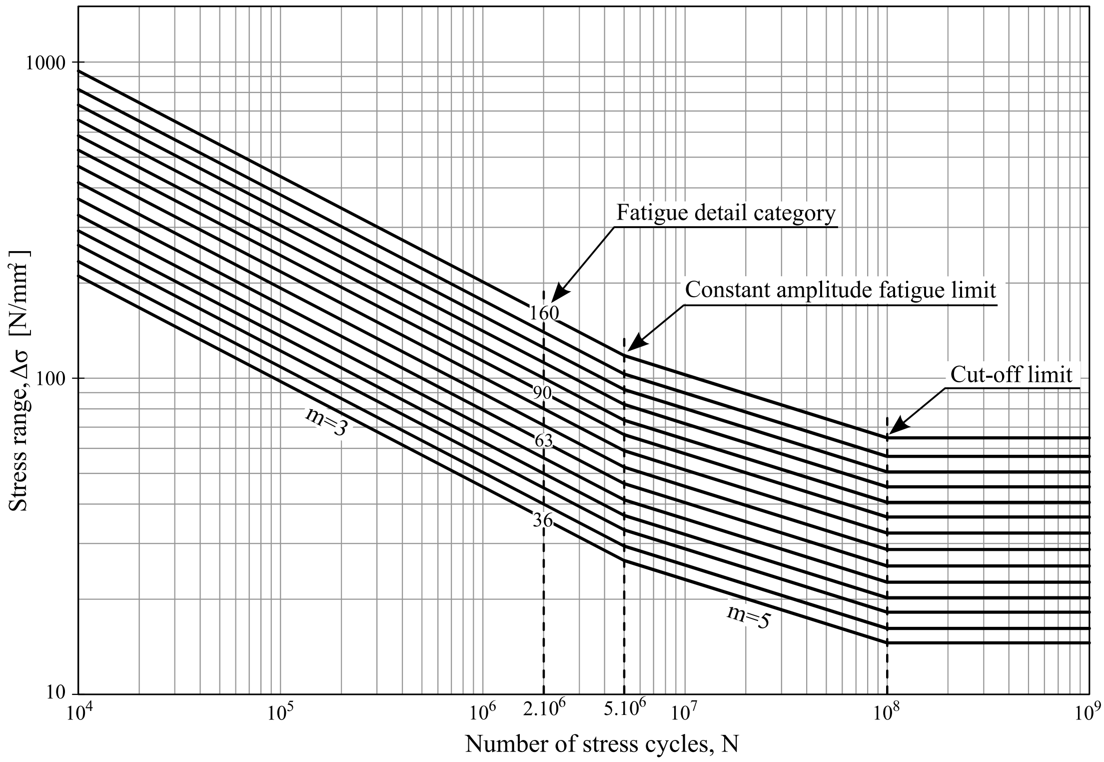


Figure 2-2 Fatigue strength curves for normal stresses according to EN 1993-1-9

3 Fatigue assessment methods

3.1 Introduction

A variety of fatigue assessment methods have been introduced to estimate the fatigue life of welded steel structures under fatigue loading. The main methods which are among the most common and have been adopted in structural steel design codes are divided into two groups as follows:

1. The ***classification method*** (also called the *S-N curve approach*), including the nominal stress approach, structural hot-spot stress approach and effective notch stress approach and
2. The ***fracture mechanics method,*** such as linear-elastic fracture mechanics for high cycle fatigue.

The fatigue design and assessment of welded structures is traditionally performed using the classification method as the basis for estimating the total fatigue life of a structural detail using an S-N curve related to the applied stress range. A second method used in a fatigue design context is the fracture mechanics method, which is a relatively complex method.

Assessing fatigue life is a complex procedure and requires a complete knowledge of the whole structure and the assessment methods that are going to be applied. The welded details in large steel structures can experience different load effects depending on their geometric configuration and complexity level. The “best” assessment method for the fatigue design of a welded detail can therefore be dependent on the ability of the methods to capture the load effects in the detail. In this chapter, the most common methods recommended in fatigue design codes for the fatigue assessment of welded steel structures and studied in this thesis are briefly presented.

3.2 Nominal stress approach

The nominal stress approach is the simplest and most commonly 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 linear theory of elasticity. In view of the fatigue design, the nominal stress is determined by excluding the local stress-raising effects of the welded joints but including the effects of macro-geometric features, the geometric configurations or irregularities of the main component, if these effects have not already been included in the corresponding S-N curves (IIW 2008; Niemi 1995). The geometric configurations and irregularities can be defined as a cut-out hole, a discontinuity in a cross-section or a bend/curve in a beam; in other words, geometric modifications that often have a considerable effect on the stress distribution across the entire cross-section.

The fatigue classes and corresponding S-N curves based on the nominal stress are available in most design codes and guidelines. As the use of this method is always associated with a specific geometry and load configuration, as well as crack location, the studied welded detail must be similar to the detail given in the design code. Care must therefore be taken to ensure that the stress-raising effects of the welded joint are disregarded, while the effects of macro-geometric features are included when calculating the nominal stress, as shown in Figure 3-1.

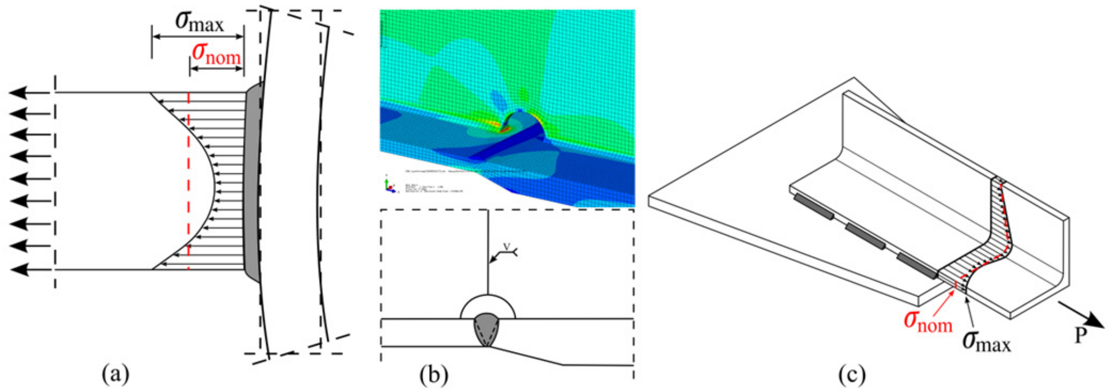


Figure 3-1 a) Local flexibility/local deformation; b) local flange bending at thickness transition and c) local force transfer

The limitations and difficulties involved in estimating the nominal stress can be clearly seen in complex details and in details with complex load situations, as shown in Figure 3-1. At a more global level, load effects, such as shear lag effects, normal stresses due to torsion and warping and flange curling, might be substantial and are often difficult to estimate in really complex structures. It is even more difficult to estimate and capture local stress concentrations that result from local flexibilities (Figure 3-1 (a)) and abrupt changes in stiffness (Figure 3-1 (b)) and details with local force transfer, such as the detail shown in Figure 3-1 (c).

Furthermore, in large structures with complex details and loading conditions, such as bridge joints susceptible to distortional cracking – in which an accurate estimation of the load effects in the detail is often difficult to obtain – a local stress concept, which takes account of the stress-raising effects due to the geometry and interaction of structural members, might provide an accurate estimate of the fatigue design stress. Using the nominal stress concept in such cases can yield unrealistic results. This type of complex detail therefore requires advanced fatigue life evaluation techniques based on accurate fatigue design stress calculations using the finite element method.

3.3 Structural hot-spot stress approach

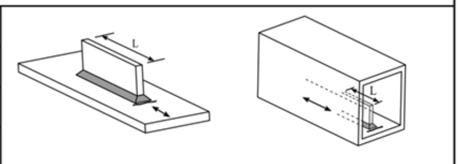
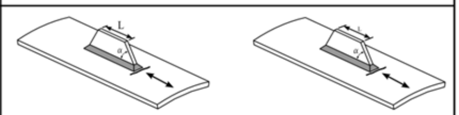
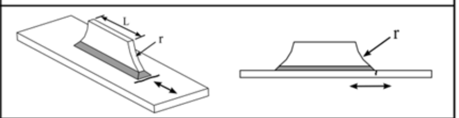
The structural hot-spot stress method (or only hot-spot stress method) has been developed to enable the evaluation of the fatigue strength of welded structures in cases where the nominal stress is difficult to estimate because of geometric and/or load complexities. This method has been used in the fatigue design of pressure vessels and welded tubular structures since the 1960s. The method was subsequently transferred to non-tubular welded joints in ships and FPSOs (Floating Production, Storage and Offloading units) (Marshall and Wardenier 2005; Niemi 1995; Radaj et al. 2006) and has finally become a codified procedure for evaluating the fatigue life of welded structures.

The principle of the structural hot-spot stress method is to base the fatigue verification on the structural/geometric stress at the point of crack initiation (usually a weld toe), the so-called hot-spot points[5]. The calculated stress will thus include the geometric stress concentrations generated by the geometry of the detail, as well as any local load

[5] These points are also called reference points, i.e. the critical points in the vicinity of the weld toe; the hot-spot points.

redistribution effects, such as those caused by shear lag or warping (Fricke 2002; Fricke et al. 2002; Niemi 1995; Niemi and Marquis 2002). One consequence is that the number of *S-N* curves needed for fatigue evaluation using the structural hot-spot stress method is substantially reduced, which is another advantage of this method.

An illustrative example in Figure 3-2 explains the principal difference between the conventional nominal stress method and the structural hot-spot method. While six different detail categories are needed to estimate the fatigue strength of a simple non-load-carrying attachment, based on different geometric parameters, only one fatigue category is needed when the structural hot-spot stress method is used. The effect of the stress concentration caused by the geometry of the detail is – in the case of the structural hot-spot stress method – accounted for on the load-effect side, while, in the nominal stress method, this effect is covered on the resistance side (by assigning different fatigue categories).

Nominal stress method		
Detail category	Construction detail (longitudinal attachments)	
C80	$L \leq 50$mm	
C71	$50 < L \leq 80$mm	
C63	$80 < L \leq 100$mm	
C56	$L > 100$mm	
C71	$L > 100$mm $\alpha < 45°$	
C80	$r > 150$mm	

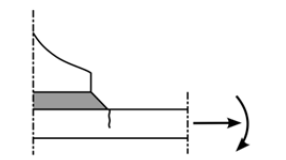
Structural hot-spot stress method	
Detail category	Construction detail (longitudinal attachments)
C100	

Figure 3-2 Fatigue class recommendations based on the nominal and hot-spot stress methods according to EN 1993-1-9

The structural hot-spot stress is usually derived from finite element models of the structure or the structural element or detail under consideration. As a result, both global and local stress effects, such as those mentioned above, are directly and accurately accounted for in the calculation of load effects. These effects might be substantial, even in elements with relatively simple geometry and – for fatigue-loaded structures – might determine the fatigue performance of the structure. It is worth pointing out again here that, if the hot-spot stress in the detail shown in Figure 3-2 is obtained from a finite element analysis, the effects of all essential geometric parameters on the stress in the detail are directly and more accurately accounted for (width of main plate, shape, length and thickness of attachment and so on).

The **fatigue strength** of any welded detail is basically a function of three main parameters:

1. The stress concentration effects caused by detail geometry, also called geometric discontinuities
2. The local stress-raising effects caused by the shape and dimensions of the weld and the surrounding region
3. Local weld defects such as undercuts, porosities, lack of fusion and so on

When fatigue verification is performed using the conventional nominal stress method, all these parameters are accounted for on the fatigue strength side, i.e. in the process of selecting a suitable S-N curve. As a result, as was mentioned in connection with Figure 3-2 above, the same structural detail can be assigned different S-N curves based on the parameter (or parameters) that govern the fatigue strength of that detail. Only nominal stresses are therefore needed in the fatigue verification. On the other hand, the stress range used in fatigue design with the structural hot-spot stress method already includes the stress-raising effects, emanating from geometric discontinuities and/or caused by complex loading conditions (point 1 above). Including the stress-raising sources in the design stress calculations leads to the main advantage of the structural hot-spot stress method for welded structures. The S-N curves that are used with this method only need to cover the local stress-raising effects and the local weld defects in different welded details, which require only a few S-N curves. However, local stress effects due to the weld itself (point 2 above) are excluded in the derivation of the hot-spot stress and need to be accounted for on the fatigue resistance side.

Figure 3-3 shows a simple detail with the stress distribution in front of the weld toe at the location of anticipated crack initiation. The stress in the main plate at this location is composed of: 1) nominal membrane stress; 2) bending stress caused by the geometry of the detail; and 3) non-linear stress caused by the weld shape and local weld geometry. Following the definition of hot-spot stress, excluding the non-linear local stress, results in a combination of membrane and bending stresses which together give the hot-spot stress in the detail.

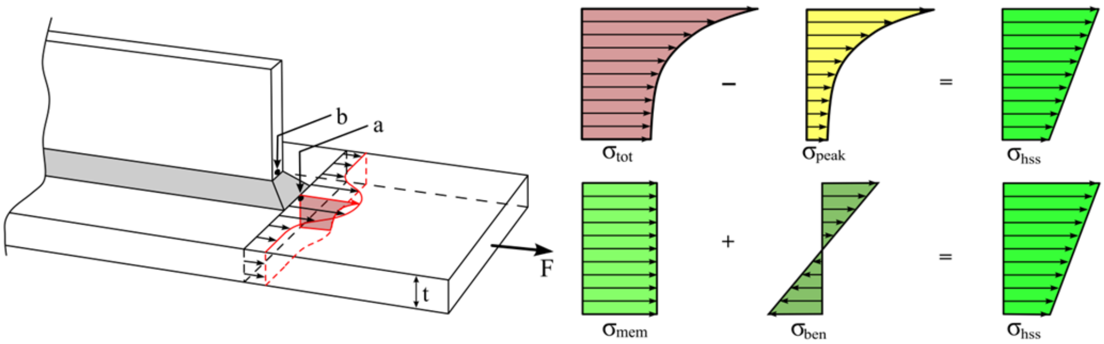


Figure 3-3 Stress distribution in front of weld toe and definition of the hot-spot stress

The calculation of the structural hot-spot stress should be performed assuming linear-elastic material behaviour. Since the structural hot-spot stress – by definition – is to be calculated at the point of crack initiation (i.e. at the weld toe), the method solves the problem of stress singularity at these sharp points. The "correct" theoretical value of the stress at the weld toe is infinity. With reference to this problem, various stress linearisation techniques are proposed to exclude the non-linear stress component close to the weld toe. To determine the structural hot-spot stress, a distinction should be drawn between two types of "hot spot", type "a" and type "b", as shown in Figure 3-3. The main difference between these two types is seen in the stress distribution through the thickness of the plate with anticipated cracking. While the stress in type "a" hot spots varies substantially through the thickness of the cracked plate, it is more uniform in type "b" hot spots. It follows that a linearisation of the stress in type "a" details should consider the plate thickness as a parameter, while the linearised hot-spot stress in type "b" details is insensitive to the plate thickness.

The design value of the stress range for fatigue verification using the structural hot-spot stress method can be obtained by using stress concentration formulas for specific details (analytically), using FEM or other numerical methods (numerically), and by measuring the strain at reference points (experimentally). The main disadvantage of analytical formulas for determining hot-spot stress is their limited applicability. Even though stress concentration formulas for calculating the structural hot-spot stress are widespread in the literature, they are usually applicable to the particular detail within specific geometric and dimensional limits. The determination of the structural hot-spot stress from testing using strain gauges was the main technique that was used when the method evolved some decades ago (Radaj et al. 2006). Today, with the widespread use of the finite element method for the analysis and design of structures, numerical calculations of the stresses in welded details are by far the most common way of performing fatigue design and analysis using the finite element method.

For the purpose of fatigue verification using the hot-spot stress method, FE models are generally created assuming ideal geometry in the structural detail. Possible unintended misalignments and other types of imperfection are indirectly covered on the resistance side, i.e. in the S-N curves. S-N curves for the hot-spot stress method are derived from statistical analyses of test data, where imperfections – within specific limits – exist in the test specimens. Other geometric imperfections or misalignments outside the range covered by the S-N curves should be accounted for, either directly in the model, or by employing a relevant stress concentration factor.

The stress values obtained from FE models may also differ, depending on element size and type and whether or not the welds are represented in the model. It is therefore necessary to establish ***consistent procedures*** for the determination of the structural hot-spot stress in welded details, so that a correct correlation is obtained between calculated stresses and fatigue lives for these details. This modelling and mesh dependence is the main disadvantage of the structural hot-spot stress approach. The recommendations provided by the International Institute of Welding, IIW (IIW 2008), provide the most comprehensive rules for the application of the structural hot-spot stress method. EN 1993-1-9 (EN1993-1-9 2005) also allows the application of this method for the fatigue verification of welded structures. However, apart from a list of structural details with the corresponding fatigue design curves, EN 1993-1-9 provides no recommendations or instructions regarding the application of the method, i.e. modelling and extrapolation techniques and type of hot-spot points.

One major feature that is always needed in the calculation of the structural hot-spot stress from an FE model (irrespective of the details of the FE model) is the process of ***stress linearisation***. This process is necessary in order to separate the membrane and bending stress components in the detail from the non-linear stress peak generated by the local weld geometry, see Figure 3-3. Stress linearisation is commonly performed by means of ***surface linear or quadratic stress extrapolation*** from specific points some distance away from the region affected by high local stress gradients. In some special cases, the linearisation of stress through the thickness might be needed to obtain more accurate results.

The linear surface stress extrapolation technique involves reading the nodal stresses at two reference points and then using these stress values to extrapolate a value for the structural hot-spot stress at the weld toe. This is the most common procedure[6] to derive the hot-spot stress from FE analysis. The notch stress (non-linear stress) due to the weld itself is excluded through the linear extrapolation of surface stress from the

[6] Recommended by most design codes and regulations; IIW, DNV, ABS, GL, AWS

two reference points, which should be located outside the region affected by the local weld geometry. Extensive strain measurements and FE analyses of welded details show that the non-linear notch stress effects usually diminish a small distance from the weld toe. This distance was regarded as a function of the plate thickness, around 0.3t[7] (Haibach and Oliver 1974). Linear surface stress extrapolation can be used for welded details with type "a" or type "b" hot spots. The location of the two reference points for stress extrapolation is, however, different for these two types. The location of stress extrapolation points is also dependent on the mesh density in FE models.

Figure 3-4 shows the position of stress extrapolation points for type "a" and type "b" hot spots in FE models with "fine" and "coarse" mesh respectively. The reference points on the stress curve are normally located at the weld toe. For a type "a" hot-spot point, the first reference point closest to the weld toe is positioned at 0.4t or 0.5t in models with fine or coarse mesh (IIW 2008). These values are selected in order to include the effect of detail geometry but exclude the effect of the notch stress due to the weld profile, as mentioned before. The second point is positioned at 0.9t, 1.0t or 1.5t from the weld toe, depending on the mesh density, which is accepted as the point at which the effect of the geometric features of the detail will diminish.

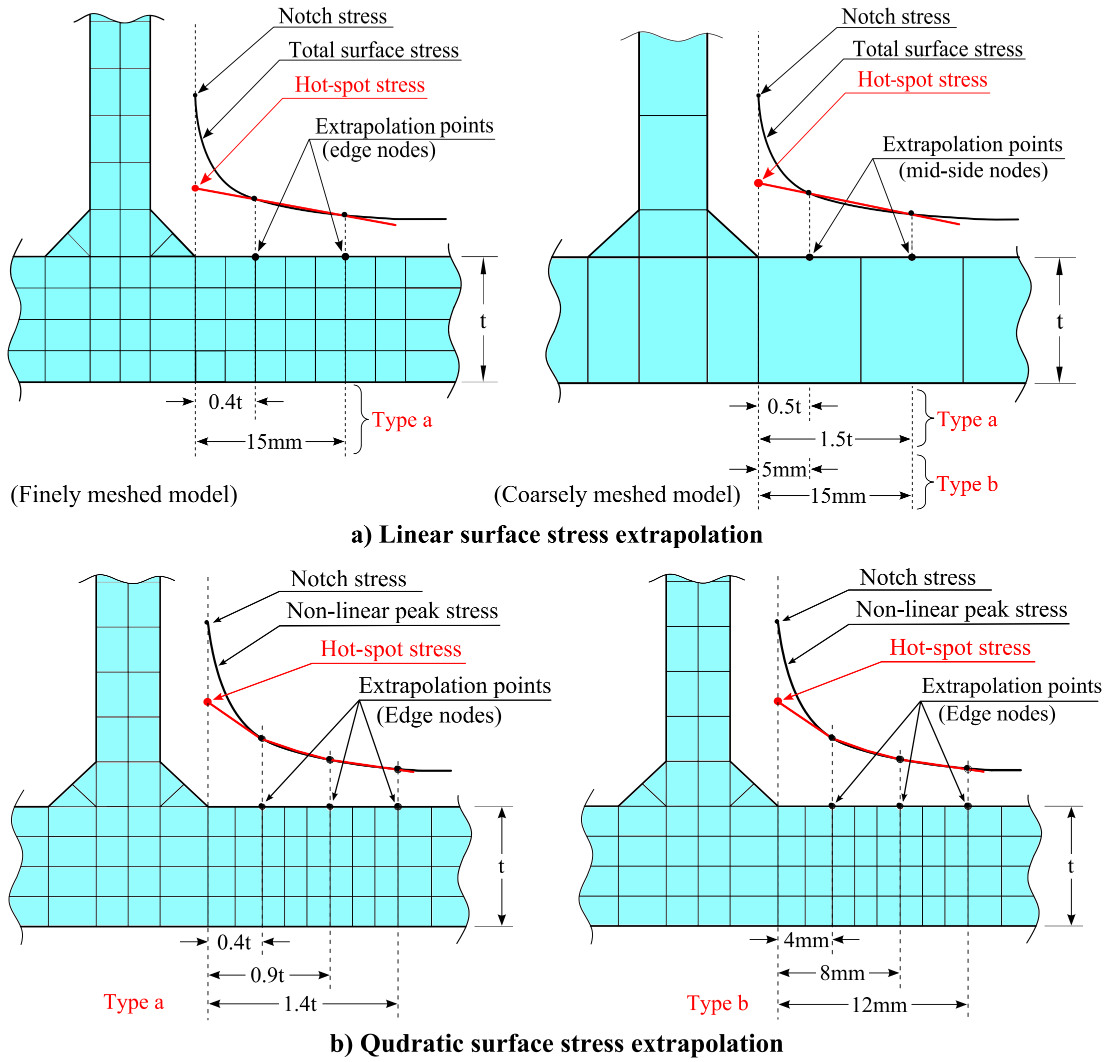


Figure 3-4 a) Linear and b) quadratic extrapolation of surface stress

[7] Haibach measured the stress at this point by assuming that the stress here is free from notch stress

For fatigue-critical points located at the plate edges (type b), the same surface stress extrapolation procedure can be used, but with different locations for the reference points (IIW 2008). In this case, the stress is uniform through the thickness of the plate and the location of the extrapolation points is therefore no longer a function of plate thickness (Fricke 2001; Niemi and Tanskanen 1999). For linear extrapolation, using the reference points located 5mm and 15mm respectively in front of the weld toe is recommended in IIW (IIW 2008) for coarsely meshed models, see Figure 3-4 (a). For structural details with type "b" hot spots, the extrapolation recommended for FE models with fine mesh is the quadratic extrapolation, as shown in Figure 3-4 (b).

It should be noted that the properties of the finite element model (i.e. element size and element type) usually influence the derived stresses in the hot-spot region. For this reason, the mesh – whether coarse or fine – should comply with the rules of stress extrapolation given in the design codes. For example, FE models with coarse mesh usually have one quadratic FE element through the thickness of the plate (Doerk et al. 2003; Fricke 2001; Lotsberg 2004; Poutiainen 2006; Poutiainen et al. 2004). The stress extrapolation points are therefore found at the element intermediate nodes, as shown in Figure 3-4 (b). Recommendations relating to meshing techniques and the selection of suitable element types will, however, be presented in the next chapter.

In some specific cases, linear extrapolation may lead to non-conservative results and the more accurate method using the quadratic (non-linear) surface stress extrapolation procedure is recommended. A typical example is found in welded details where the stress distribution is strongly non-linear near the weld toe due to geometric complexities or/and local loading conditions. Three reference points are required to obtain the structural hot-spot stress with quadratic extrapolation. When it comes to linear extrapolation, the locations of these reference points are different for type "a" and type "b" hot spots, see Figure 6-10. For "type a" hot spots, the reference points should be located 0.4t, 0.9t and 1.5t from the weld toe, again dependent on the thickness of the cracked plate. For details with "type b" hot spots, the reference points have constant distances; 4, 8 and 12mm from the weld toe. Apparently, the above-mentioned reference points require finely meshed FE models. In order to obtain sufficiently accurate stresses at the extrapolation points, the element mesh close to the weld toe must be sufficiently fine and the reference points must coincide with element edge nodes. The stress values at the reference points are the surface stresses at the nodes, i.e. nodal stress (nodal stress values are the average values of stress at each element edge node).

Apart from the two common stress extrapolation techniques, a simpler approach has been suggested by Fricke (Fricke 2001). In this case, the value of the structural hot-spot stress is read directly from one point, 0.5t from the weld toe. Neither extrapolation nor integration (as in other techniques covered in Section 6.5) is needed. Previous studies have shown promising results when the one-point stress method was used to evaluate available fatigue test results. For example, a smaller scatter was observed in test results when the stress in these tests was calculated with this method in (Fricke 2001) and (Storsul et al. 2004). It has, however, been shown that, in order to get a good fit with fatigue test results, the structural hot-spot stress obtained from the one-point stress determination method should be magnified by a factor of 1.12. This is equivalent to one S-N curve reduction (i.e. from C90 to C80 or from C100 to C90). When a finite element analysis is performed using a model with an element size of $t \times t$, which is normally practical for structural analysis, the point at a distance of $0.5t$ from the weld toe is a useful validation. The stress at this point located in the mid-element side of a second-order element can be read directly from the FE model.

3.3.1 Fatigue verification using structural hot-spot stress

The fatigue verification of welded details using the structural hot-spot stress method follows the same procedure applied in the nominal stress method. It goes without saying that, as the fatigue load effects are different in these two methods, different S-N curves also have to be used when the hot-spot stress method is applied. The fatigue classes given in EN 1993-1-9 (EN1993-1-9 2005) for use with the structural hot-spot stress method are similar to the nominal stress-based S-N curves, with the same slope and limit for constant amplitude fatigue loading (CAFL), i.e. a line with a constant slope of 3.0 in the logarithmic scale and a CAFL at five million cycles.

The structural hot-spot stress is defined by EN 1993-1-9 as the maximum principal stress in the plate where toe cracking is anticipated, taking account of the stress concentration effects due to the overall geometry of a particular structural detail. Apart from the detail categories for the structural hot-spot stress method, EN 1993-1-9 provides no information or recommendations as to how the structural hot-spot stress in welded details can or should be determined. It should be mentioned again that the fatigue classes given in EN 1993-1-9 already cover the effect of unintended small misalignments and imperfections in welded joints. However, significant misalignments, which reduce fatigue strength due to secondary bending stress, must be considered explicitly during the stress determination stage.

3.4 Alternative structural stress approaches

The structural hot-spot stress approach is generally a procedure of transferring the fatigue strength calculations of welded details to a semi-local analysis level where the effect of detail geometry is included in the calculation of load effects. As stated previously, the stress distribution close to the weld toe (whether surface stress or through-thickness stress) is generally highly non-linear. This stress non-linearity has to be excluded when the load effects for fatigue verification are calculated. This can be achieved either through stress extrapolation, or by the linearisation of the stress into a combination of membrane and bending stress. Stress linearisation also means – at least in principle – that the derived structural stress becomes “mesh insensitive” (equilibrium of forces has to be fulfilled at any section in the detail).

The concept of linearised structural stress over the plate thickness was firstly developed by Radaj (Radaj et al. 2006) and subsequently modified by Dong at the Battelle Institute (Dong 2001; Dong and Hong 2003; Dong et al. 2002). Another, relatively new concept for determining the structural stress has been proposed by Xiao and Yamada (Xiao and Yamada 2004), where the computed stress value at a depth of 1mm below the surface at the weld toe is assumed to give a good representation.

3.5 Fatigue design using the effective notch stress approach

Stress raisers or notches emanating from geometric discontinuities, such as holes, sharp local changes in geometry and other geometric discontinuities, are fairly common and cannot be avoided in welded steel structures. These highly localised stress raisers have a significant influence on the fatigue strength of welded details (Gurney 1968; Maddox 1991; Radaj and Zhang 1993). The stress at these localised stress raisers is often referred to as the "notch stress". The notch stress in welded joints is the total local stress caused by both the component geometry and the local stress raiser, e.g. the shape and local geometry of the weld itself and the local surrounding region. A notch stress at the weld toe or root in a welded joint can attain very high levels, depending on the notch "sharpness" or what is more frequently referred to as the "notch radius" (Radaj et al. 2006). For very sharp notches (radius approaching zero), the theoretical elastic notch stress tends to infinity, i.e. the stress is referred to as being "singular". Singular (infinite) stresses cannot – of course – be used for fatigue evaluation. To overcome this problem, the effective notch stress was defined as the average stresses over a certain distance (2D) or volume (3D) (Radaj 1996). Since it is not possible to measure "effective notch strains" at weld toes or roots, the effective notch stress cannot be determined experimentally using strain gauges, as is the case in the hot-spot stress method.

The basic concept of the effective notch stress method states that, if the local stress at the point of crack initiation in a welded detail is calculated – assuming a predefined reference notch radius – the fatigue strength of this detail can be related to a single fatigue strength curve, a common S-N curve. The term "local stress" implies that the welded detail should be modelled in details, including the welds, weld shape and any significant local geometric discontinuities in the region of anticipated crack initiation. The effective notch stress method was first proposed by Radaj (Radaj 1996; Radaj et al. 2006), who took account of stress averaging in the micro-support theory according to the Neuber Rule, with a fictitious radius of 1mm for plate thicknesses of 5mm and above (IIW 2008). The reference notch radius, as illustrated in Figure 3-5, is calculated assuming the worst-case conditions[8] (ρ=0) for welded joints in order conservatively to account for the variation in local discontinuities at the weld toe or root, where the notch radius in real welded joints varies substantially. When the micro-support length (ρ*) is taken as 0.4mm with the constraint factor (s) of 2.5 for steel members, the final rounding radius of notches becomes 1mm in the calculation of the reference radius. The reason for considering a small region (ρ*) to average the notch stress according to Neuber's micro-support theory is that the crack initiation in this small area is controlled by the average notch stress.

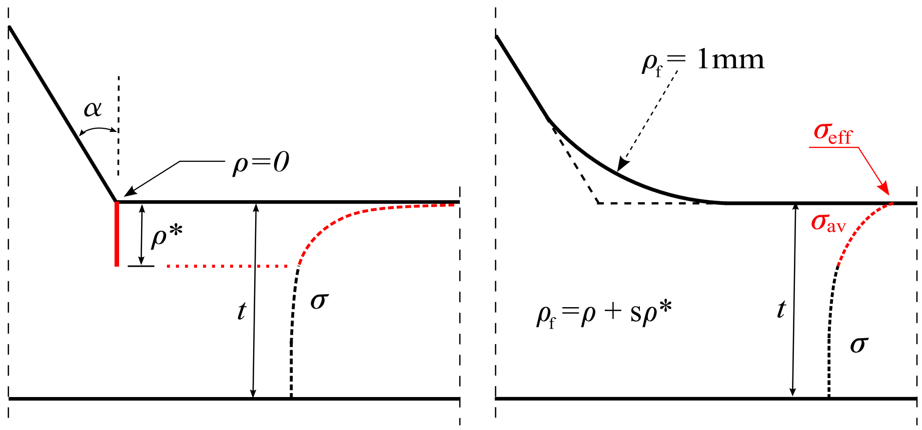


Figure 3-5 Utilising Neuber's micro-support concept in a welded joint

[8] The reason for considering the worst-case conditions is that the notch radius, which is a primary effect on the stress concentration factor in welded joints, is widely scattered.

The fatigue life assessment of welded joints using the effective notch stress method requires a fairly accurate definition of the detail geometry in and around the region of stress concentration, with a sufficient density of FE elements to capture the maximum stress at the point of stress concentration. The sharp notches in regions of anticipated crack initiations (the notches) are modelled as rounded with the reference notch radius to avoid stress singularities and arrive at a convergent stress value that can be used for fatigue calculations, see Figure 3-6 (IIW 2008; IIW 2010). Finite element models for use in conjunction with the effective notch stress method are usually created with 3D solid element models. 2D plane strain element models can, however, also be used for cases when the loading and geometry allow an idealisation of this kind.

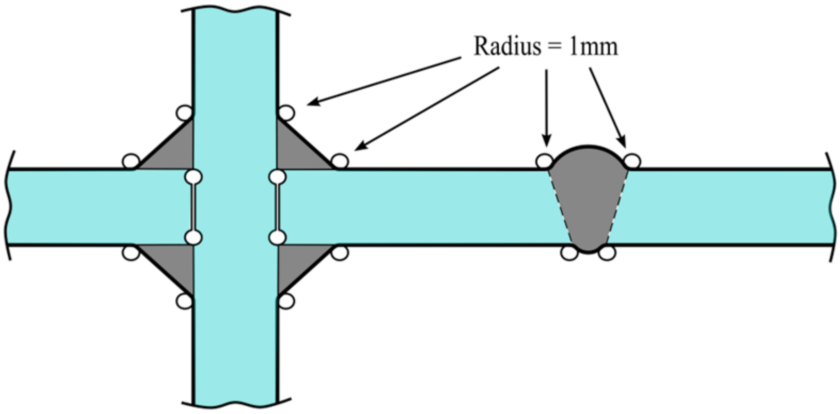


Figure 3-6 Rounding of weld toes and roots (IIW 2008)

The effective notch stress approach has been included in a number of fatigue design regulations and codes of standards, such as the IIW recommendations (IIW 2008) and the DNV (DNV 2011), as an alternative fatigue life assessment method. Recommendations for finite element modelling and the fatigue S-N curve to be used are also given. Unlike the hot-spot stress method, the effective notch stress method can be applied in fatigue design with respect to toe cracking, as well as for the root cracking of fillet welds.

As mentioned earlier, sharp notches at crack initiation sites (weld toe or root) should be rounded in order to avoid stress singularity. At weld toes, a radius of 1mm (r = 1mm) should be used for plates with thicknesses of 5mm and above, see Figure 3-6. For smaller plate thicknesses, Zhang (Zhang and Richter 2000) has proposed the use of a fictitious radius of 0.05mm, which is based on the relationship between the stress-intensity factor and the notch stress (Radaj et al. 2009; Sonsino 2009; Sonsino et al. 2012). Fillet welds can be modelled in two different ways; assuming an idealised weld profile or considering the actual weld profile. For an idealised weld profile, the recommendations for rounding at the weld toe and root are to use a flank angle of 45° for fillet welds and 30° for butt welds, as recommended in IIW (IIW 2010).

3.5.1 Fatigue life evaluation using effective notch stress

As the effective notch stress covers the global stress concentration effects, as well as the effect of local geometry, a single S-N curve should be sufficient to represent the fatigue strength of any welded detail. EN 1993-1-9 (EN1993-1-9 2005) has no recommendations relating to the application of the effective notch stress method. The IIW recommendations, however, propose four different S-N curves for use in the fatigue verification of welded details with the effective notch stress method, based on the plate thickness and type of stress considered in the calculations (IIW 2008; IIW 2010). For plates thicker than 5 mm, an S-N curve with FAT225 (C225) is recommended when the fatigue verification is based on the maximum principal stress. Detail category FAT200 (C200) should be applied if the von Mises stress is used. For plates thinner than 5 mm, an S-N curve with FAT630 (C630) is recommended when the fatigue verification is based on the maximum principal stress. Finally, detail category FAT560 (C560) should be applied if the von Mises stress is used (Sonsino 2009). These S-N curves have a constant slope of 3 before the knee point, which is placed at 10 million cycles. Thereafter, a slope of 22 is used to replace the cut-off limit, see Figure 3-7. The application of these four S-N curves, along with the recommended notch radius and thickness, can be found in Table 3-1.

Table 3-1 IIW recommendations for fatigue life evaluation based on the effective notch stress

Reference radius	**Principal stress**	**von Mises stress**
r = 1.0mm	FAT225	FAT200
r = 0.05mm	FAT630	FAT560

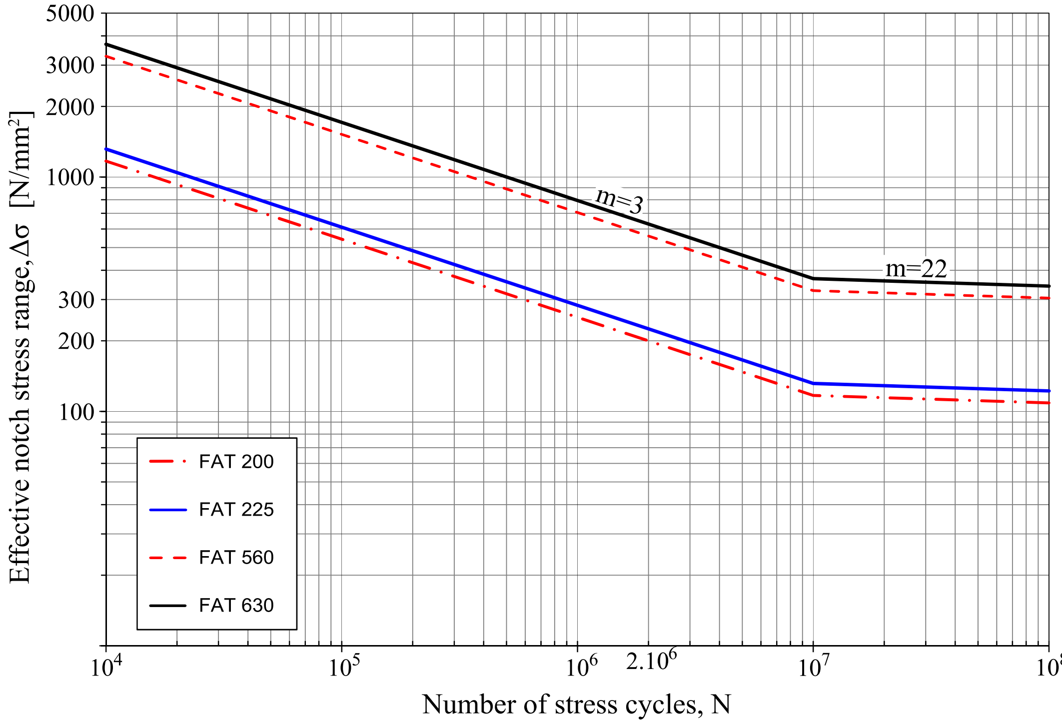


Figure 3-7 Effective notch stress-based fatigue S-N curves recommended by the IIW (IIW 2010)

As mentioned earlier, the effective notch stress is defined as the maximum elastic stress at a notch, computed by taking account of all stress-raising sources and assuming linear-elastic material behaviour. The effective notch stress can either be obtained directly by reading the nodal stress on the notch surface or be derived by considering the tangential and normal stress in different sections.

In a detail that experiences a uniaxial state of stress at the location of crack initiation, the maximum principal stress gives a good representation of the fatigue-deriving stress range at this location (Sonsino 2009). If stress multiaxiality exists, however, the direction of the principal stress might be constant (proportional loading) or will vary – in both magnitude and direction – over the loading cycle (Sonsino et al. 2012). In both cases, another (scalar) stress is needed to relate the load effects to the fatigue life in a more representative manner.

Fatigue verification with the effective notch stress method under stress multiaxiality is still the subject of on-going research. For details experiencing proportional multiaxial stress at the location of crack initiation, the following recommendations are given by the IIW (IIW 2010; Sonsino 2009).

1. If the first and second principal stresses have the same sign, the first (maximum) principal stress should be used in the fatigue verification.
2. Otherwise, the equivalent von Mises stress using the range of stress components should be used.

The applicability and reliability of the effective notch stress method for different types of welded detail have been investigated by many researchers.

Park and Miki (Park and Miki 2008) investigated the applicability of the effective notch stress approach to the fatigue assessment of welded details by studying some existing fatigue tests on details of different types, such as cruciform joints, diaphragm joints and out-of-plane gusset joints. The results of this investigation showed that the recommended design curve is on the safe side and FAT300 should be used instead. It also stated that the effective notch stress was significantly influenced by the weld size and weld penetration size.

Petershagen (Petershagen 1991) investigated the applicability of this method to cruciform joints and stated that the recommended S-N curve was correctly classified for this type of joint.

Fricke and Kahl (Fricke and Kahl 2005) presented the fatigue life prediction results for different welded connections, such as one-side double plates, plate-edge gussets and T-joints. The effective notch stresses were obtained by following the recommendations of the IIW, using coarse-mesh global FE models and 3D and 2D submodels. The weld profiles have been idealised or have been derived from the scanned geometry using the laser-based sheet-of-light system as the measurement technique. The study confirmed that the idealised weld profile was conservative in relation to the recommended S-N.

In ***Paper I*** in this thesis, it is shown that some of the welded details, such as connections with longitudinal attachments, cover plates and overlap joints, might be classified as FAT300. Similarly, in ***Paper II***, the recommended S-N curve FAT225 is shown to be on the safe side for welded details in an orthotropic deck plate when applying the effective notch stress method. Also in ***Paper III,*** the estimated fatigue life of the investigated detail obtained from the effective notch stress method would coincide more effectively with that obtained from the hot-spot stress method when using FAT300.

It is worth mentioning here that the effective notch stress method is not applicable if there is a significant stress component parallel to the weld. In such cases, fatigue evaluation is more appropriately performed with the nominal stress method.

3.6 Fracture mechanics method – LEFM

Fatigue assessment methods based on fracture mechanics address the relationship between geometric defects, material properties and applied stress. A fatigue failure occurs at a critical combination of these three parameters. The philosophy of fracture mechanics is that the stress state at a crack tip or crack-like discontinuities in a structural member can be determined by a single parameter, the stress intensity factor (SIF), depending on these three parameters, and the "damage tolerance" or "crack capacity" of a structure can thereby be estimated (Andersson 2005; Barsom and Rolfe 1987; Schijve 2009). A stress state in members with discontinuities, such as holes and notches, can be determined by applying the effective notch stress method. However, to determine the stress state at a crack tip in which the radius of the crack tip approaches zero, resulting in infinite stress, the use of fracture mechanics becomes necessary, i.e. stress analysis for structural members with cracks.

The behaviour of fatigue crack growth is commonly divided into three main phases in fatigue-loaded structures. Figure 3-8 shows these three crack growth phases from the crack initiation to failure, the crack growth per stress cycle as a function of the stress intensity factor range in the logarithmic scale. The crack process in the first phase, usually known as the threshold region, presents the material limit for crack propagation (ΔK_{th}). In this region, the material has a resistance to crack propagation, which means that the crack does not propagate or that it propagates extremely slowly. For the stress intensity factor ranges over this limit, stable crack growth occurs up to the critical limit (ΔK_C). In this second phase, the relationship between the crack growth and crack driving force is linear (in a log-log scale) and Paris law is thereby valid. In the third region, when the crack driving force is over the critical limit, fracture occurs.

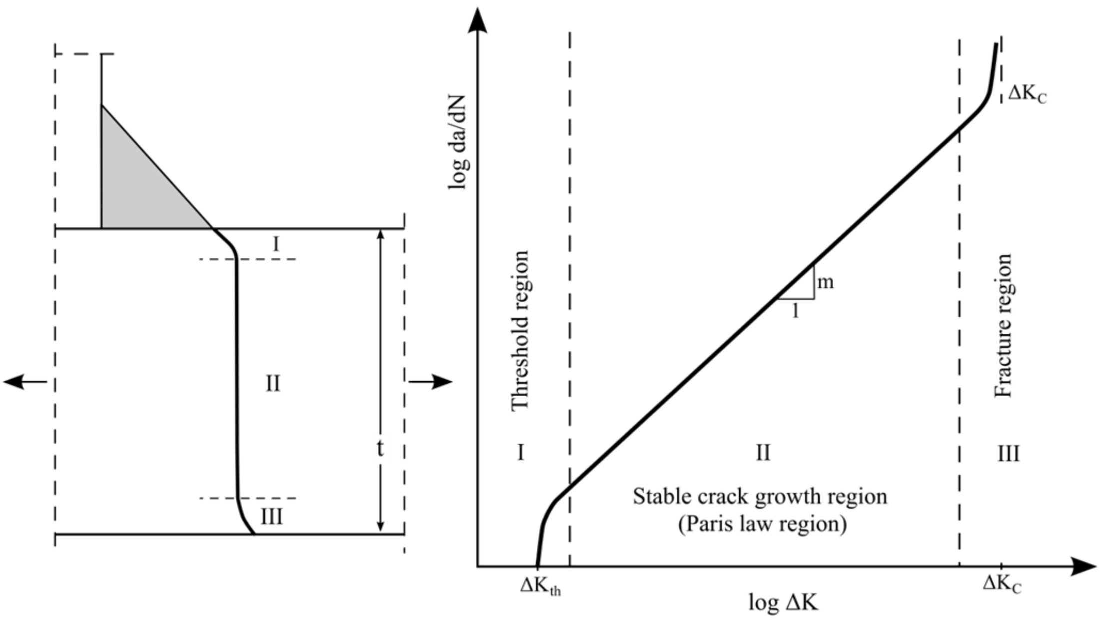


Figure 3-8 The three main regions defined for crack growth

For the fatigue evaluation of welded structures, linear-elastic fracture mechanics (LEFM) is generally applied, with the assumption of an existing crack due to the welds. The size of these existing cracks emanating from cold laps, inclusions, lack of fusion and undercuts may vary from 0.05mm to 1mm (Barsoum 2008; BS7910:1999

2000; EN1993-1-10 2005; Radaj et al. 2006; Samuelsson et al. 2008). Linear-elastic fracture mechanics describes the stress conditions at a crack tip depending on the stress applied to the structural member and the crack configuration (shape, size and orientation) using the basic assumption of the material conditions which are linear elastic during the crack growth process. This means that LEFM does not take account of plasticity, even though ductile materials such as steel always show some plasticity. However, in most cases, LEFM is sufficient to model high-cycle fatigue crack growth (Andersson 2005).

3.6.1 Mixed-mode crack growth

As stated earlier, the main parameter influencing the fatigue strength of either damaged or undamaged members is the applied stress, i.e. the load. In fracture mechanics, the effect of loading is described by the different loading conditions. Figure 3-9 shows the three loading conditions that are generally considered in fracture mechanics methods. Mode I is the opening mode, which is the most common loading condition in fatigue-loaded welded structures. Mode II is the sliding mode or in-plane shearing mode and mode III is the tearing mode or anti-plane shearing mode. In fatigue-loaded structural members, the loading mode may vary from pure mode I, mode II and mode III to mixed-mode conditions. However, fatigue crack initiation and growth are usually the result of mixed-mode conditions generated by complex load conditions, geometry or a combination of both in practical engineering cases.

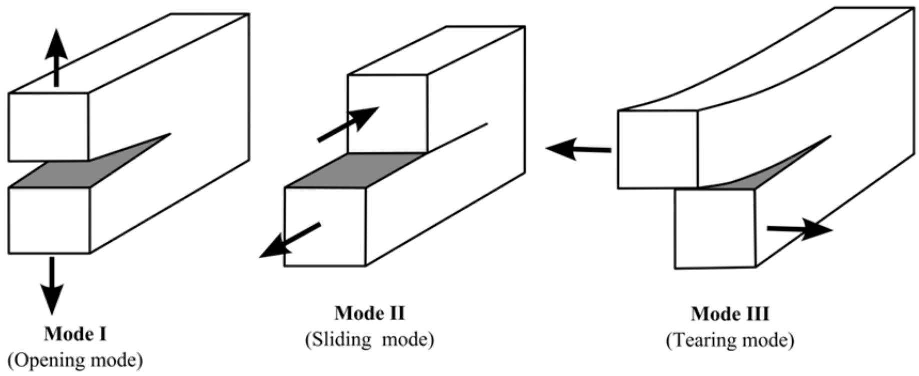


Figure 3-9 The three loading conditions/modes in fracture mechanics

The degree of mode mix may vary during crack propagation, depending on the level of loading, crack location and crack closure. The fatigue crack growth under combined mode-I and mode-II loading has been investigated by researchers (Hua et al. 1985; Iida and Kobayashi 1969; Qian and Fatemi 1996). A common conclusion from their investigations was that the fatigue crack growth under combined mode-I and mode-II loading was influenced significantly by ΔK_{II}, even those for small values. In a combination of mode I and mode III, mode I is the dominant mode when the stress intensity factors are low, while mode III is the governing mode for the higher stress intensity factors (Barsoum 2008; Radaj et al. 2006).

The distortion-induced crack growth investigated in the Söderström Bridge presented in ***Papers IV and V*** in this thesis showed that the load was a combined mixed mode of all three modes, even though the effects of KII and KIII were non-essential. The study showed that mode I was clearly the governing mode during crack growth.

3.6.2 Fatigue life evaluation using LEFM

The fatigue life of the welded structures based on fracture mechanics is estimated by idealising a hypothetical initial defect recommended by design codes such as BS 7910:1999, EN 1993-1-10 and IIW (BS7608:1993 1999; EN1993-1-10 2005; IIW 2008) or by using an actual defect (crack). The life estimation can be made by integrating the fatigue crack growth rate model with the Paris law (Paris and Erdogan 1963), as shown in Eq. 3-1.

$$\frac{da}{dN} = C \cdot \Delta K^m \qquad \textit{Eq. 3-1}$$

where *C* and *m* are the material constants, including the effect of environment, which are determined experimentally. Paris and Erdogan proposed an exponent of 4 (m=4) according to their experimental data. However, many investigations have since shown that *m* was a range of 2 and 4 for most materials used in fatigue-loaded structures (Andersson 2005).

For mixed-mode conditions, the effective stress intensity factor range considering modes I, II and III, a modified Paris law shown in Eq. 3-2 can be used.

$$\frac{da}{dN} = C \cdot \Delta K_{eff}^m \qquad \textit{Eq. 3-2}$$

The threshold stress intensity factor (ΔK_{th}) for assessing welded joints can be determined by a material toughness test of the material or by following the recommendations given in various design codes, such as BS 7910:1999 (BS7910:1999 2000), EN 1993-1-10 (EN1993-1-10 2005) or IIW (IIW 2008).

3.7 Comparison of the methods

Based on the literature studies and evaluations performed in this research thesis, the advantages and disadvantages of the fatigue life assessment methods can be summarised, as in Table 3-2.

Table 3-2 Advantages and disadvantages of fatigue life assessment methods

Advantages	**Disadvantages**
Nominal stress approach	
Simple calculations Well-established Available experimental data Available parametric formula Available fatigue classes in design codes Suitable for weld root and toe cracking	Fatigue detail category dependence Limitation for misalignment and macro-geometric changes Less accuracy in complex structures
Hot-spot stress approach	
Fewer S-N curves needed Using existing FE models Acceptable accuracy Less FE modelling effort Macro-geometric effect included	Dependent on element size Dependent on element arrangement Different stress determination procedures Limited to weld toe cracking
Effective notch stress approach	
Thickness effect included in calculations Independent of element type Suitable for weld roots and toes cracking A “single” S-N curve	Applicable only with FEA Dependent on mesh density Effort for modelling – time consuming Multi-sub-modelling
Fracture mechanics - LEFM	
Thickness effect included in calculations Not affected by the stress direction Suitable for weld roots and toes cracking Fatigue life after inspection intervals Effect of variable amplitude loading	Time consuming Complex calculations Influenced by many parameters; initial crack size, final crack size, crack increment, material properties and so on

4 Fatigue evaluation using FEM – in design

4.1 Introduction

The four most common assessment methods for the fatigue life estimation of steel structures recommended in several fatigue design regulations and codes of standards were presented in the previous chapter. These methods can be mainly categorised in two groups:

1. The ***global method*** – the nominal stress method, which is the simplest and most common method
2. The ***local methods*** – the structural hot-spot stress, the effective notch stress and the fracture mechanics method (LEFM)

A typical stress distribution in front of the weld toe and a definition of the stresses used in the fatigue assessment methods are shown in Figure 4-1. The nominal stress in the parent material as shown in this figure is influenced by neither the attached member nor the weld, i.e. only the consideration of global response in the stress calculations. As stated in the previous chapter, these effects are considered in the S-N curve instead. On the other hand, the hot-spot stress is influenced by the attached plate and the effective notch stress is influenced by both the plate and the weld, whose effects need to be considered in the stress calculations, i.e. considering the local effects in the stress calculations. A common characteristic factor for these three methods is fatigue strength curve dependence when estimating service life. The fracture mechanics method, LEFM, is based on the principles of fracture mechanics which cover the behaviour of defective details and service life independently from any fatigue strength curve. LEFM for the fatigue assessment in the design phase is not covered in this study, but the assessment of existing steel structures in service will be presented in the next chapter.

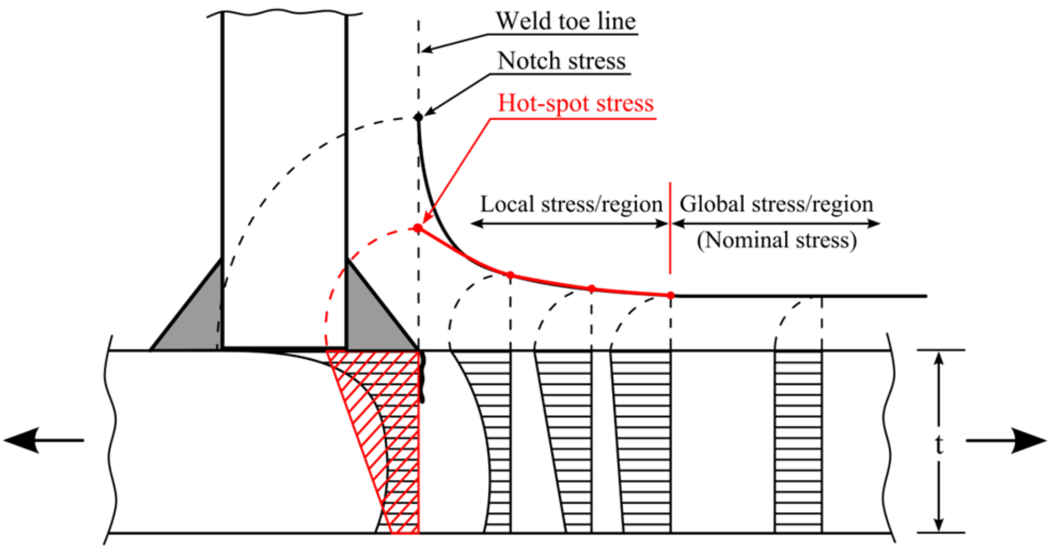


Figure 4-1 Stress distribution in the "global" and "local" region

The application of the finite element method to compute the design stresses to be used in the fatigue life calculation requires a good understanding of the principles of FEM and the philosophy behind the above-mentioned fatigue assessment methods. The computation of the local stresses based on the local failure methods when using FEA is highly sensitive to the finite element modelling technique, as these stresses are frequently in an area of high strain gradients, i.e. stress singularities (Fricke 2003; Niemi 1995; Radaj et al. 2006). The resulting stresses may differ substantially, depending on the type and size of elements and the procedure used to extract the values of the design stresses. An appropriate finite element model can be created by following the recommendations given in the design codes for most types of detail, especially for simple "basic" details. However, for complex details, i.e. welded joints which are complex in terms of geometry and loading, the modelling work should be performed with extra care and only following the recommendations may result in an unconservative estimation (***Papers II and III***). In this section, the various aspects of appropriate modelling techniques that can be applied in conjunction with the FE analysis of welded details for fatigue verification using structural hot-spot and effective notch stress are presented on the basis of IIW (IIW 2008) and DNV (DNV 2011), as well as the results obtained from the studies presented in this thesis.

4.2 General "rules" for finite element modelling

The recommendations given in this section are applicable in most general cases. The subject of weld modelling is treated, along with examples of when and how the welds in structural details should be modelled. As complex details, two welded joints, complex in terms of geometry (***Paper II***) and complex in terms of loading (***Paper III***), are presented.

4.2.1 Modelling "rules" for the structural hot-spot stress approach

With respect to the use of the finite element method, there are a number of general "rules" that should be respected when performing fatigue verification using the hot-spot method (DNV 2011; IIW 2008; Lotsberg 2006; Maddox 2001). Some of these rules that apply irrespective of the type of detail and FE elements used are as follows.

- ***The size of the FE elements*** within the region of stress extrapolation in the detail should be chosen with regard to the reference stress extrapolation points. The latter should coincide with the mid-side or edge nodes of the elements.
- Select ***element type*** and the ***number of elements*** in order to produce a linear stress distribution through the thickness of the cracked plate in the detail. This can be achieved by using at least one quadratic or two linear FE elements through the thickness.
- To avoid inaccuracy, the maximum ***aspect ratio*** of FE elements (i.e. the ratio of the longest dimension to the shortest dimension in the FE element) should be kept below 1:3. A ratio between 1:1 and 1:2 is recommended.
- ***Mesh transitions***, from finely meshed to coarsely meshed regions, should be gradual and smooth, especially when this transition is taking place close to the reference stress extrapolation points.
- ***Stress averaging*** over element boundaries (nodal averaging) has no effect on the structural hot-spot stresses determined by the surface stress extrapolation procedure. On the contrary, ***stress averaging*** should be used for the through-thickness structural stress approach, while ***stress averaging*** should be avoided for the Battelle structural stress approach.

In many cases, especially when modelling large welded structures, such as complex bridge details and details in ships and offshore structures, it is more practical to use shell elements in fatigue design with the structural hot-spot stress method. In these cases, the following recommendations when constructing the FE models should be considered:

Modelling with shell elements:

- ***Higher-order shell elements***: eight-node (second order) should be used in the following cases:
    1. In models with coarse mesh; in order to read the stress in the mid-side node
    2. To capture the high stress gradient in fatigue-critical areas, especially in the vicinity of welds in complex details
- ***Mid-plane orientation***: shell elements should be arranged in the mid-plane of the plate. In the event of eccentricity between the plates, the plates may be modelled considering the mid-plane or by using the offset function which is available in most FE software
- ***Modelling the welds:*** in shell element models, the welds are usually not modelled, except in cases where the results are affected by high local bending (due to an offset between plates, for example) or in the event of an eccentric weld arrangement (e.g. cover plate joints and welded joints with cut-out holes).

Shell elements should be avoided when the fatigue verification of the following details is performed using the structural hot-spot stress method (DNV 2011; Lotsberg 2006):

1. Cruciform joints; simple T-joints in plated structures
2. Simple butt joints that are welded from one side only.

An analysis of these details with shell elements will generally give a structural hot-spot stress that is equal to the nominal stress in the loaded plate. The principle is illustrated in Figure 4-2. It is obvious that, for the load in the transverse direction (direction I), there will be no stress flow into the transverse plate, which is represented in the model by a single plane of shell elements only. On the other hand, for loads in the longitudinal direction (direction II), the stiffness of the longitudinal plate is correctly represented.

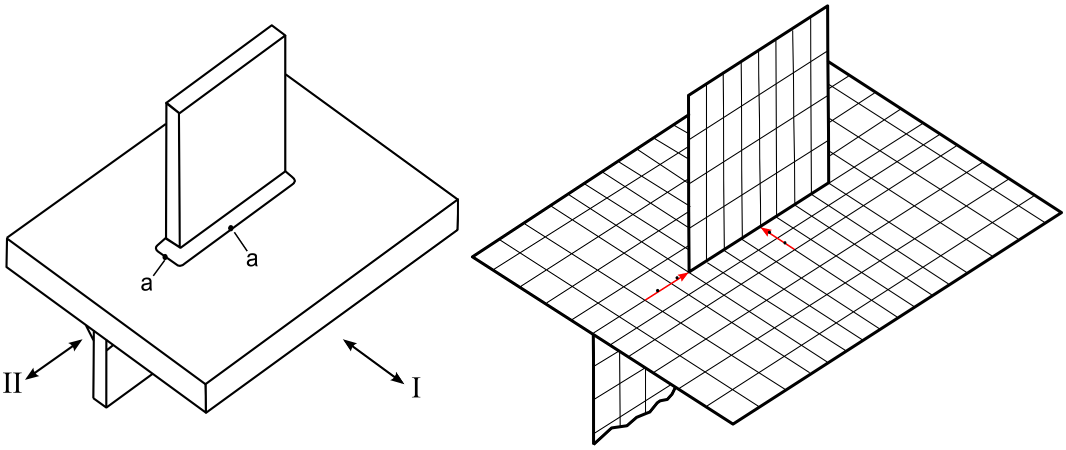


Figure 4-2 Illustration of the limitation of the structural hot-spot stress method for simple joints (Lotsberg 2006)

Modelling with solid elements:

- ***Higher-order solid elements***: 20-node (second order) solid elements should be used in the following cases:
    1. For coarsely meshed solid element models; in order to read the stress in the mid-side node, as linear extrapolation requires the stresses at the mid-side nodes
    2. To capture high stress gradients in fatigue-critical areas, especially in the vicinity of welds in complex details.
- The ***displacement function*** of the FE element should allow steep stress gradients, as well as plate bending, giving linear stress distribution in the plate thickness direction
- For hot-spot stresses obtained with surface stress extrapolation, only one[9] 20-node element is required through the thickness of the plate in question
- The welds should usually be incorporated in models constructed with solid elements.

4.2.2 Modelling "rules" for the effective notch stress approach

As stated in Chapter 4, the effective notch stress approach is included in the IIW as an alternative fatigue life assessment method and the recommendations for modelling can be found in (Fricke 2003; IIW 2008; Sonsino 2009). The effective notch stress method is applicable for 2D plane and 3D solid finite element models and requires an accurately defined FE model. This means that FE models that are going to be used to determine the effective notch stress should reproduce the "exact" geometry of the studied detail, including welds. Gaps between the connected plates in fillet-welded joints and any major misalignments not covered by the S-N curve should also be accounted for. It is not possible to use FE models with shell elements in fatigue verification with the effective notch stress method. For simple loading conditions in which the stresses in the transverse direction are negligible, 2D plane-stress elements can be used. In welded steel structures that rarely contain simple details or simple loading conditions, 3D solid element models are usually preferred. Building finite element models with solid elements in large structures can, however, easily lead to large FE models that require very long computation times and the handling of heavy data. To overcome this problem, sub-modelling can be used to analyse smaller parts of the structure.

4.2.3 Sub-modelling

The purpose of using the sub-modelling technique is commonly to obtain a more detailed result (stresses and deformation) in local regions which are of special interest for design. Sub-models are therefore constructed with more details and equipped with a much finer mesh than the global model to which they belong.

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[9] In the case of a one-layer solid element in the thickness direction, the surface stress extrapolation is recommended. When using multi-layer (two or more) elements in the thickness direction, the non-linearity is effectively considered, as is the accuracy of the stress, but a stress linearisation is still possible.

A sub-modelling technique thus includes a two-step analysis: an analysis of the global structure and a refined analysis of a detail in that structure. The global model and the sub-model are usually two distinct finite element models. The global model is usually a simplified representation of the whole structure, with minimum detailing and with a fairly coarse mesh. The sub-model, on the other hand, is usually made of a smaller part of the structure with a sufficiently detailed representation of local details that are judged to affect the load effects in the region of interest. As such, sub-models usually require fine meshing and more modelling work. It is important to note that, in a sub-model, the co-ordinates at the cut-regions should be same as those in the global model. The boundary conditions along the "cutting edges/surfaces" in a sub-model are obtained from the global model, either as displacements or as sectional forces/stresses.

4.3 Fatigue evaluation of simple details

The evaluation of "basic" welded details to compare the equivalence between the nominal, structural hot-spot and effective notch stress approaches based mainly on the results obtained in ***Paper I*** is presented in this section. The FE models with solid elements and evaluations of the studied details were performed by following the modelling requirements of each fatigue assessment method in the IIW recommendations (IIW 2008; IIW 2010). Moreover, different element types and sizes of shell elements were used in the FE models to plot the diversity between the modelling techniques when using the structural hot-spot stress approach. However, the results from the different models were not presented in ***Paper I***. Instead, the recommendations for FE modelling with shell elements and stress extrapolation are given in this section in each case, if there is diversity between the models. The results and recommendations are summarised in Table 4-1 and Table 4-2 when it comes to the different fatigue life assessment methods.

Plate-edge details

Plate-edge details are fairly common in fatigue-loaded structures. Gusset plates in bridge beams are a typical example. The length of the attached plates has a significant effect on the fatigue strength of welded plate-edge joints when considering the nominal stress. The fatigue strength of the joints decreases as the length of the plate increases. This is not, however, recognised in EN 1993-1-9, where the fatigue strength of 40 N/mm^2 is assigned to this detail, irrespective of the length of the attached plate. This recommendation appears to be fairly conservative considering the results from the evaluation of 1,018 specimens.

The IIW recommends using a fatigue strength of 90 and 100 N/mm^2 for the hot-spot stress method, depending on the length of the attached plates, while, in EN 1993-1-9, no recommendation is 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. Nevertheless, based on the results for the studied details, fatigue category 100 appears to give a good representation of the fatigue strength of this particular detail. The recommended detail category 225 for the effective notch stress is, however, in good agreement with the results, both for all the specimens and for the specimens with $R > 0$.

In addition to the general "rules" for modelling given in Section 4.2, the following recommendations for modelling plate-edge details can be considered:

- When using the hot-spot stress method, FE modelling with shell elements without modelling welds yields accurate hot-spot stresses
- For plate-edge details with fillet welds, the modelling work required is fairly high for the application of the effective notch stress method. The structural hot-spot stress method is therefore recommended for fillet-welded plate-edge details.

Overlap joints

Figure 4-3 shows the main geometric parameters of an overlap joint, along with the two possible cracking modes in this type of joint. A distinct difference in fatigue strength could be seen for this detail, depending on the failure location. The fatigue strength was higher when the fatigue failure occurred in the main plate. This difference is also recognised in both the EN 1993-1-9 and the IIW.

The EN 1993-1-9 and IIW recommend using a fatigue strength of 90 N/mm^2 when using the hot-spot stress method. Based on the results in ***Paper I***, this appears to be inappropriate for cracking in the main plate. The recommended detail category 225 for the effective notch stress method appears to be conservative in comparison with the results.

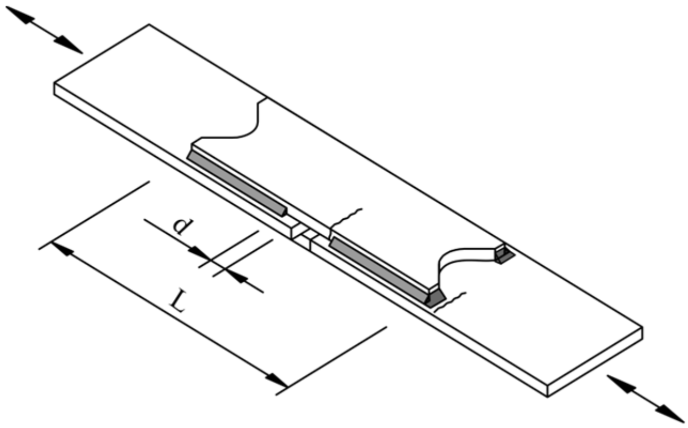


Figure 4-3 Geometric parameters and failure modes in a overlap joint

In addition to the general "rules" for modelling given in Section 4.2, the following recommendations for the structural hot-spot and effective notch stress method for modelling overlap joints can be considered.

- The weld must be included in FE models and the attached plates should be separated from the main plate.
- When the distance between weld ends on each side of the main plates is so short that the stress extrapolation points lie outside this region, the one-point stress evaluation method can be used when using the hot-spot stress method.
- To use the effective notch stress method, it is important to verify the stress direction before using the maximum principal stress.

Longitudinal attachment

The fatigue strength for this type of detail is a function of the length of the attached plates. This has been recognised in both EN 1993-1-9 and IIW. The results obtained in ***Paper I*** showed that EN 1993-1-9 provides a good representation of the fatigue strength of this detail when considering the nominal stress method. However, the results for the 50 mm length of the attached plates appear to be non-conservative. The IIW recommendations for the failure in the main plate are more consistent with the test results, apart from the attached plate length of 200 mm.

The fatigue strength of 90 N/mm^2 should be more consistent with the test results instead of the recommended fatigue strength of 100 N/mm^2 when using the hot-spot stress method. The recommended detail category 225 for the effective notch stress method is conservative in comparison with the results obtained in ***Paper I***. In order to obtain a reliable stress value at the weld toe or root, the general "rules" given in Section 4.2 can be followed.

Cope-hole details

Welded joints with cope holes are usually used as field-welded joints in steel girders to facilitate the transverse butt welds in the flanges and avoid weld crossing when creating built-up girders. The fatigue strength of welded details with cope holes is generally not influenced by geometric variations, such as the size of cope holes. Instead, the ratio of shear stress to normal stress in the details (τ_a/σ_m) affects the fatigue strength in this kind of joint. It is stated in (Miki and Tateishi 1997) that the higher presence of shear stress at the anticipated crack location, i.e. weld toe in the cope-hole section, can cause lower fatigue strength. This effect has been recognised in the IIW recommendations, where the fatigue strength of this detail is a function of the ratio of shear (τ) to normal (σ) stress. In EN 1993-1-9, however, one fatigue class is assigned, irrespective of the τ_a/σ_m ratio.

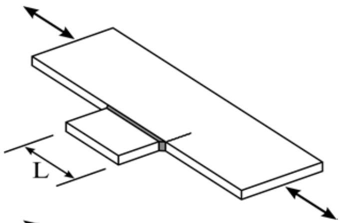
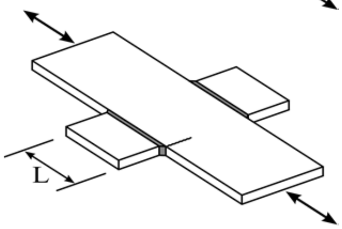
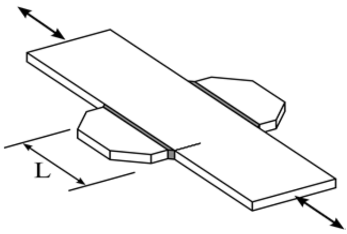
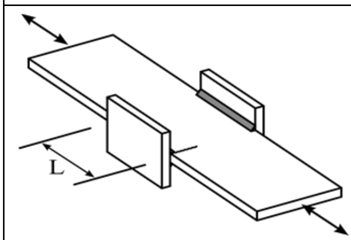
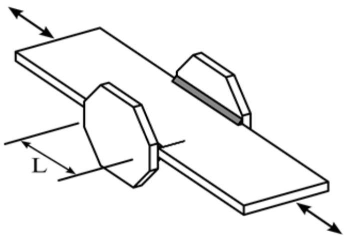
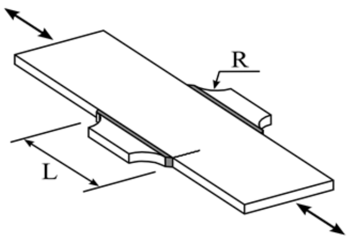
Based on the results in ***Paper I***, fatigue detail category 100 recommended by the IIW for non-load-carrying welds when applying the hot-spot stress method is not consistent with the results. However, if the results from detail type 4D (see Table 2-9 in Paper I), which has a high τ_a/σ_m ratio, are excluded, fatigue detail category 100 appears to be a reasonable representation. When using the effective notch stress method, the recommended fatigue class of 225 appears to be in good agreement with the evaluated cope-hole details.

Cover-plate details

Partial-length cover plates are usually welded to the flanges of steel girders in order to increase the moment capacity and the stiffness of bridge spans, giving better material utilisation. The main parameter governing the fatigue strength of this detail is the cover plate to main plate thickness ratio (t_c/t_m), which causes a reduction in fatigue strength as the ratio increases. This effect has been recognised in both EN 1993-1-9 and IIW recommendations. The results showed that the recommendations given in EN 1993-1-9 are more consistent with suggesting either of two values; for a ratio above or below 1.0. In IIW, several intervals are given.

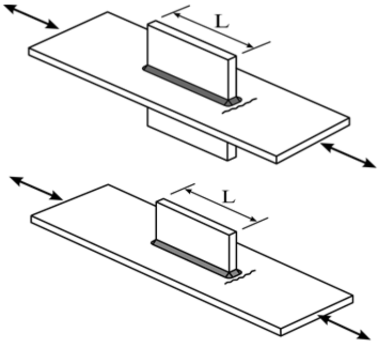
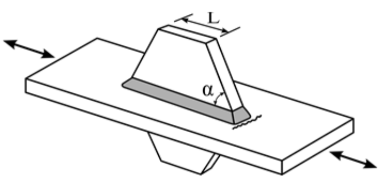
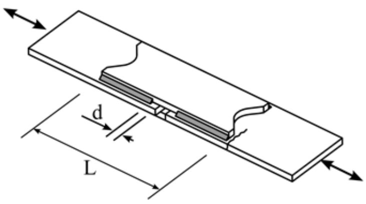
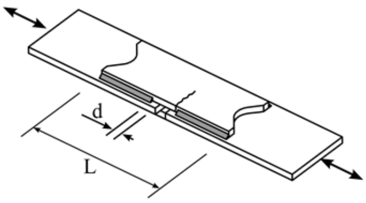
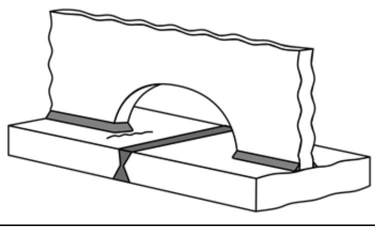
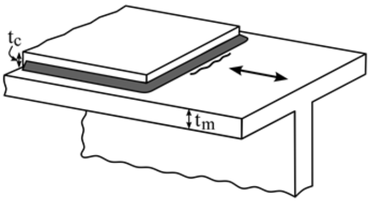
The recommended fatigue strength of 100 N/mm^2 in EN 1993-1-9 and IIW for the hot-spot stress method appears to produce reasonable agreement, while the recommended fatigue strength of 225 N/mm^2 for the effective notch stress method is conservative in comparison with the results obtained in ***Paper I***.

Table 4-1 Recommended fatigue strength class for different types of plate edge joint

Structural detail	**Fatigue life assessment method**			
	Nominal stress		**Hot-spot stress**	**Effective notch stress**
 	L ≤ 100	C63	C100	C225
	100 < L ≤ 200	C50		
	200 < L ≤ 300	C50		
	L ≤ 100	C71		
	300 < L	C56		
	100 < L	C63*		
	100 < L	C50**		
	$\frac{1}{6} \leq \frac{R}{L} \leq \frac{1}{3}$	C63		

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

Table 4-2 Recommended fatigue strength class for various welded joints

Structural detail	Fatigue assessment methods			
	Nominal stress		Hot-spot stress	Effective notch stress
	$L \leq 150$	C71	C90	C300
	$150 < L$	C56		
	$150 < L$	C71	C80	
	$\alpha < 45$ $\alpha > 45^{\circ}$			
	$100 < L \leq 120$ All t	C56	C80	
	$120 < L$ All t	C56		
	C45 All configurations		C100	
	Correction factor for $\tau_a/\sigma_m \geq 0.2$	C71	Correction factor for $\tau_a/\sigma_m < 0.2$ C90	C225
	$t_c/t_m < 1$, $t_m \leq 20$	C56	C100	C300
	$t_c/t_m \geq 1$, $t_m \leq 20$	C50		

4.4 Fatigue evaluation of complex details

The evaluation of complex welded details to compare the equivalence between the nominal, structural hot-spot and effective notch stress approaches based on the results obtained in ***Paper II*** and ***Paper III*** is presented in this section.

Orthotropic bridge deck details – complex geometry

An orthotropic bridge deck is a multifaceted structural system which is composed of several intersecting elements that interact in a complex manner to provide the required stiffness and strength of the deck. Typically, an orthotropic bridge deck is built up of a deck plate welded to longitudinal ribs (open or closed) and transverse cross-beams, see Figure 4-4. The intersection of these elements may result in a number of complex welded joints, which have been shown to be very sensitive to fatigue cracking (Frýba and Gajdos 1999; Kolstein 2007).

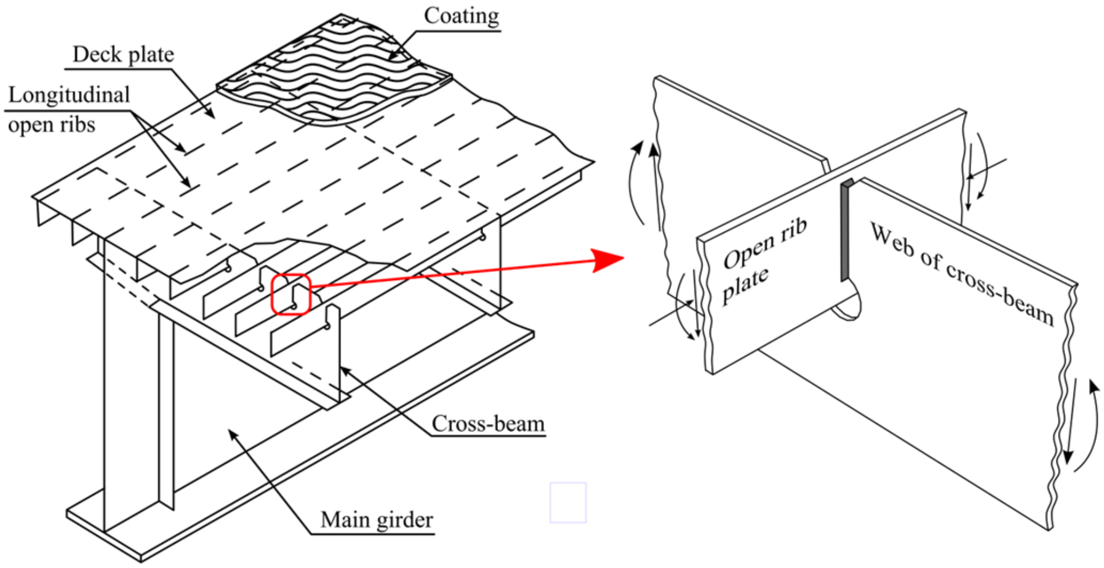


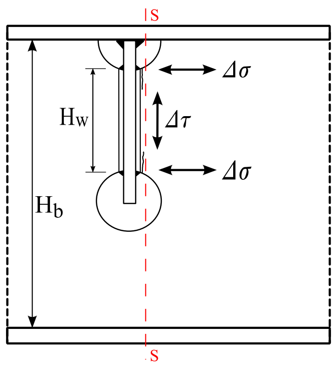
Figure 4-4 Orthotropic bridge deck and sectional forces in an orthotropic bridge deck with open ribs

The nominal stress method provides good agreement with the test results presented in ***Paper II*** only when the shear stress distribution over the welded section and the normal stress distribution over the girder section are considered correctly. When using the structural hot-spot stress approach, the importance of correctly representing the welds in complex details is clear in welded joints with cut-out holes. The modelling work when it comes to using the effective notch stress approach requires far more effort than the work involved in using the structural hot-spot stress approach.

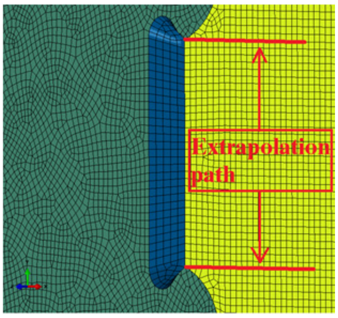
In addition to the general "rules" for modelling, the following recommendations for orthotropic bridge deck details with open ribs relating to the different fatigue life assessment methods are given in Table 4-3.

Table 4-3 Recommendations for orthotropic bridge deck details with open ribs

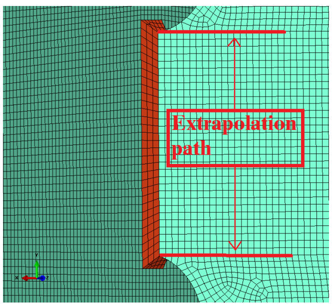
<table>
<tr><th>Method</th><th>Structural detail</th><th>Description</th><th>Requirements</th></tr>
<tr>
<td>Nominal stress

C56</td>
<td>
</td>
<td>Connection of continuous longitudinal rib to cross-girder
$\Delta\sigma = \frac{\Delta M_S}{W_{net,s}}$
Use H_b in cross-section calculations.
$\Delta\tau = \frac{\Delta V_S}{A_{w,net,s}}$
Use H_w in cross-section calculations.
$A_{w,net,s} = H_W \cdot t$</td>
<td>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:

$\Delta\sigma_{eq} = \frac{1}{2}\left(\Delta\sigma + \sqrt{\Delta\sigma^2 + 4 \cdot \Delta\tau^2}\right)$</td>
</tr>
<tr>
<td rowspan="3">Hot-spot stress

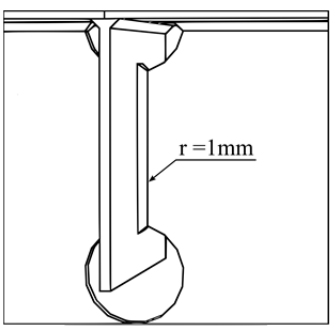
C90</td>
<td>
</td>
<td>Connection of continuous longitudinal rib to cross-girder

A linear or quadratic stress extrapolation technique can be used to determine the hot- spot stress at the weld toes.</td>
<td>Finite element model with eight-node shell elements

The welds should be modelled by using oblique shell elements, including the web plate.</td>
</tr>
<tr>
<td>
</td>
<td>Connection of continuous longitudinal rib to cross-girder

A linear or quadratic extrapolation technique can be used to determine the hot-spot stress at the weld toes.</td>
<td>Finite element model with solid elements

The welds should be created with flank angles of 45° in FE models.</td>
</tr>
<tr>
<td colspan="3">For quadratic surface stress extrapolation (max. first/second order element ≤ 4mm)
$\Delta\sigma_{hss} = 3\sigma_{4mm} - 3\sigma_{8mm} + \sigma_{12mm}$
For linear surface stress extrapolation (max. second order element ≤ 10mm)
$\Delta\sigma_{hss} = 1.5\sigma_{0.5mm} - 0.5\sigma_{15mm}$</td>
</tr>
<tr>
<td>Effective notch stress

C300</td>
<td>
</td>
<td>Connection of continuous longitudinal rib to cross-girder

Maximum principal stress perpendicular to the weld toe should be used.</td>
<td>The recommended radius of 1mm should be applied along the weld line.

Maximum size of second-order hexahedral elements to be used around the hole: r/4.

Maximum size of second-order tetrahedral elements to be used around the hole: r/6</td>
</tr>
</table>

Details subjected to distortion-induced fatigue – complex in loading

Distortion-induced fatigue damage is generally generated by out-of-plane deformation in local flexible regions such as web gaps at the connection between different members, see Figure 4-5. Even though the deformation of the connected members at the location of cracking is generally very small, the concentration of this deformation in local flexible regions might result in high local stresses that will eventually generate fatigue cracking. Many bridge types have a system of cross-beams connected to longitudinal main girders to form a floor system (Al-Emrani 2006; Al-Emrani et al. 2004). In old bridges in particular, the flanges of the connected members are cut short to avoid transverse welds in the flange. This way of detailing may result in local flexible web "gaps" that are prone to distortional fatigue cracking.

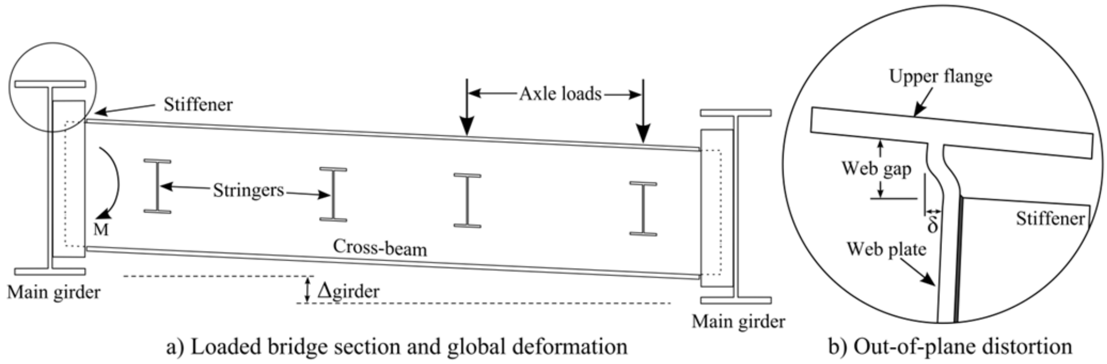


Figure 4-5 Out-of-plane distortion located in the web plate of the main girder

Distortional fatigue cracking in web gap details is a very complex problem due to the interaction of structural members. The stresses acting in the web gap are difficult to determine without a detailed finite element analysis of the structure. In addition to the highly localised nature of the problem, this makes the application of the conventional nominal stress method for the fatigue verification of such details unfeasible. A more "local" failure approach, which can be used in conjunction with FE analysis, is therefore preferable. Based on the results presented in ***Paper III***, the following recommendations can be made.

- The fatigue assessment of fatigue-critical details prone to distortional cracking can be performed with more accurate results by using local fatigue assessment approaches. This type of fatigue damage cannot be evaluated using the conventional nominal stress-based methods.
- When it comes to the use of the structural hot-spot stress method, FE models with shell elements should not be used for details subjected to distortional loading. The high stress gradients caused by bending cannot be captured accurately when using shell elements around the studied region.
- The effective notch stress method yields a conservative life prediction when considering detail category 225. Detail category 300 has been found to be more suitable for the studied detail. The effort involved in modelling and computation time is somewhat higher than the structural hot-spot stress method, due to the use of the multi-level sub-modelling technique.
- FE models with solid elements yield representative stress ranges, regardless of the stress determination procedure. The use of solid element models to evaluate the structural hot-spot stresses for welded details prone to distortional cracking is therefore recommended.

5 Fatigue evaluation using FEM – in service

5.1 Introduction

The majority of steel and composite bridges with welded connections which have been built since 1950 have not yet reached their designed service life (Kühn et al. 2008). Nevertheless, a relatively large amount of fatigue damage induced by either the primary loads due to increased loads and traffic volumes or the secondary stresses due to their unforeseen effects in the design phase has been reported (Al-Emrani 2006; Fisher 1978; Kühn et al. 2008). The classification methods discussed in Chapter 3 and Chapter 4 can be also used to evaluate the residual fatigue life of the structural components, provided that these components are free from cracks. These methods therefore share the common disadvantage of only being valid for welded details without cracks. When a welded joint contains a fatigue crack, it is necessary to determine the stress state with the crack in the welded joint in order to estimate the fatigue life and this can only be accomplished using methods based on fracture mechanics. Several guidelines and recommendations given in design codes, such as the step-by-step procedure, referring to the fracture mechanics methods that can be used to estimate the residual fatigue life of existing steel structures with or without fatigue damage, are available (BS7608:1993 1999; BS7910:1999 2000; EN1993-1-10 2005; Helmerich et al. 2007). In this part of the thesis, the fatigue assessment of a welded detail with a distortion-induced fatigue crack in an existing railway steel bridge which is fairly complex was examined.

5.2 Distortion-induced fatigue cracking

Distortion-induced damage has become a common fatigue issue in bridges and it is caused by the stresses in secondary members whose effects are difficult to quantify. Many reported cases have shown that this type of cracking is significantly more common than fatigue cracking due to primary load effects (Al-Emrani 2006; Bowman et al. 2012; Connor and Fisher 2006; D'Andrea et al. 2001; Fisher et al. 1979; Fisher and Keating 1989; Fisher et al. 1998; Fraser et al. 2000). The behaviour of distortion-induced fatigue cracks (crack growth rates during propagation) generally differs from the behaviour of load-induced fatigue cracks, due to the complex stress distribution between the components. This means that distortional fatigue crack growth can end with a local/global failure or crack arrest due to relaxation. The distortion-induced fatigue problems therefore present many challenges in the fatigue assessment, when it comes to both estimating the crack growth behaviour and assessing the retrofitting technique. Retrofitting or repairing this type of fatigue damage is difficult, due to the above-mentioned complexity in the stress distribution and geometric constraints which might limit the type of repair/retrofitting methods that can feasibly be used to prevent further fatigue cracks. The suitability of a repair technique based on drilling holes is one of the focal points of this study.

Distortion-induced fatigue cracks are mainly generated by out-of-plane distortion in a web gap region in which transverse cross-beams are connected to the web of the longitudinal main girders, see Figure 5-1. In steel girder bridges, transverse cross-beams are usually connected to the longitudinal main girder using transverse connection stiffeners welded to the web plate of the main girder. Cut-out holes between these stiffeners and the web plate were commonly used to avoid intersecting welds in these connections. Furthermore, the stiffeners are usually not welded to the main girder flanges to avoid transverse welded details in the regions with high tensile stresses and to leave a gap between the connection plate and main girder flanges in order to facilitate fabrication. This web gap in the connection plate to the longitudinal main girder can cause concentrated deformation in the web gap region, due to the end rotation at the end of cross-beams which can result in very high stresses, even though the deformation is relatively small in comparison to the deformation of the entire structure. In many reported cases (Al-Emrani 2005; Al-Emrani 2006; D'Andrea et al. 2001; Fisher et al. 1998; Stallings et al. 1993), small magnitudes of measured local displacements in this detail have been sufficient to initiate and grow fatigue cracks. This highly concentrated deformation, which induces secondary stresses in the small web gap region, is not easy to determine without using finite element models, due to complex geometry, i.e. varying stiffness in a small region and loading conditions.

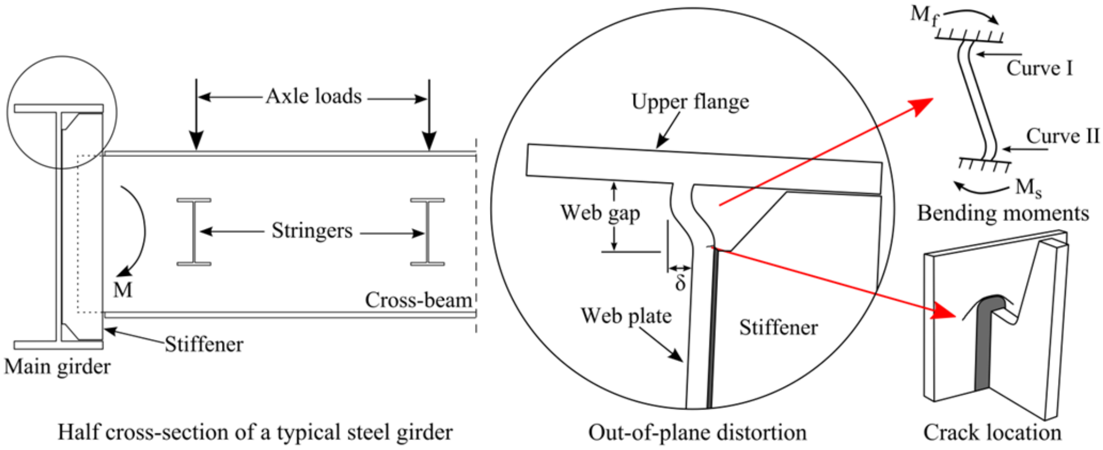


Figure 5-1 Diagram of out-of-plane distortion in a web gap and bending moments

The out-of-plane deformation in the web plate may result in bending stresses within the gap, as shown in Figure 5-1. They represent the highest stressed locations due to the reversed curvature bending (curve I and curve II in Figure 5-1) that occurs in the web gap. When the web plate in the gap region bends and the ends of the web gap experience rotation stiffness, i.e. when the rotation is partially restrained, the bending moment will become smaller and this will then lead to a reduced risk of fatigue cracking. The web plate of the cross-beam or connection plate welded perpendicular to the main girder web plate provides a constraint end on the one side. The main girder flanges, which usually have high stiffness in order to be able to carry the traffic loads on the bridges, provide a constraint end on the other side. Fatigue cracks can initiate from the weld toe of the vertical stiffener to the web plate of the main girder and propagate first along the weld toe line. However, cracking at the weld roots has also been reported (Al-Emrani 2006; Ekelund 2008).

Distortion-induced fatigue cracking in welded details was first investigated by Fisher (Fisher 1978; Fisher et al. 1979) and subsequently by other researchers (D'Andrea et al. 2001; Fraser et al. 2000). According to these investigations, the distortion-induced fatigue cracking in a web gap is the result of mixed-mode conditions; a combination of mode I (opening mode) and mode III (tearing mode). In practical engineering cases, fatigue crack initiation and growth are usually the result of mixed-mode conditions generated by complex load conditions, geometry or a combination of both. Fatigue tests performed by Fisher et al. (Fisher and Keating 1989) and Stallings et al. (Stallings et al. 1993) confirmed that the secondary stress in the web gap due to out-of-plane distortion was much higher than the primary fatigue stress caused by the design load.

5.3 Case study – Söderström Bridge

The Söderström Bridge is a welded railway girder bridge with a length of 190m built in the 1950s and located in Stockholm in Sweden. The bridge has two rail tracks and six continuous spans, see Figure 5-2. The bridge superstructure consists of two main girders connected by cross-beams which are skewed at an angle of 80°. Four stringers run between the cross-beams and carry the timber ties that form the track on the bridge. Steel quality st44 (yield strength of 260N/mm^2) was used for the built-up profiles, including the main girders, cross-beams and stringers, while, for the diagonal bracing members, steel quality st37 (yield strength of 220 N/mm^2) was used. The bridge was designed according to the Swedish standard for bridges with a traffic load model consisting of a 12 x 25-tonne axle load and an 8-tonne/m uniform load over a span (Leander 2008). Nowadays, the Söderström Bridge carries very heavy train traffic; more than 500 trains – both commuter and freight trains – pass over the bridge every day (Leander et al. 2010).

Figure 5-2 The Söderström Bridge and the crack location

The behaviour of the fatigue cracks detected in the Söderström Bridge was analysed by performing crack-propagation analysis based on LEFM and the results were presented in ***Paper IV*** and ***Paper V***. In this chapter, a more detailed description of the most important parameters used in the crack-propagation analyses and the suitability of a repair technique based on drilling holes is presented.

5.4 Crack propagation analysis – LEFM

LEFM is based on the assumption that the material is isotropic and linear-elastic. This means that the stress near the crack tip is calculated while considering the theory of elasticity, even though the stress at the crack tip can be higher than the yield stress, i.e. small-scale yielding. When the plastic zone at the crack tip is very small in relation to the crack length and component size, LEFM is valid and provides a good estimation. However, when the plastic zone is too large, i.e. large-scale yielding, the stress calculations based on LEFM are no longer valid, as the results produced by LEFM are too conservative. Instead, the methods based on elastic-plastic fracture mechanics can be used.

The main reason for using LEFM in the cracked structures is to find answers the following questions:

- What are the main load effects that govern the crack-propagation process?
- If the crack is propagating, what is the speed of the crack growth associated with load history, i.e. crack growth rate?
- What is the correct inspection period and need to repair or retrofit the cracked component/s?
- Assess the risk of brittle fracture and the safety of the structure

It is worth mentioning that LEFM is intended to provide data about crack growth conditions such as rate and direction, but it is not able to treat the crack initiation phase, which is normally followed by the propagation phase in the development process of fatigue damage in steel structures. However, as stated earlier this initial phase is usually assumed to be exhausted due to the presence of weld defects in welded steel structures.

In steel structures, the residual fatigue life of a detail containing a crack when using LEFM is usually determined by using the crack growth relationship proposed by Paris and Erdogan, known as the Paris law (Paris and Erdogan 1963), given in Eq. 5-1:

$$\frac{da}{dN} = C \cdot (\Delta K, \Delta K_{eff})^m \quad \rightarrow \quad N = \frac{1}{C} \cdot \int_{a_0}^{a_f} \frac{da}{(\Delta K, \Delta K_{eff})^m} \qquad \textit{Eq. 5-1}$$

The Paris law parameters, C and m, are material parameters. In the current study, these parameters were defined by following the recommendations given by BS7608:1993, with $C = 5.21 \cdot 10^{-13}$ $N/mm^{3/2}$ and $m = 3$. As shown in Eq. 5-1, the fatigue life calculation is based on integrating the Paris equation from the initial crack size, a_0, with the final crack size, a_f. These parameters are the most important crack growth parameters defined in the performed crack growth analyses and for the fatigue life calculations performed in this thesis and they are discussed in the next section.

5.4.1 Crack growth parameters

The fatigue life estimation based on LEFM is dependent on many parameters, e.g. the computed stress intensity factor ranges, initial crack size, crack growth increment, final crack size, the threshold stress intensity factor and fracture toughness.

Stress intensity factor range, ΔK

There are two common criteria for describing the crack conditions in LEFM. The first is the stress intensity factors which locally characterise the stress, strain and displacement near the crack tip. For fatigue loading, a stress intensity factor range, ΔK, can be described as follows:

$$\Delta K = K_{\max} - K_{\min} = f(a) \cdot \Delta\sigma \cdot \sqrt{\pi \cdot a} \qquad \textit{Eq. 5-2}$$

where

a: crack size (i.e. depth or length)

Δσ: applied cyclic stress range (nominal stress)

f(a): is a function of geometry, load and crack shape, which can be found in the literature (BS7910:1999 2000; Maddox 1974; Maddox 1989; Radaj et al. 2006).

The second criterion is the J integral which considers the stress-strain field near the crack tip and quantifies the global potential energy changes for crack growth (Schijve 2009). For linear-elastic behaviour, the J integral is identical to the energy release rate, G, since the resistance of a material to crack propagation is equal to the sum of the elastic-surface energy and the plastic work following up crack propagation (Barsom 1973). In LEFM, the plasticity is not considered and this means that the J integral is equal to the surface energy per unit crack propagation. This relationship can be expressed as follows:

$$G_I = \frac{K_I^2}{E} \qquad \text{for plane stress} \qquad \textit{Eq. 5-3}$$

$$G_I = \frac{K_I^2}{E}(1-\upsilon^2) \qquad \text{for plane strain} \qquad \textit{Eq. 5-4}$$

The use of stress intensity factors to describe the crack-propagation conditions for fracture mechanics analysis is more common than the energy approach (Andersson 2005; Radaj et al. 2006). Fracture toughness data, "threshold values", which characterise the resistance of a material to cracking, are rarely given in terms of critical energy values, but it is necessary to know this for the fatigue life estimation based on crack growth analysis. The stress intensity factors have therefore considered in all the crack growth analyses and fatigue life calculations performed in this thesis.

The initial crack size, a_0

The size of the initial crack, a_0 and a_0/c_0 (crack depth and shape), is one of the most important parameters influencing the length of the period of crack propagation when using LEFM (Radaj et al. 2006). In traditional fatigue design, no distinction has been drawn between the crack initiation and propagation phases (Barsoum 2008) and LEFM is only concerned with the crack-propagation phase. The accuracy of the estimated fatigue life based on the fracture mechanics methods is therefore critically dependent on an accurate definition of initial crack size (Maddox 1974; Maddox 1989). An initial crack size may be determined by either assuming an initial crack size depending on the welding process and inspection accuracy or following the recommendations given in design codes. However, the second of these is more common in the context of design.

The IIW recommends an initial crack size of 0.15mm with a shape ratio of 0.1 (a_0=0.15mm and a_0/c_0=0.1), while BS7910 recommends an initial crack size of 0.1mm to 0.25mm with different crack shape ratios, depending on the type of welds and cracks. EN 1993-1-10 (Nussbaumer et al. 2011; Sedlacek et al. 2008) recommends that the initial crack is assumed to depend on the plate thickness, which can be obtained by following expressions:

$$a_0 = 0.5 \cdot \ln\left(1 + \frac{t}{t_0}\right) \qquad \text{for plates, t < 15mm} \qquad \textit{Eq. 5-5}$$

$$a_0 = 0.5 \cdot \ln\left(\frac{t}{t_0}\right) \qquad \text{for plates, t} \geq \text{15mm} \qquad \textit{Eq. 5-6}$$

The code also recommends using a crack shape (a_0/c_0) of 0.15 for transverse welds and 0.40 for longitudinal welds.

Radaj et al. (Radaj et al. 2006) stated that the initial crack size to be used at the weld toe should be larger than a "short crack", i.e. $a_0 > 0.1$mm, as LEFM is not suitable for shorter cracks. According to the authors, a reasonable initial crack size can be defined by considering the fatigue limit and threshold stress intensity factor, i.e. maximum size of a non-propagating crack.

When applying the recommendations given in Eq. 5-6, the depth and width of an initial crack for the studied detail in the Söderström Bridge is 1.66mm and 3.87mm respectively, which is much larger than the recommended size in the above-mentioned design codes. The technical surface crack (a crack depth of 0.5mm and semi-circular shape) recommended by Radaj et. al. (Radaj et al. 2006) has therefore been used as the initial crack in all crack growth analyses performed in this thesis. Furthermore, this technical crack defined as the initial crack is generally related to the assessment of fatigue strength according to the notch stress.

Crack growth increment, Δa

No recommendations are given in the literature or in design codes for the crack growth increments that should be used. The sizes of the crack growth increment were defined in the performed crack-propagation analyses by considering the total crack length and the number of analysis steps, as, in the case of long fatigue cracks, the small size of the crack growth increments would result in many analysis steps. On the other hand, to capture the effects of the deformation which was the source of fatigue cracking on the distributed stresses accurately, the chosen size of the crack increment should not be too large. Since distortional fatigue cracks generally display a varying growth rate with extended crack length, the crack growth increment was not kept constant during the analysis, but a stepwise increasing value has been defined. For the first 20 steps of crack growth analysis, the crack increment was 0.1mm and this value increased to 0.2mm in the second 20 steps. The increase in the crack increments with an extended crack continued up to 1mm, see Figure 5-6.

The computation of a newly propagated crack front is based on the crack increment and the computed SIF values at the crack front points, as expressed in Eq. 5-7, as well as the defined crack kink angle criterion (see Section 5.4.3).

$$\Delta a_i = \Delta a_{median}\left(\frac{\dfrac{da}{dN_i}(\Delta K_i, R_{i,} ...)}{\dfrac{da}{dN_{median}}(\Delta K_{median}, R_{median,} ...)}\right) \qquad \textit{Eq. 5-7}$$

where Δa_i is the crack extension in the crack front point, Δa_{median} is the crack extension specified for the crack front point, where the median stress intensity factor range, da/dN_i, is the crack growth rate computed at the point and da/dN_{median} is the crack growth rate computed at the crack front point with a median stress intensity value.

Since the computed SIFs are not constant at the crack front points, the crack does not propagate uniformly at these points along the crack front for non-planar crack growth. Once the crack increment and the local kink angle for each point along the crack front have been determined, the propagated crack front line consisting of crack edges fits a polynomial curve through the determined crack front points, see Figure 5-3.

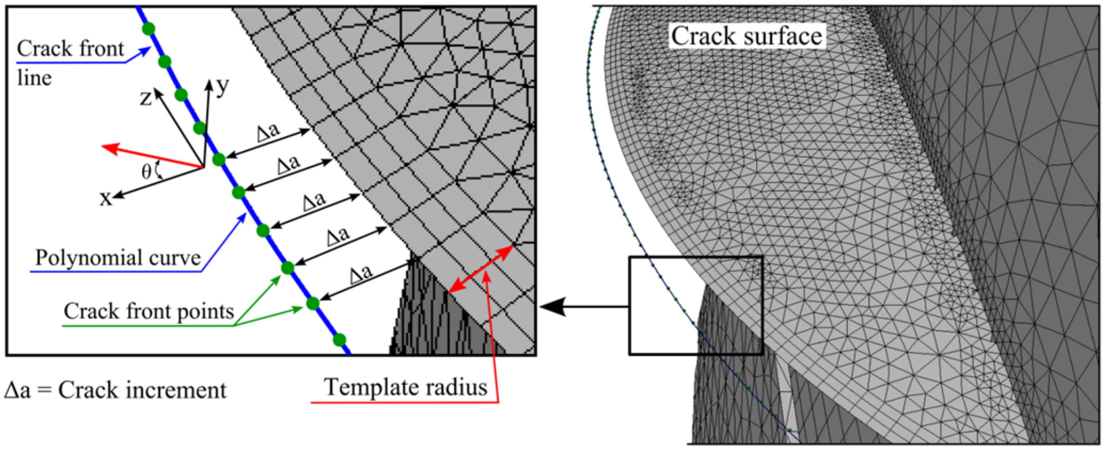


Figure 5-3 Estimating the new crack front points along the crack front

The final crack size, a_d

The definition of a critical crack length, final crack size (a_f), is essential to ensure that a crack does not grow to its critical size, especially for structures where the consequences of a failure are serious. The final crack size can be dependent on the type of analysis and failure, such as leakage in vessel structures by the crack size of through-thickness or unstable fracture (BS7608:1993 1999; Maddox 1989). The design condition when using the methods based on fracture mechanics compares the K-values of the load effects to the resistance, as shown in Eq. 5-8 (Nussbaumer et al. 2011):

$$\Delta K_{Ed} \leq \Delta K_{Rd} \qquad \textit{Eq. 5-8}$$

According to this equation, the critical crack length in the fatigue life calculations can be defined by considering material toughness (ΔK_C), i.e. the unstable crack growth in Region III (see Figure 3-8 in Section 3.6).

A general recommendation for the definition of the final crack size for steel structures is to consider the crack length in the thickness direction (Maddox 1974). A surface crack depth equal to half or two thirds of the plate thickness can be used as the critical crack size (Radaj et al. 2006). This is due to the fact that crack propagation for the second half of the plate thickness consists of a very small part of the total service life.

No final crack size for the studied welded detail in this thesis has been defined by following the above-mentioned criteria, as the crack was arrested in the thickness direction and propagated with the reduced crack growth rate in the direction of the web plane. The crack size before repairing the cracked details in the Söderström

Bridge was chosen as the "final" crack size for the fatigue life calculations. The crack length was 30mm on the left side and 36mm on the right side of the stiffener in the web plane direction (see ***Paper IV*** and ***Paper V***). The crack length in the thickness direction was not reported and so the corresponding crack length in the thickness direction, which was 17mm obtained from the crack growth analysis, has been used in the fatigue life calculations.

The threshold stress intensity factor, ΔK_{th}

Another important factor for the fatigue life calculations based on LEFM is the threshold stress intensity factor (ΔK_{th}), which is an important design criterion for crack propagation. The stress intensity factor ranges are actually related to the threshold stress intensity factor which indicates the material resistance to crack propagation.

The threshold stress intensity factor for assessing welded joints recommended by BS7910:1999 (BS7910:1999 2000) and the IIW (IIW 2008) was applied in the fatigue life calculations performed in this thesis. The threshold stress intensity range for as-welded steel structural components given by these codes was $63\text{N/mm}^{3/2}$. The same value has also been used for the mixed-mode conditions (for ΔK_{eff}, see the next section). An experimental investigation into the different grades of steel under different stress ranges performed by Tanaka and Soya (Tanaka and Soya 1989) showed that all the examined steels could be represented by the same ΔK_{th}.

5.4.2 Mixed-mode conditions

In fatigue-loaded structural details, the loading mode may vary from pure mode I, mode II and mode III to mixed-mode conditions (see Chapter 3). Due to the complexity of loading and geometry in the studied detail, the fatigue-cracked region is subjected to mixed-mode fracture. It is reported in (Fraser et al. 2000) that distortion-induced fatigue cracking is "generally" a result of mixed-mode loading effects; mode I (opening) and mode III (tearing). In the fatigue crack-propagation analyses performed in the current work, two alternatives have been considered: 1) a dominant mode-I condition, i.e. ΔK_I as the governing crack-opening mode, and 2) mixed-mode loading conditions using ΔK_{eff}, considering the combined modes of I, II and III. The ΔK_{eff} is calculated using the expression given in Eq. 5-9. This expression is recommended by BS7910:1999 (BS7910:1999 2000), which is based on the strain energy release rate.

$$\Delta K_{eff} = \sqrt{\Delta K_I^2 + \Delta K_{II}^2 + \frac{\Delta K_{III}^2}{1-\nu}} \qquad (\nu = 0{,}3) \qquad \textit{Eq. 5-9}$$

5.4.3 Crack direction – kink angle

It is well known that the crack growth direction has a great influence on the computed stress intensity factors and is directly dependent on the loading conditions. In the event of mode-I conditions, the crack will grow in its original crack plane. However, in complex cases, such as the studied detail in the Söderström Bridge where the crack is subjected to complex stress conditions, the crack growth direction is not obvious and not easy to predict. In order to compare the crack size and direction in the FE analysis with the real cracks detected in the Söderström Bridge, three common crack growth direction criteria were applied to determine the kink angle. These criteria were the maximum tensile stress criterion (MTS) proposed by Erdogan and Sih (Erdogan and Sih 1963), the maximum generalised stress criterion (GEN) and the maximum strain energy release rate criterion (SERR) proposed by Sih (Sih 1974). All three criteria were available in Franc3D v6 (Franc3D 2011) and each criterion was calculated during the crack growth simulation as follows.

The MTS criterion predicts that a crack propagates in the direction of the maximum tensile/opening stress, σ_θ (see Figure 5-4). The MTS criterion has been applied widely due to its simplicity and has the following expression:

$$K_I^r(\theta) = \sigma_{\theta\theta} \cdot \sqrt{2 \cdot \pi \cdot r} = \cos\frac{\theta}{2}\left[K_I \cos^2\left(\frac{\theta}{2}\right) - \frac{3}{2}K_{II}\sin(\theta)\right] \qquad \textit{Eq. 5-10}$$

$$\sigma_{\theta\theta} = \frac{1}{\sqrt{2 \cdot \pi \cdot r}}\cos\frac{\theta}{2}\left[K_I \cos^2\left(\frac{\theta}{2}\right) - \frac{3}{2}K_{II}\sin(\theta)\right] \qquad \textit{Eq. 5-11}$$

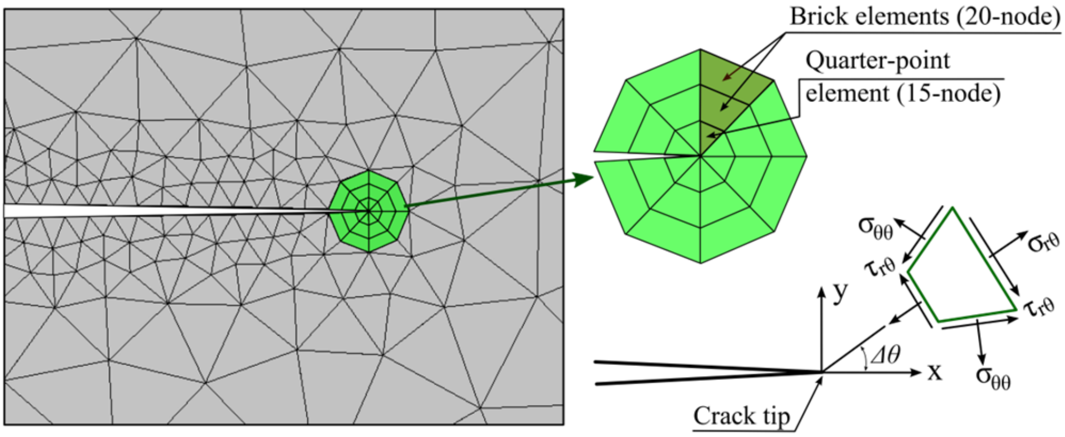


Figure 5-4 Definition of stress and crack direction at the crack tip

The direction of maximum tensile stress can then be found by equating the derivative of Eq. 5-11 to zero, as given in *Eq. 5-12*, since $\sigma_{\theta\theta}$ is largest (maximum) when $\sigma_{r\theta}$ is zero.

$$\Delta\theta = 2\tan^{-1}\left(\frac{1-\sqrt{1+8(K_{II}/K_I)^2}}{4(K_{II}/K_I)}\right) \qquad \textit{Eq. 5-12}$$

The second crack direction criterion is the maximum generalised stress criterion (GEN), which considers both the MTS and the maximum shear stress (MSS) criterion at the crack tip. According to this criterion, the crack growth direction corresponds to the direction obtained from the stress intensity factors from MTS and MSS (Franc3D 2011). The maximum shear stress in a crack front can be computed as:

$$\sigma_{Shear} = \sqrt{\sigma_{r\theta}^2 + \sigma_{z\theta}^2} \qquad \text{Eq. 5-13}$$

$$K_{II}^r(\theta) = \sigma_{r\theta} \cdot \sqrt{2 \cdot \pi \cdot r} = \frac{1}{2}\cos\frac{\theta}{2}\left[K_I \cos\theta - K_{II}(3\cos(\theta - 1)\right] \qquad \text{Eq. 5-14}$$

$$K_{III}^r(\theta) = \sigma_{z\theta} \cdot \sqrt{2 \cdot \pi \cdot r} = K_{III}\cos\frac{\theta}{2} \qquad \text{Eq. 5-15}$$

The third crack direction criterion is the maximum strain energy release rate (*SERR*). According to this criterion, the crack-propagation kink angle can be predicted by assuming that the crack will propagate in the direction that maximises the strain energy, which is based on the principle of the minimum potential energy in elasticity. Under mode-I loading conditions, the maximum strain energy release rate is equivalent to the corresponding stress intensity factor as:

$$G_I(\theta) = \frac{1 - \upsilon^2}{E}(K_I^r(\theta))^2 \qquad \text{Eq. 5-16}$$

For mixed-mode conditions, the maximum strain energy release rate is determined from all three stress intensity factors as follows:

$$G(\theta) = (K_I^r(\theta))^2 + (\beta_{II}K_{II}^r(\theta))^2 + (\beta_{III}K_{III}^r(\theta))^2 \qquad \text{Eq. 5-17}$$

where β_{II} and β_{III} are model weighting parameters. In the crack-propagation analyses performed in this thesis, these parameters have been used as $\beta_{II} = 1.0$ and $\beta_{III} = (1/1\text{-}\nu)$.

5.4.4 Crack closure

As stated earlier, crack growth under cyclic loading is a complex process influenced by many variables, such as load, geometry, material microstructure and environmental factors, all of which might have an important effect on the crack growth rate. When the crack surfaces are in contact due to compressive stress or low stress ratios causing smaller crack tip opening displacements, i.e. the crack is not fully open during the entire load cycle, crack closure may occur. Prior to the research reported by Elber (Elber 1971), it was assumed that crack closure was only caused by the parts of the load that produce compressive stresses. However, Elber (Elber 1971) showed that crack closure occurs even under loads that produce tensile stress at the crack front and that this mechanism has significant effects on the acceleration and retardation of fatigue crack propagation. According to Elber, a crack closure exists during a lower part of the load cycle, K_{open}, as the crack remains closed, see Figure 5-5 a). The reason for crack closure under low tensile stress is the effect of plasticity left in the wake of the growing crack, as the stress at the crack tip is extremely high, which causes plasticity in the crack tip region, see Figure 5-5 b). When the crack surfaces come into contact, there is no change in crack-tip strain during the cyclic loading of a closed crack (Elber 1971). As a result, the cyclic load, which produces compressive stress, and the lower part of cyclic loading, which generates tensile stress, do not contribute to crack propagation. Crack closure will reduce the fatigue crack growth rate by reducing the stress intensity at the crack tip.

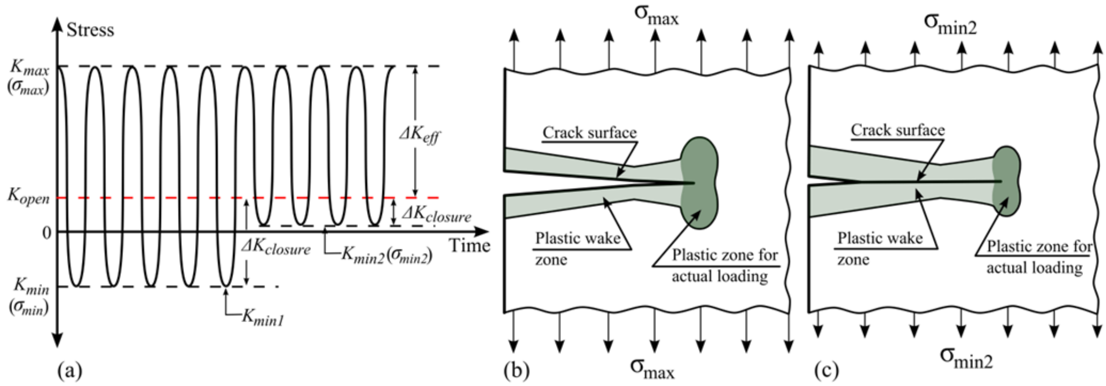


Figure 5-5 a) Crack opening and closure loads, b) plastic zone along the crack with maximum stress and c) with minimum stress

The effect of plasticity is not, however, directly considered in LEFM calculations; instead, this effect is included by using semi-empirical formulas considering the elastic stress state at the crack tip during crack propagation. The reduction in the crack growth rate due to the effect of crack closure is handled by introducing an effective stress intensity range when applying LEFM, as shown in Eq. 5-18.

$$\Delta K_{eff} = K_{\max} - K_{op} \qquad \textit{Eq. 5-18}$$

In this study, however, the effect of crack closure caused by cyclic loading has been accounted for only "globally" by excluding the compressive stresses (the crack remains closed) from the variable amplitude fatigue load. The effective stress intensity factor was defined in Eq. 5-19 as follows:

$$\Delta K_{eff}^{cc} = K_{\max} - \max(K_{\min}, 0) \qquad \textit{Eq. 5-19}$$

It has been reported that lower R ratios contribute to lower crack growth rates and higher R ratios to higher crack growth rates, i.e. mean stress-sensitivity in crack growth (Andersson 2005; Schijve 2009; Zhang et al. 1987). A change in the stress ratio will directly influence crack closure, as a change in the stress ratio with a fixed stress range means that the mean stress will be changed and thereby the plastic deformation at the crack tip.

In addition to Elber's mechanism, known as plasticity-induced crack closure, additional types of mechanism causing crack closure have been identified. The most common are roughness-induced closure, depending on the material microstructure, and oxide-induced closure in structures subjected to an aggressive environment (Andersson 2005).

5.4.5 Analysis process

The work flow for the crack growth analysis performed in this study is shown in Figure 1. In the first step, a large part of an FE model of the bridge without including a crack was created by using Abaqus v6.11. This model was divided into two different FE models, a global and a local model, without changing the mesh density (by using orphan meshing). Note that the local model was not included in the global model. This local part was simply removed from the global model.

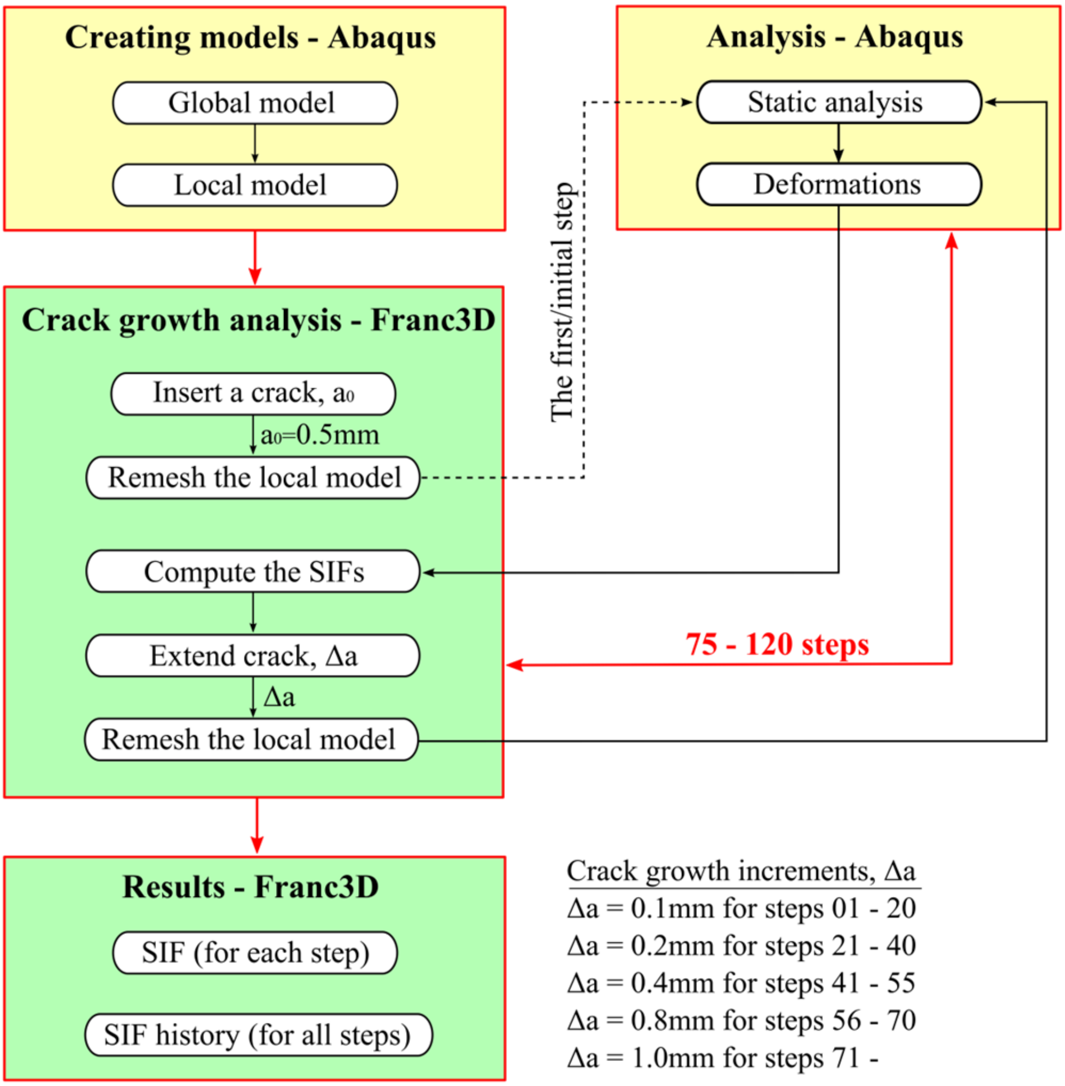


Figure 5-6 Work flow for crack-propagation analysis using Abaqus and Franc3D and the crack increments used in all crack growth analyses

The second step started by inserting the initial crack into the local model which was remeshed by Franc3d v6.0. This remeshed local model with the initial crack was integrated by Franc3D v6.0 into the global model in order to calculate the displacement. The static analysis in this step was performed by Abaqus v6.11. The computed stress intensity factors (SIFs) for all nodes along the crack front were computed by Franc3D v6.0 using the result file obtained from Abaqus v6.11. These SIFs were needed to estimate the direction and amount of crack propagation along the crack front points. The crack was subsequently extended by the crack increment, Δa, as shown in Figure 5-6, and was kept the same for all crack growth analyses. The local model was remeshed for another static analysis to compute displacements. This process, remeshing the local model and computing the displacements, was repeated for the chosen number of crack steps, which varied from 75 steps to 120 steps.

In the last step, the computed SIFs for each crack step or all history can be obtained from Franc3D v6.0.

5.5 Crack propagation analysis – repairing or retrofitting

Different methods are available for repairing distortion-induced fatigue cracks and retrofitting the welded details prone to distortional fatigue cracking. In general, the choice of these methods depends on the location of the fatigue cracks, i.e. at the weld toe or root, and the availability of certain skills, i.e. contractor dependence (Dexter and Ocel 2005). For instance, surface treatments such as improvements to weld geometry and the reduction of tensile residual stress only influence the weld toes. Stiffening with welded attachments and bolted connections is also widely used for retrofitting the cracked details. The most widely used repair method is drilling stop holes at the crack tips. Since distortion-induced fatigue cracking is distortion controlled, the crack driving force may be reduced by the extended crack. In this case, the best choice is to monitor the crack propagation and not to repair the crack (Dexter and Ocel 2005). The main disadvantage of not repairing the crack is that the crack propagation must be monitored with extra care. This involves that the monitoring may require a deeper inspection to identify the location of the crack tip and growth over time as accurately as possible.

The cracks detected in the Söderström Bridge were repaired by increasing the weld thickness by additional welding around the cracked region and grinding the weld toes in order to obtain a smooth transition between the weld and plates. Figure 4-1 shows the repaired welded detail in the Söderström Bridge. It was reported (Ekelund 2008) that the cracked details were repaired by first grinding in order to identify the crack extension. Secondly, the weld thickness was increased by additional welding around the details – as much as was needed. However, there are no additional data about the size of the increased weld. The retrofitting of cracked details was continued by grinding the increased weld in order to obtain a smooth transition at the weld toes and to fulfil the weld quality requirements. Finally, the repair of the cracks was completed by applying corrosion protection. During the repairs, the welds were inspected by NDT[10] to ensure the quality of the welds and make sure that they did not contain any weld defects. It is worth mentioning here that the studied crack detail investigated in ***Paper IV and Paper V*** was one of the longest cracks detected in the bridge.

Figure 5-7 Retrofitted damage welded detail in the Söderström Bridge

[10] Magnetic-particle testing was used

Increasing the weld thickness for the purpose of retrofitting can be effective for small cracks which initiate through the weld and have not yet propagated outside the weld region, which means that the crack propagation is still inside in the weld. In this case, the most important question to be answered is the thickness of the weld that will be used in order to increase the stiffness of the welded joints against distortional fatigue cracking and to prevent a new fatigue crack initiation and propagation. On the other hand, for longer fatigue cracks such as the crack in the studied welded detail in which the crack was initiated at the weld toe and propagated out of the welded region to an "open region", i.e. left- and right-hand side of the stiffener, retrofitting by increasing the weld thickness can be highly questionable. There are two main reasons for the uncertainty relating to retrofitting the studied welded detail by increasing the weld thickness; 1) performing a crack repair in the weld and the cracked plate and 2) stress conditions in the welded detail after retrofitting.

Performing a successful crack repair, i.e. arresting crack growth, can be dependent on the size of crack lengths and the type of cracks, such as through-thickness cracks. As mentioned earlier, the studied crack propagated to the "open region" in the web plate, but the crack was not a through-thickness crack. The crack growth in the thickness direction reached almost half the thickness. Nevertheless, this means that the material along the crack length should be removed by arc-gouging a V-shaped weld preparation along the crack path and then welding, i.e. Vee-and-weld method (Dexter and Ocel 2005). The stress state in the retrofitted welded detail is another aspect to be considered after retrofitting to ensure that the stresses causing the fatigue crack are lower, due to the increased stiffness, and the residual stresses introduced by welding are not too large.

For the above-mentioned reasons, the repair method using a stop hole at the crack tip is recommended for the longer cracks detected in the Söderström Bridge. A demonstration of the performed retrofitting of the cracked detail, i.e. to arrive at this decision using a crack-propagation analysis, was not possible due to the lack of retrofitting data. However, the efficiency of the repair method using stop holes has been demonstrated using the crack-propagation analysis presented below.

The crack growth analysis began by identifying the location of the crack path, which had already been obtained in the previous analysis presented in ***Paper IV.*** The size of the stop holes was determined by following the recommended stop-hole diameter (20mm) in Sweden. As shown in Figure 5-8, the stop holes were centred in order to remove the crack tip. Since the crack propagated downwards in the web plate and was not a through-thickness crack, two possible stop-hole drilling procedures were demonstrated.

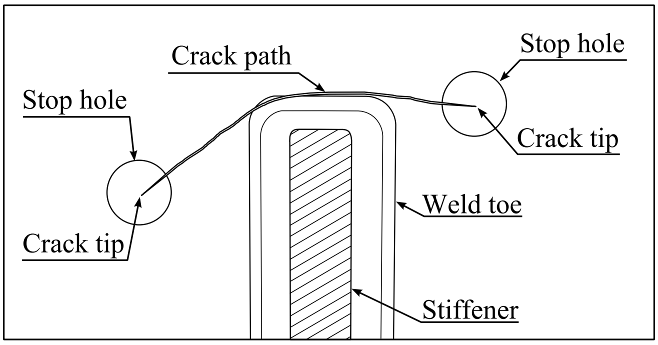


Figure 5-8 Illustration of drilling stop holes in the studied welded detail

The first type was stop holes with a certain depth (blind hole) in the thickness of the web plate, see Figure 5-9. The second type of stop hole was stop holes through the thickness of the web plate (through hole), which was more common for repairing cracks, Figure 5-10. Another reason for demonstrating two different types of stop hole was to compare the efficiency of these different types of hole drilling.

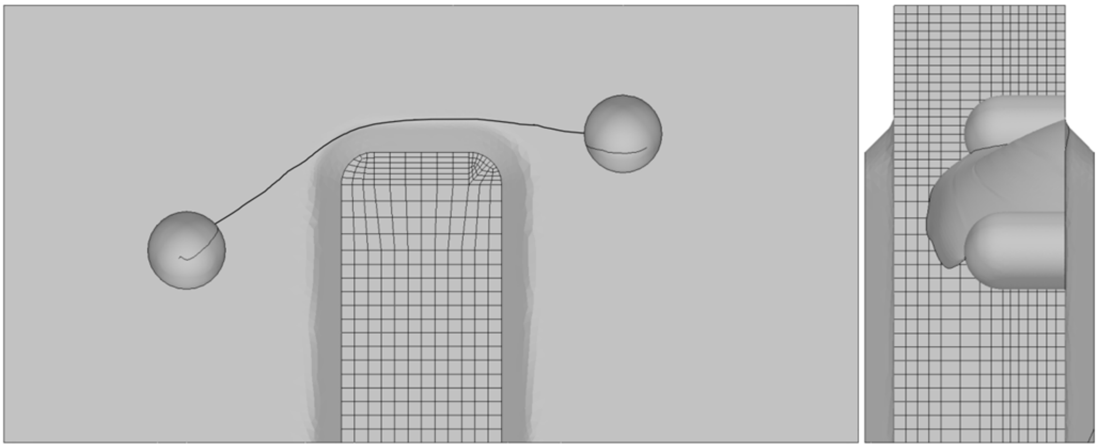


Figure 5-9 Fatigue damage repairing technique – blind hole

The diameter of 20mm and the location of stop holes were kept the same for both cases in the crack growth analyses. The only difference between these two types of hole was the depth in the thickness direction. The depth size of the blind hole was chosen as 14.5mm (Figure 5-9), which was sufficiently deep to remove the crack tip in the repaired crack location and was two thirds of the plate thickness, as recommended by Radaj et al. (Radaj et al. 2006). The bridge loads were defined to be the same as in the fatigue crack growth analysis with constant amplitude loading generated by the X60 train type presented in ***Paper IV***, in order to compare the results of the analyses.

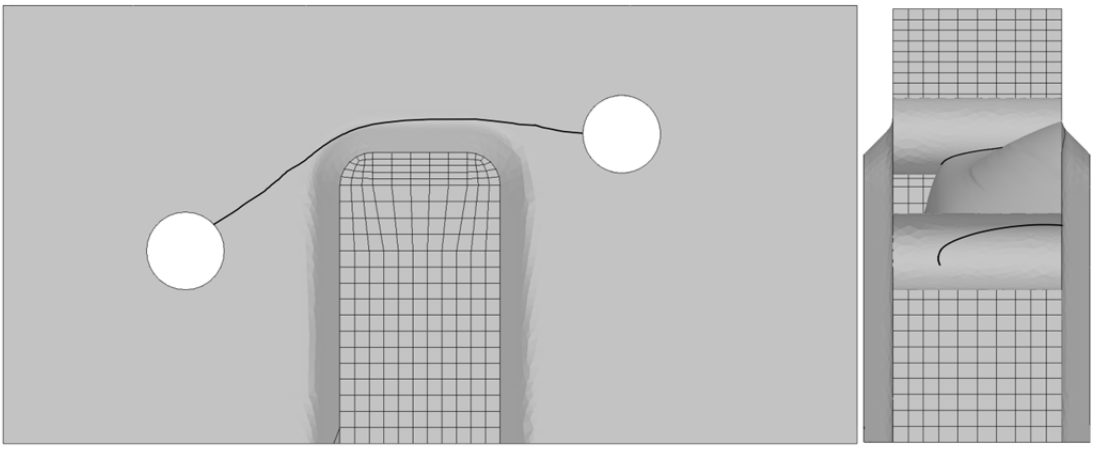


Figure 5-10 Fatigue damage repairing technique – through hole

Figure 5-11 shows the results with stop holes and a comparison of these results with the results of the crack growth analysis with constant amplitude loading (CA analysis in ***Paper IV***). As shown in this figure, the repair technique arrests the crack propagation in all crack-propagation directions; in the thickness direction and in the direction of the web plane of the main girder. Figure 5-11 shows a crack length of 25mm in the thickness direction with the repair techniques, which exceeds the thickness of the web plate. However, as shown in Figure 5-9 and Figure 5-10, the crack in this direction is non-planar and propagates downwards. The results also present very high SIF values with the holes at the beginning of the repair, which might be dependent on the reduced material in the cracked region. On the other hand, the welded joint becomes more relaxed in relation to the deformation, causing the fatigue cracking which leads to a rapid reduction in SIF values.

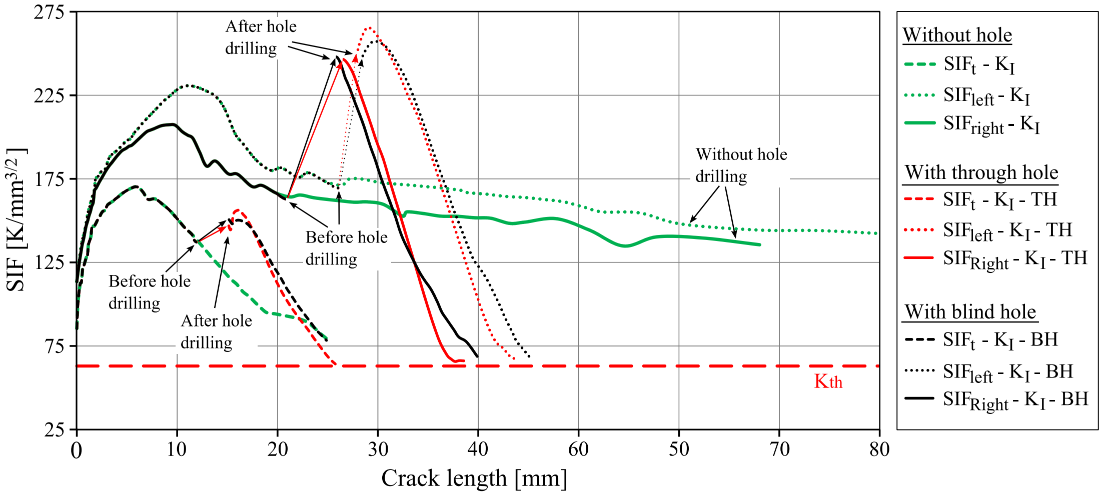


Figure 5-11 Comparison of the results of damage retrofitting techniques with the results without retrofitting the damage

The difference between these two repair techniques, as shown in Figure 5-11, is very small. The repair technique with the through-thickness hole yields a slightly faster reduction (relaxation) in comparison with the repair with a blind hole. It is worth noting that there is no need for the instructions for a proper hole-drilling depth when employing the repair technique with a through hole. For this reason, this technique is preferable in this case. Moreover, the crack growth analysis for this technique was easier to perform when it came to inserting the extended crack fronts and meshing the local model.

6 Conclusions

6.1 General conclusions

The conclusions based on the studies performed in this thesis are divided into two parts following the fatigue assessment methods in the design phase and in the service phase. In the first part, the conclusions and recommendations for fatigue assessment based on the local failure approaches in the design phase are given. In the second part, the conclusions and recommendations for the fatigue assessment of damaged details when using LEFM in the service phase are presented.

The application of the fatigue assessment methods to "basic" and complex welded details showed that the local failure approaches yield more accurate fatigue life estimations in comparison with the conventional nominal stress method. Based on the investigations performed in the first part (***Paper I***, ***Paper II*** and ***Paper III***), the following conclusions can be drawn.

- The results from the fatigue assessment of the studied welded details show that the local failure approaches provide more accurate fatigue life estimation in comparison with the nominal stress method, even though the methods require more effort for modelling.
- The fatigue assessment of fatigue-critical details prone to distortional cracking can be obtained more accurately by using local failure approaches. This type of fatigue damage cannot be assessed using the conventional nominal stress based methods due to the highly localised deformation.

The following conclusions relating to each approach can be drawn.

Nominal stress approach:

- When using the nominal stress method for the welded details with cut-out holes, special attention should, however be paid to the distribution of shear stress over the welded section (***Paper I, Paper II***).
- The nominal stress method for the fatigue assessment of orthotropic bridge details provides good agreement with the test results, if the shear stress along the weld and the normal stress over the entire girder section are considered. A more clear definition for critical cross-sections where the stress calculations would be performed therefore needs be outlined in EN 1993-1-9 (***Paper II***).

Structural hot spot stress approach:

- In general, the structural hot-spot stress-based fatigue strength of 90 N/mm^2 can be used for the details with load-carrying welds and 100 N/mm^2 for details with non-load-carrying welds, with the exception of some cases presented in ***Paper I.***
- The results from the estimation of the welded plate-edge joints based on the hot-spot stress method showed that a single fatigue strength of 100 N/mm^2 can be used, irrespective of the length of the attached plates (***Paper I***).
- When using the structural hot-spot stress approach, it is essential correctly to represent the welds in complex details with cut-out holes. For the studied welded joints on the orthotropic bridge details, finely meshed solid element models yield more representative stress ranges at the hot-spot points. The solid element models including the welds to evaluate the structural hot-spot stresses

for welded details with cut-out hole should be used. For models incorporating shell elements, it is important to represent the welds in complex welded joints, not only in terms of stiffness (thickness) but also with regard to shape (geometry). The study shows that a correct representation of the welds in this type of detail can be achieved by using oblique shell elements (***Paper II***).

- The straight stress evaluation path presented in ***Paper II*** yields more reliable results and should be used to determine the structural hot-spot stresses. Moreover, the calculated hot-spot stresses without any extrapolation (i.e. using the 0.5t stress derivation procedure) yield accurate results in comparison with the results calculated using the surface stress extrapolation procedures.
- The 1mm stress method produces accurate results for the investigated hot-spot points in ***Paper II***. However, the accuracy of the method is dependent on finely meshed FE models.
- Even though the hot-spot stress method is a mesh-sensitive method when using FEM, the accuracy of the results can be verified by the measured strain, 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 strain at fatigue-critical points. The essential need to use strain gauges in complex welded details in fatigue tests is substantiated in ***Paper II***.
- FE models with solid elements yield representative stress ranges, regardless of the stress determination procedure. The use of solid element models to evaluate the structural hot-spot stresses for welded details prone to distortional cracking should therefore be considered (***Paper III***).
- When using the structural hot-spot stress method, FE models with shell elements should not be used for the details subjected to distortional loading. The high stress gradients caused by bending cannot be captured accurately when using shell elements around the studied region (***Paper III***).

Effective notch stress approach:

- Using smaller tetrahedral solid elements facilitates the modelling work and the differences between the results when using hexahedral and tetrahedral elements are very small (***Paper II***).
- Based on the experience obtained from the modelling work in the performed study in this thesis, the effective notch stress method appears to be more suitable for evaluating the components of small structures such as trucks, cars and machinery. The hot-spot stress approach is more applicable for larger structures, such as offshore, ships and bridges, in which the effects of the weld in the stress calculations are generally negligible (***Paper II, Paper III***).
- The effective notch stress method yields a conservative life prediction when considering detail category 225 and the effort required for modelling and computation time is somewhat higher than that used in the hot-spot stress method due to the use of the multi-level sub-modelling technique (***Paper III***).

Part II of the study comprises analysing the distortion-induced crack behaviour and estimating the residual fatigue life of the welded details in the presence of a crack. Based on the second part of the studies (***Paper IV*** and ***Paper V***), the following conclusions can be drawn.

- In the studied welded detail with a distortion-induced fatigue crack in the Söderström Bridge, the crack growth rate decreases as the crack in the studied detail propagates, as the cracks are generated by bending stresses. In particular, the crack propagation in the thickness direction will be arrested at a certain depth. Nevertheless, the crack growth in the web plane direction (along the main girder) will continue propagating with the reduced crack growth rate.

- According to the studied crack behaviour and computed stress intensity factors, it is essential to be aware that the residual fatigue life of a cracked detail could be calculated by considering the crack tip conditions. Measured stress may also be used in cases where the geometry and load are not too complex. The measured stress data may present a relaxed stress condition on the plate surface due to the propagated crack, while the stress conditions at the crack fronts are still at a critical level.
- The crack direction criteria studied in this investigation present more or less the same crack propagation and stress intensity factors.
- In the welded detail with a distortion-induced fatigue crack in the Söderström Bridge, the crack propagation is the result of a mixture of mode I and mode III over the welded region in the thickness direction, even though mode I is unquestionably operative, which is actually valid for the whole crack development. In the longitudinal direction, the behaviour is more complex, as the crack propagation is the result of all three modes.
- When the crack propagation passes over the welded region and the crack tip is in the "open" region, the crack propagation is the result of all three modes in all directions. The combinations of all three modes can be confirmed by the crack shape, which indicates crack growth in its original plane (mode I), with kinking (mode II) and twisting (mode III). However, it should be noted that the cross-beam connected to the main girder at an angle is not perpendicular to the main girder, which may affect the combination of the modes.
- The structural properties, such as bending stiffness, geometric configurations and skewed beams, are the most important parameters which influence crack behaviour.
- The crack growth rate is controlled by the out-of-plane distortion, which is the reason for categorising this crack behaviour as displacement-controlled cracks not load-controlled cracks.
- The crack growth rate decreases as the crack length extends, due to relaxation, as the web gap becomes more flexible because of the extended crack. The out-of-plane distortion causing fatigue cracking is also an indicator of the retardation effect.
- The results confirm that the stress intensity factors have three different crack growth rates in this studied welded region.
- The crack direction criteria studied in this investigation provide basically the same crack formation and crack growth rate.
- The effect of mean stress is assumed to be less significant in the studied detail due to the presence of a notch, i.e. crack tip.
- The results underline the great importance of accurately defining the design load. Considering the worst case may produce a fatigue life estimation on the safe side, but a not very high conservative life estimation, as the uncertainties in the calculations and assumptions can be accommodated.
- The repair technique with hole drilling results in the crack arresting. Since there is a very small difference between the repair technique with through and blind holes, the repair technique using a through hole is recommended. This is

due to fact that, with this technique, there is no need for any requirement relating to the depth of hole drilling.

6.2 Suggestions for future research

There are number of closely related subjects that need to be considered in future research on the fatigue assessment of welded steel structures.

- The results from the studied details showed that some welded details might be classified as a fatigue strength of 300 N/mm^2 when using the effective notch stress method. More detailed investigations of these welded details are needed to draw a firm conclusion or to give a recommendation of this kind.

- The 1mm stress method takes account of the thickness effect very effectively, even though the method requires finely meshed models around the critical regions. Further research could deal with applying this method to the studied welded details in ***Paper I*** and other welded details to confirm the accuracy of the structural hot-spot stress method with the thickness correction factor.

- In complex details, more accurate estimations can be obtained by applying crack-propagation analysis-based fracture mechanics. Further work could deal with the application of crack-propagation analysis to the orthotropic bridge deck welded details investigated in ***Paper II.***

- The effect of template/pattern radius[11] on the computed SIF values should be investigated. No recommendation is given for this parameter.

- The Paris law ignores the effect of the stress ratio, R. The dependence of crack growth rates on R can be included in further work by focusing on other growth models, such as the Norman law.

- The effect of crack closure defining the plasticity-induced closure around the crack tip and residual stress need to be included in the crack-propagation analysis in order to obtain more reliable inspection periods.

- Crack-propagation simulations with variable amplitude loading need to be investigated in more detail, considering the load-sequence effect, i.e. overload and underload.

- The repair technique which involves increasing the weld applied to the Söderström Bridge should be analysed by crack growth analysis, as this technique will increase the stiffness of the welded joint in response to distortional deformation but will not remove the presence of the distortional deformation.

[11] Template radius controls element sizes and shapes around the crack tip

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