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Ilkka Poutiainen

A MODIFIED STRUCTURAL STRESS METHOD FOR FATIGUE ASSESSMENT OF WELDED STRUCTURES

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Supervisor | Professor Dr. Gary Marquis
Department of Mechanical Engineering
Lappeenranta University of Technology
Finland

Reviewers | Professor Dr. Wolfgang Fricke
Institute of Ship Structural Design and Analysis
Hamburg University of Technology
Germany

Professor Dr. Károly Jármai
Department of Materials Handling and Logistics
University of Miskolc
Hungary

Opponents | Professor Dr. Wolfgang Fricke
Institute of Ship Structural Design and Analysis
Hamburg University of Technology
Germany

Dr. Timo P. J. Mikkola
Senior Structural Consultant
SWECO Marine
Finland

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ABSTRACT

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Fatigue life assessment of welded structures is commonly based on the nominal stress method, but more flexible and accurate methods have been introduced. In general, the assessment accuracy is improved as more localized information about the weld is incorporated. The structural hot spot stress method includes the influence of macro geometric effects and structural discontinuities on the design stress but excludes the local features of the weld. In this thesis, the limitations of the structural hot spot stress method are discussed and a modified structural stress method with improved accuracy is developed and verified for selected welded details.

The fatigue life of structures in the as-welded state consists mainly of crack growth from pre-existing cracks or defects. Crack growth rate depends on crack geometry and the stress state on the crack face plane. This means that the stress level and shape of the stress distribution in the assumed crack path governs the total fatigue life. In many structural details the stress distribution is similar and adequate fatigue life estimates can be obtained just by adjusting the stress level based on a single stress value, i.e., the structural hot spot stress. There are, however, cases for which the structural stress approach is less appropriate because the stress distribution differs significantly from the more common cases. Plate edge attachments and plates on elastic foundations are some examples of structures with this type of stress distribution. The importance of fillet weld size and weld load variation on the stress distribution is another central topic in this thesis.

Structural hot spot stress determination is generally based on a procedure that involves extrapolation of plate surface stresses. Other possibilities for determining the structural hot spot stress is to extrapolate stresses through the thickness at the weld toe or to use Dong's method which includes through-thickness extrapolation at some distance from the weld toe. Both of these latter methods are less sensitive to the FE mesh used. Structural stress based on surface extrapolation is sensitive to the extrapolation points selected and to the FE mesh used near these points. Rules for proper meshing, however, are well defined and not difficult to apply.

To improve the accuracy of the traditional structural hot spot stress, a multi-linear stress distribution is introduced. The magnitude of the weld toe stress after linearization is dependent on the weld size, weld load and plate thickness. Simple equations have been derived by comparing assessment results based on the local linear stress distribution and LEFM based calculations. The proposed method is called the modified structural stress method (MSHS) since the structural hot spot stress (SHS) value is corrected using information on weld size and weld load. The correction procedure is verified using fatigue test results found in the literature. Also, a test case was conducted comparing the proposed method with other local fatigue assessment methods.

Keywords: Fatigue, welded structures, structural hot spot stress, structural stress, stress analysis

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PREFACE

This work was carried out in the Department of Mechanical Engineering at Lappeenranta University of Technology between 2001 and 2006. This thesis consists of five published articles plus an extended introduction. Dr. Pasi Tanskanen performed some of the analysis used in the second paper and assisted as a co-author. He was also a helpful discussion partner as I was formulating my thoughts. Professor Gary Marquis helped motivate and gave support throughout this task and guided my ideas into a more understandable form. He also helped present these ideas at several international forums which provided an important driving force for my thesis work All the ideas and conclusions presented in the papers are my own.

I am grateful for the following people for their advice on technical issues: Dr. Pasi Tanskanen in the field of FE method and stress determination, Dr. Timo Nykänen for his help and comments concerning fracture mechanics, Dr. Timo Björk for his expertise in fatigue and welding, Emeritus Professor Erkki Niemi for the guidance during my hole academic career and Dr. Tapani Halme for proofreading the manuscript.

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Final thanks are reserved for my wife Minna and children Senja and Eino. They provided much needed balance to my thesis work and understanding during the whole process.

CONTENTS

LIST OF ORIGINAL PUBLICATIONS

This thesis consists of an introductory report and five appended publications.

I Poutiainen, I., Determination of parametric hot spot stress equation for the cover plate on an I-beam, Design and analysis of welded high strength steel structures, J. Samuelsson (ed.), Fatigue 2002, EMAS, Stockholm, 2002.

II Poutiainen, I., Tanskanen, P. and Marquis, G., Finite element methods for structural hot spot stress determination - a comparison of procedures. Int J Fatigue 2004;26:1147-1157.

III Poutiainen, I. and Marquis, G., Improving the accuracy of structural hot-spot stress approach, Steel Research International 2006;12:901-905.

IV Poutiainen, I. and Marquis, G., A fatigue assessment method based on weld stress, Int J Fatigue 2006;28:1037-1046.

V Poutiainen, I. and Marquis, G., Comparison of finite element based local approaches for fatigue analysis of welded structures, submitted to Journal of Strain Analysis for Engineering Design, 2006.

NOMENCLATURE

a	= Crack length
FAT_0	= Fatigue strength of a non-load carrying welded detail
FAT_{0B}	= Fatigue strength of a non-load carrying welded detail in bending load
FAT_{0T}	= Fatigue strength of a non-load carrying welded detail in tension load
F_E	= Correction factor for the crack shape
F_G	= Correction factor for the non-uniform stress distribution
F_i	= Force
F_S	= Correction factor for the free surface
F_W	= Correction factor for the finite width
H	= Generalized modulus of elasticity
K_{1j}	= Notch stress intensity factor in symmetric stress field
K_{2j}	= Notch stress intensity factor in skew-symmetric stress field
K_I	= Stress intensity factor for tension mode
K_{II}	= Stress intensity factor for shear mode
K_{III}	= Stress intensity factor for tearing mode
K_r	= Reference stress intensity factor
K_{sa}	= Additional stress concentration factor
L	= Toe to toe length
l_w	= Weld leg length
$m(x,a)$	= Weight function
M_i	= Moment
n	= Thickness correction exponent
r_j	= Distance from the crack tip or the notch root
s	= Multiaxial coefficient
T	= Plate thickness
T_I	= Depth of the first turning point in the multi linear stress distribution
T_{ref}	= Reference thickness
u_r	= Crack opening displacement of the reference stress intensity factor
δ	= Dong's structural stress determination distance
δ_b	= Degree of bending
λ_1	= First eigenvalue for mode I in Williams's equation
λ_2	= First eigenvalue for mode II in Williams's equation
ρ	= Actual radius
ρ^*	= Material constant
ρ_f	= Fictitious radius
σ	= Stress
σ_{nom}	= Nominal stress
σ_{shs}	= Structural hot spot stress
$\sigma_{w,m}$	= Membrane weld throat stress
$\sigma_{w,s}$	= Structural weld throat stress
σ_{weld}	= Weld stress
σ_x	= Stress perpendicular to weld toe
$\sigma_{x,m}$	= Membrane vertical weld leg stress
$\sigma_{x,s}$	= Structural vertical weld leg stress
$\sigma_{y,m}$	= Membrane horizontal weld leg stress
$\sigma_{y,s}$	= Structural horizontal weld leg stress
$\sigma_{\theta,j}$	= Tangent stress component
$\tau\perp$	= Perpendicular shear stress at the weld throat

$\tau_{r\theta}$ = Shear stress in radius plane
τ_x = Shear stress in the horizontal weld leg
τ_{xy} = Shear stress in xy-plane
τ_y = Shear stress in the vertical weld leg

ABBREVIATIONS

BEM = Boundary element method
FAT = Fatigue class
FE = Finite element
FEA = Finite element analysis
FEM = Finite element method
LEFM = Linear elastic fracture mechanics
LSE = Linear surface extrapolation
LUT = Lappeenranta University of Technology
MSHS = Modified structural hot spot
N-SIF = Notch stress intensity factor
SHS = Structural hot spot
TTWT = Through thickness at the weld toe
SIF = Stress intensity factor
JSSC = Japanese Society of Steel Construction
CMM = Crack modelling method
2D = Two dimensional
3D = Three dimensional

1 INTRODUCTION

Fatigue is a common mode of failure for metals and metallic structures. Under the influence of repeated loading with a sufficiently high amplitude and mean stress, single or multiple small cracks will form. Normally these will form in regions of metallurgical discontinuities and, in structures, at points of stress concentration. The cracks will grow due to repeated loading. Upon reaching a critical size the structure will fail due to either brittle fracture or ductile rupture. This can lead to catastrophic results if the failure area forms part of a critical structural component, e.g. in aircraft, vehicles, bridges, etc. In some special cases the growing cracks can be detected before the final failure and the structure can be repaired and reinforced. Fatigue failure is rarely only a material problem, in many cases it is a design problem. In the case of welded structures, combinations of design problems and fabrication errors lead to failure. During the design phase of fatigue loaded structures attention must be given to the magnitude of the loads and how to keep the stresses or strains below an acceptable design value. Another aspect of design is to minimize the number of reversals, for example, by preventing undesired vibrations.

Common constructional materials, e.g., steel, stainless steel and aluminium are ductile. Static design of the structures made of these materials is normally achieved without the need to consider the local behaviour of the sharp notches and other local details. Local yielding is allowed as long as the surrounding material can withstand the given load. This design philosophy is permitted only if the predominant loads during service are static. For example, the limit for the number of load reversals in pressure vessel design is 500 cycles (EN 13445-3, 2002). If a larger number of load cycles are expected, fatigue assessment is required.

In sharp contrast to static design concepts, the local behaviour of the structure is a key element during fatigue design analysis. Notches, shoulders and grooves are examples of common details found in machine elements and these are often the regions of highest stress concentration. Such details are potential locations for fatigue crack initiation. The severity of some stress concentration details can be assessed using predefined stress concentration factor equations or figures. An extensive collection can be found, e.g., from the book by Peterson (1974). Guidelines for the fatigue design of machined elements can be found in numerous texts, e.g., Stephens et al. (2001) and Dowling (1999).

Welded structures have many features that lead to lower fatigue strength. The assembly of a welded structure is often a collection of plates and beams. These constructional elements restrict the design of a structure. The end result will frequently consist of a variety of complex joints. Also, the weld geometry is difficult to control precisely so the weld bead itself may have an irregular shape. Sharp notches are formed at the toe and root area of a weld due to the welding process. In the most cases fatigue cracks originate from the surface. An important minority initiate sub-surface at internal weld defects. In addition to problem of geometric irregularities in welds, the fusion process frequently introduces high residual stresses in the weld and around the weld area. Residual stresses are also an important source of misalignments in plate-type structures. These are the most significant stress raising elements in welded structures. They must be considered during the fatigue assessment of a structure, but are often difficult to forecast during the design phase. Residual stresses also decrease the mean stress effect on fatigue strength because the high residual stresses always lead to a worst case scenario. The local stress cycle in the material adjacent to weld will vary from yield stress tension downwards (Gurney 1979).

Numerous fatigue assessment methods have been introduced to assess the durability of metal structures under fatigue loading. These methods have been developed in conjunction with advances in an engineer's capacity to perform more detailed structural analysis. In the 1980's fatigue experiments were often evaluated based on photoelastic or brittle lacquer tests. Today, however, fatigue assessment is largely based on numerical results obtained using the FE (finite element) method or occasionally BEM (boundary element method).

Fatigue assessment of welded structures can be based on strains, stresses, or stress intensity factors. Methods can generally be divided into global and local approaches. Strength assessments are termed "global approaches" if they proceed directly from the external forces and moments (Radaj and Sonsino 1998). The nominal stress method is categorized as a global approach, because the local geometry properties of the weld are not specifically evaluated but are included in the corresponding detail classes and S-N curves. The structural stress based method omits the detail classes, but the local weld geometry is still considered to be included in the S-N curve. In another sense, however, this is a local method because the structural stress occurs only locally and the method captures the local macro-geometric effects of the joint. However, the structural stress method excludes the notch effect caused by the weld. The effect of local weld toe geometry can be included in the analyses using the effective notch stress method or local strain methods. Application of these methods to welded structures has been presented by Radaj and Sonsino (1998). The effective notch stress method is included in the IIW (International Institute of Welding) recommendations (Hobbacher 2005). Fracture mechanics based methods can also be used to determine fatigue strength of a welded structure. The actual weld toe geometry is considered and an initial crack is assumed. The fatigue life consists of the number of cycles to propagate the crack from that initial size to a critical size. Initial cracks used in fatigue analyses are often in the range of 0.05-0.2 mm, but sometimes even larger initial defects are assumed. Guidelines for application of fracture mechanics are well established and the application of this method to welded structures are presented in publications by Maddox (1991), Gurney (1991) and Smith (1983)

The above mentioned local methods are typically more accurate than the nominal stress method, especially as the geometric complexity of a structure increases. However, numerical models of complex structures quickly become large and time consuming when the local geometry is modelled for fatigue assessment. The structural stress method releases the requirement of small element sizes and FEM models normally have only a fraction of the degrees of freedom as compared to those used for local methods. The structural stress method assumes a linear through-thickness stress distribution beneath the weld toe. This can be determined with fairly coarse element meshes and therefore the structural stress method is widely used as a compromise between global and local approaches (Dong et al. 2001), (Poutiainen et al. 2004). The structural stress based method is included, e.g., in the recommendation of IIW by Hobbacher (1995) and in European design guidance documents for steel structures (ENV 1993) and pressure vessels (EN 13445-3 2002).

2 FATIGUE ASSESSMENT METHODS FOR WELDED STRUCTURES

Many different approaches have been developed for fatigue life assessment of welded structures. The most widely used methods have been mentioned briefly in the previous chapter. Every method has advantages and disadvantages. Some methods are easy to use and are less laborious, but they may lack in accuracy or flexibility. Some methods demand knowledge, experience and more detailed analysis of the structural behaviour. The main approaches for fatigue assessment of welded structures have been summarized by Radaj and Sonsino (1998). These are presented Fig. 2.1. The main characteristics of several of these methods are presented in this chapter while a detailed description of the structural stress method given in Chapter 3.

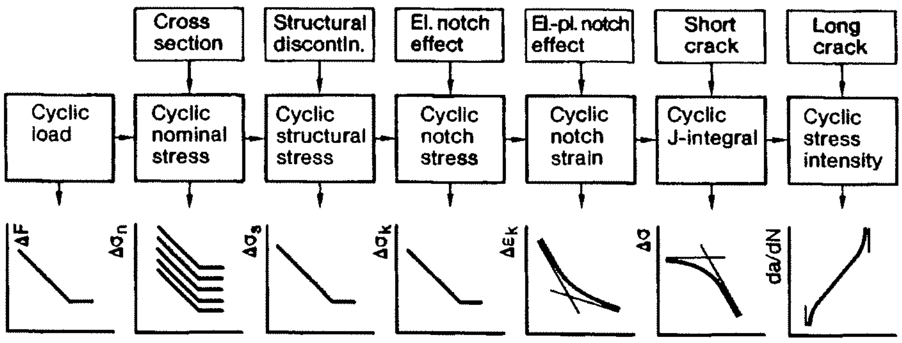


Fig. 2.1 Fatigue assessment methods for the welded structures (Radaj and Sonsino 1998).

2.1 Nominal stress method

Structural design codes for fatigue of welded structures have traditionally relied on the nominal stress approach in which different weld details are assigned fatigue strength values based largely on laboratory fatigue testing. Weld details have then been grouped into classes that have similar fatigue strength. Fatigue strength of a particular detail can be assessed by selecting the suitable S-N curve that typically represents a 97.7 % survival probability. These curves include the structural effect, local stress concentration and weld imperfections with normal fabrication tolerances and welding residual stresses (Hobbacher 2005). Care must be taken when determining the relevant stress component and its direction. The details found in the design catalogues do not generally include macro-geometric effects. The macro-geometry effect is accounted by determining local or modified nominal stress.

IIW (Hobbacher 2005) and Eurocode (ENV 1993) define 14 weld classes that correspond to the allowable alternating stress range at two million cycles to failure. Fatigue classes range from FAT 36 to FAT 160 with steps following a geometric series, see Fig. 2.2. The highest fatigue class, FAT 160, is reserved for non-welded details. The next lower value, FAT 140, is assigned, e.g., to plate edges that have been gas cut or sheared by machine. The progression to lower classes is according to details having more severe local geometries and macro-geometric stress raisers. The lowest class, FAT 36 is for details where the fatigue crack is expected to propagate from the weld root. The highest FAT 160 curve has the S-N curve slope m=5, because the fatigue life of non-welded components has a significant crack initiation period. Structural details for which the crack propagation period dominates the total fatigue life, S-N curves with a slope m=3 have been found to fit well to the test data. The S-N curves have a knee point, i.e., a constant amplitude fatigue limit, at a stress range corresponding to about $N_f = 10^7$ cycles. The precise knee point value varies somewhat depending on the design guidance document being used. The S-N curves in IIW recommendation (Hobbacher 2005) and Eurocode (ENV 1993) are applicable to joints in air and mildly corrosive environments. Figure 2.2 illustrates the IIW curves. An extension of the nominal stress method also for different environments is presented by HSE (2001).

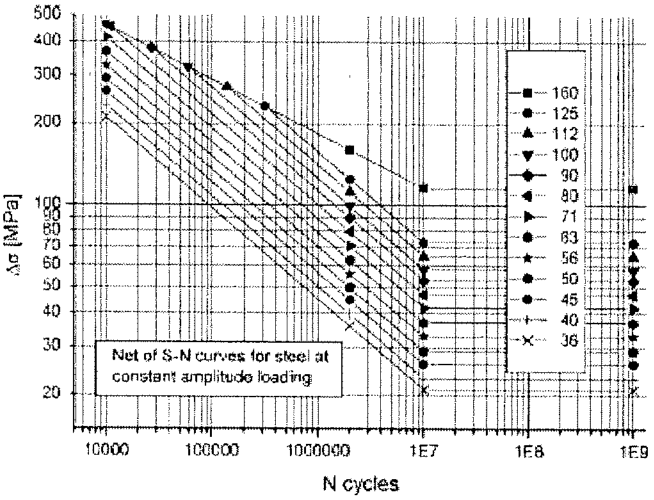


Fig. 2.2. Nominal stress classes according to IIW recommendation (Hobbacher 2005).

From the analyst's point of view, the nominal stress method is the easiest way to assess the fatigue strength of a structure. Unfortunately, the joint catalogues cover only the most typical details. Many structural details are left without fatigue classification. Also, fabricated structures are often so geometrically complex that the determination of the nominal stress is difficult or impossible. Constraints and load directions can differ from the details in the nominal stress catalogues making the method unsuitable. The nominal stress approach has also an obvious drawback in that it largely ignores the actual dimensional variations of a particular structural detail. For example, the attachment size variation can alter the fatigue strength of the base structure (Poutiainen 2002).

The nominal stress based fatigue analysis method can be used in design cases where the structure comprises standardized details. Basically, all the fatigue related features of the weld, nominal stress range excluded, are included in the S-N design curves. The design philosophy is well founded in industries where structural details are simple and weld quality is uniform. To be on the safe side in the fatigue design, the S-N curve are based on assumptions that lead to lower fatigue strength. This means that, e.g., weld toe geometry represents poor quality in the nominal stress method.

2.2 Local methods

The fatigue assessment of non-welded structures is generally based on notch stress or notch strain. The application of these methods to welded structures is not straightforward. For welded structures, questions arise regarding the irregular shape of the weld toe, uncertain material properties in the HAZ zone, mean stress effects and residual stresses. Review of the local methods have been presented, e.g., by Radaj (1996), Radaj and Sonsino (1998) and Fricke (2003).

Local methods can predict only the early stage of total fatigue life in welded structures. They give an estimate to crack initiation life which is normally defined as the life required to produce a 0.1-0.25mm deep crack. The remainder of the life should be assessed using crack growth calculations.

2.2.1 Notch stress approach

Notched specimens have lower fatigue strengths than unnotched specimens. This is caused by the higher local stresses in the notch. The correlation between the fatigue strength of unnotched and notched material is not proportional to the stress concentration. This means that elastic notch stress can not be directly combined with smooth specimen data during fatigue analysis. The error is most profound with the sharp notches. In the case of sharp notches the fatigue data is compared to average stress value in a small length, area or volume. This microstructural support effect is characteristic to different materials. Different hypotheses for this support effect have been reviewed by the Radaj (1990).

Applications of the notch stress method to welded structures have been developed by Lawrence et al. (1978), Radaj and Sonsino (1998) and Köttgen et al. (1987). Sonsino et al. (1999) reported on the usefulness of local stress methods in the assessment of welded aluminium alloy joints. The notch stress method developed largely by Radaj is included in recommendation of the Internal Institute of Welding (Hobbacher 2005). In order to account for the microstructural support effect, i.e., notch sensitivity, a fictitious radius is introduced in the potential fatigue crack locations. The definition for the fictitious radius ρ_f is given in Eq.(1).

$$\rho_f = \rho + s \cdot \rho^* \quad (1)$$

where

ρ_f	fictitious radius
ρ	actual radius
s	multiaxial coefficient
ρ^*	material constant

In the worst case the radius of the actual weld toe is zero. The Eq. (1) then results in a fictitious radius value $\rho_f \approx 1$ mm. The fictitious radius can be modelled in the weld toe or the weld root. The IIW recommendations (Hobbacher 2005) restrict the use of this method to plate thicknesses $T \geq 5$ mm. Applications of the effective notch method and comparisons to other methods have been published by Byggnevi (2002), Martinsson and Samuelsson (2002) and Poutiainen and Marquis (2006B).

2.2.2 Notch strain approach

In cases where the stress in a notch exceeds the yield strength, a strain based approach that includes the plastic material behaviour may be more appropriate. When sufficient load level is reached local yielding occurs in the notches. In the case of sharp notches the local plasticity can be observed with relatively low loading conditions. The strain based method was initially developed for the fairly low cycle regime (Dowling 1999).

The basic idea of this method is to apply the cyclic elastic-plastic properties measured during testing of a test specimen to the notched structural detail. The material properties needed are the cyclic stress-strain curve and the strain-life curve. The cyclic stress-strain behaviour can deviate significantly from the monotonic stress-strain behaviour. The cyclic properties for a variety of structural materials have been collected by Boller and Seeger (1987). Another step in the analysis procedure is to determine the strain amplitude in the notch. As the load on a component is increased the strains in the notch will rapidly increase once local yielding has been initiated. The notch root strains can be assessed using Neuber's macrosupport effect or Glinka's rule. Generally, Neuber's rule will give more conservative estimates of strains in the case of plane strain constraint (Fatemi et. al. 2002).

In the case of welded structures, the local strain method is used to assess the fatigue crack initiation phase, i.e., the number of cycles required to form a technical size crack of 0.25 mm. The remaining life is spend during the crack propagation phase and can be assessed using a linear elastic fractures mechanics (LEFM) based approach. Local strain based approaches applicable to the welded structures have been developed, e.g., by Lawrence and Mazumbar (1979), Seeger (1996) and Sonsino (1995), see Fig. 2.3. Radaj and Sonsino (1998) provide a review of the local methods used in analysis of welded structures.

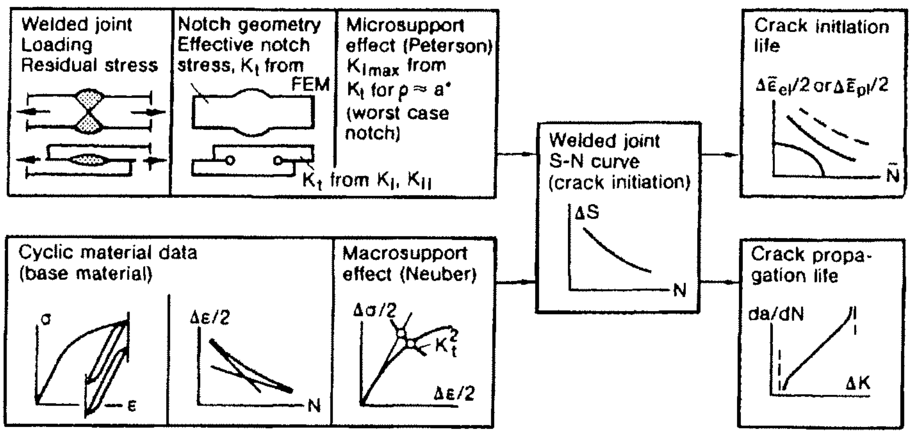


Fig. 2.3 Analysis of the welded structure using local approach according to Lawrence (Radaj 1996).

2.2.3 Notch stress intensity approach

The notch stress intensity approach is based on the stress field in the vicinity of sharp notch. Williams (1952) laid the foundation for this method by deriving an analytical solution for the stress field in a V-shaped notch. It was concluded that the stress distribution is singular and can be expressed by an exponential function. Verreman and Nie (1996) applied the notch stress intensity factor, N-SIF, and used this parameter to assess the initiation life of fillet welded details. Additional theoretical work was made by Atzori et al. (1997) and Lazzarin and Tovo (1998). The extension of the method to aluminium structures was presented by Atzori et al. (2002) and Lazzarin and Livieri (2001).

The N-SIF parameter is used to describe the stress field near the notch. According to Lazzarin and Tovo (1998) N-SIF can be expressed as:

$$K_{1,j} = \sqrt{2\pi}\,\sigma_{\theta,j} r_j^{1-\lambda_1} \tag{2}$$

$$K_{2,j} = \sqrt{2\pi}\,\tau_{r\theta,j} r_j^{1-\lambda_2} \tag{3}$$

Where the N-SIF values K_1 and K_2 corresponds to symmetric and skew-symmetric stress fields, respectively. The stress components in the region of the weld toe are illustrated in Fig. 2.4.

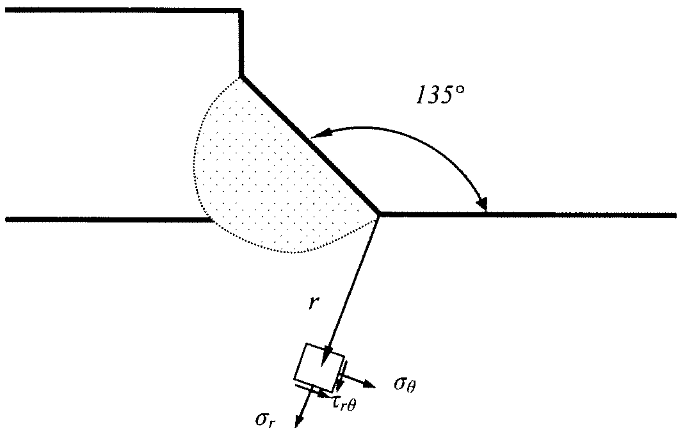


Fig. 2.4 Stress components in the bisector of the weld toe.

Tovo and Lazzarin (1999) showed the relationship between the local N-SIF based approach and the structural stress based approach. The structural stress determined for a given detail can therefore be converted to the N-SIF approach simply by combining the elementary cases of predefined elementary fillet welded joints.

2.3 Linear elastic fracture mechanics

Fatigue life of any structure consists of a crack initiation phase and a crack growth phase. Final rupture is expected when the crack reaches a critical size. The previously introduced nominal stress method covers both phases. Generally, in the case of the welded structures, the initiation phase is difficult to define. The initiation period is influenced by the local geometry of the weld toe. The geometric features like weld toe radius, flank angle, and undercut influence the stress concentration of the weld toe. The weld toe geometry can have great variation along the weld even in a short length. Normally, however, crack initiation life is considered to be very short or non-existent for most welds. Using LEFM, the total life can be assessed analysing only the crack growth period.

The main parameter in the calculation of the crack growth period is the stress intensity factor, SIF, K. The magnitudes of the stresses in the vicinity of the crack are defined based on SIF. The SIF values K_I, K_{II} and K_{III} correspond to the opening, sliding and tearing mode of the crack, respectively, see Fig. 2.5. Normally the opening mode dominates and it is only required to evaluate K_I during analysis. Other modes can be important for short crack lengths or special loading cases, but cracks tend to turn and grow along the plane of maximum normal stress.

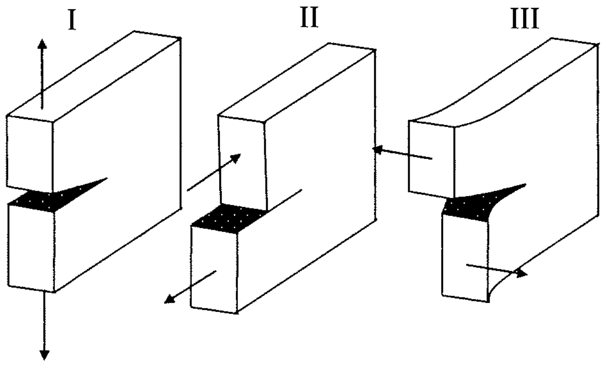


Fig. 2.5 Modes of crack extension.

Stress intensity factors can be determined for various crack loadings and configurations based on the theory of elasticity. Analytical solutions are available for many simple geometries and numerical methods are available for more complex cases. A collection of predefined SIF values can be found from the literature, e.g., Tada et al. (1985). The simplest configuration of the crack is the central trough thickness crack in an infinite plate. Value K_I in this case for the 2a long crack is expressed as:

$$K_I = \sigma\sqrt{\pi a} \tag{4}$$

Crack shape, structural geometry and loading and restraint conditions drastically affect the SIF value. Careful consideration of these factors is essential in the fatigue analysis of the structural detail. In the light of structural design the cracks can form and grow in places where analytical solutions are not possible.

A variety of numerical methods have been developed to assess the stress intensity factor for arbitrary geometries. FE analysis based solutions have evolved recently and several approaches can be used. Solutions for the SIF in a cracked body can be based on the stress field in front of the crack. This is compared to the elastic stress field solution of a crack. Other possibilities include the use of special crack tip finite elements for the displacement field solution, a virtual crack extension method based on the energy release and virtual crack growth and solutions based on J-integral evaluation.

Modelling of a cracked structural detail can be difficult and time consuming. Each analysis result gives only one SIF solution when the total life estimate requires a history of SIFs from initial crack to final crack size. To satisfy this demand crack growth simulation programs have been developed to automatically increase the crack. Intriguing results of such analysis are the crack path solutions for crack growth in complex and alternating stress field.

FE analysis can also be used to determine the K_I of a detail without modelling the crack itself. The use of special weight functions, *m(x,a)*, gives the possibility for determining K_I from the stress distribution $\sigma(x)$ in assumed crack plane using Eq. (5). Bueckner (1970) and Rice (1972) showed that weight functions, *m(x,a)*, can be determined from a known reference K_r and the corresponding crack opening displacements according to Eq.(6), see Fig. 2.6.

$$K_I = \int_0^a \sigma(x) m(x,a) dx \tag{5}$$

$$m(x,a) = \frac{H}{K_r} \cdot \frac{\partial u_r}{\partial a} \tag{6}$$

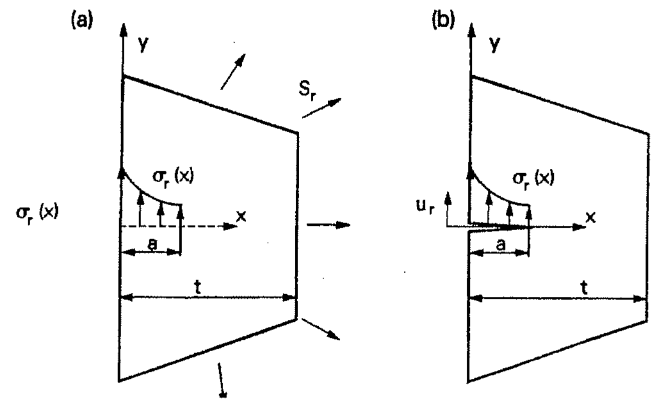


Fig. 2.6 Weight function determination: (a) loading of the system and reference stress distribution; and (b) reference stress distribution and corresponding crack opening displacement $u_r(x,a)$. Niu and Glinka (1990).

Albrecht and Yamada (1977) presented the K_I in a general form, see Eq. (7). In this equation the different factors affecting the SIF value can be accounted for during engineering calculations. In three dimensional cases, the factor F_E is used to account for the shape of the crack, which, in the early stages, can be assumed to be semi-elliptical. For edge cracks, the free surface correction is made with factor F_S. Often an estimate $F_S = 1.12$ is used. The factor F_W accounts for the effects of finite width, i.e., the corrected stress increases due to decreasing net section. The final factor, F_G, is used to include the effect of a non-uniform stress distribution in the anticipated crack path. This factor is of great importance in the case of welded structures, since the stress gradient at the most potential crack sites is high. In the literature the notation M_k factor or stress magnification factor is also used.

$$K_I = F_E F_S F_W F_G \, \sigma \sqrt{\pi a} \tag{7}$$

LEFM based approaches to assess the fatigue strength of welded structures have been developed and applied by many authors including Hobbacher (2005), Gurney (1991), IIW (1990) and Maddox (1991). These methods are potentially accurate even for complex structures, but the computational effort is significantly greater than for the nominal stress method. This has limited the application of these approaches to a relatively small number of highly safety critical components. LEFM methods are also very sensitive to the selected initial crack size and are, therefore, most suitable primarily for components with known flaws or when a defect tolerant strategy is needed.

2.4 Other methods

2.4.1 Geometric stress method

A relative new method for assessing welds has been developed by the Xiao and Yamada (2004). The method is based on the geometric stress at the depth of 1 mm from the surface. The stress peak at the weld toe is excluded, since it is dependent on the weld toe geometry and this effect largely vanishes at 1 mm below the surface. Weld geometry is often so irregular that it is included in the S-N curves as a one source of scatter. By using a reference stress 1 mm below the surface, the stress distribution variation caused by different joint configurations can be captured. As can be seen in the Fig. 2.7, the variation of the weld toe radius and flank angle is insensitive to stress value in the depth of 1mm. Finite element analysis is required for this method. The density of the element mesh is generally lower than for the local methods because the smallest element is 1 mm in thickness direction. Stress determination in this case is straightforward. The method has been tested on several fillet welded details and the design curve is near the Japanese fatigue design curve JSSC-D (JSSC 1995). Previously, Partanen (1991) suggested that the hot spot -stress could be determined from at a depth of 1-2 mm. He observed that a nearly constant fatigue life is obtained for the various joint configurations when this stress value was held constant.

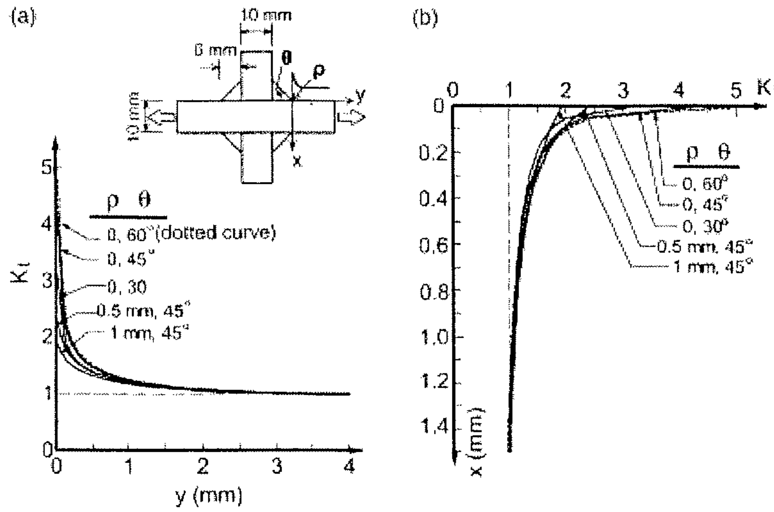


Fig. 2.7 Variation of the stress distribution in the surface (a) and in thickness direction (b) (Xiao and Yamada, 2004).

2.4.2 Crack modelling method (CMM)

In the crack modelling method, the crack itself is not modelled. Instead, the stress distribution along the anticipated crack path is determined. Then, a centre-cracked plate case is selected as a reference stress intensity factor. The load and crack length are adjusted so that stress distribution in the cracked member corresponds the stress distribution in the structure being assessed. An equivalent stress intensity factor for the component is then assumed to be the same as in the model crack (Taylor et al. 1999). The method has been tested on welded structures and compared with the results of several critical distance methods (Taylor et al. 2001).

3 THE STRUCTURAL HOT SPOT STRESS METHOD

In 2001, Commission XIII of the International Institute of Welding, IIW, approved the publication of a designers' guide for the structural stress approach to fatigue analysis of welded components (Niemi 2000, Niemi et al. 2006). This guide provides an overview of the structural hot spot method for plate-type welded structures and provides instructions and examples on the appropriate use of FEA to assess fatigue life using this method.

The hot spot or structural stress approach was first developed for fatigue analysis of welded tubular joints in offshore structures (De Back 1987 and Marshall 1992). Corresponding fatigue design rules were published by the American Petroleum Institute, the American Welding Society, Bureau Veritas, UK DEn, etc. A review of this topic is presented by Marshall (1992). There was an increasing demand for extension of the approach to plate-type structures and the first general design rule to include the structural stress approach was the European pre-standard ENV 1993-1-1 (ENV 1992). This document, however, provided only limited guidance. For certain fields of application, specific rules are now available, namely for tubular structures (IIW 1999), ship hulls (Germanisher Lloyd 1998) and pressure vessels (EN 13345-3 1999). In 1995 the IIW published a background document focusing on definitions and the determination of stresses used in the fatigue analysis of welded plate components (Niemi 1995).

The structural stress approach avoids the previously noted difficulties associated with applying the nominal stress approach and is computationally less demanding than either LEFM or the local stress methods. Structural stress takes into consideration the dimensions and stress concentrating effects of the detail at the anticipated crack initiation site while excluding the local non-linear stress peak caused by the notch at the weld toe. The exact geometry of the weld is not usually known at the design stage. This notch effect is, therefore, generally included in the experimentally determined structural hot spot *S-N* curve.

Fatigue cracks initiate at structural discontinuities. This type of stress raiser in welded structures can be formed by the weld metal in the case of butt welds or by some kind of attachment. Cracks tend to grow into the parent metal and, in some cases, also into the weld metal. The crack growth direction is generally perpendicular to the maximum principal stress. Several typical welded details are presented in Fig. 3.1. In the details a) to e) the cracks initiate at the weld toe and grow into the base plate. In the details f) to j) the initiation location is in the root side. Root side failure is mainly caused by the inadequate weld size. This is the case especially with the load carrying fillet welds. The quality of weld root is more difficult to control so the local geometry of the root is often worse in fatigue sense than in the weld toe. The root side crack growth is also more dangerous since visual inspections do not give any indication that the fatigue failure is in progress. If possible, the risk for the root side failure should be eliminated.

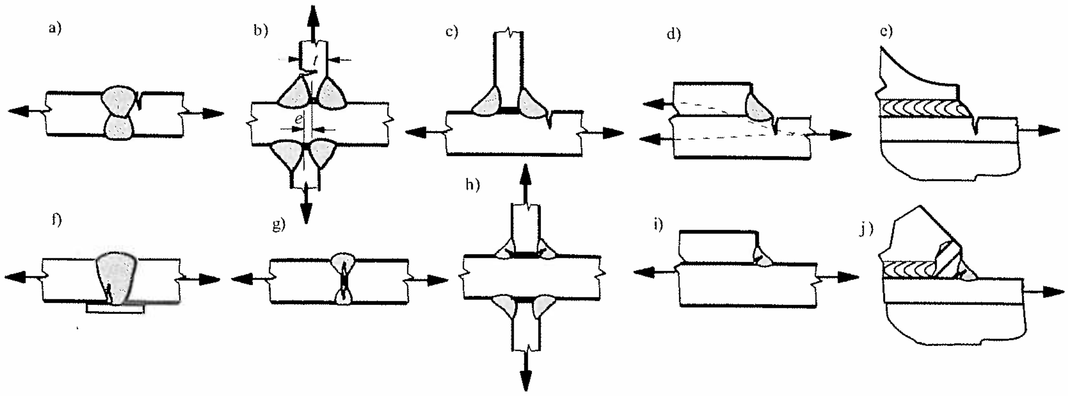


Fig. 3.1 Crack initiation locations for several joint types (Niemi 2000).

3.1 Structural hot spot stress

Structural hot spot stress is, by its general definition, a linear stress distribution in the cross section of the crack plane. In the case of plate structures this distribution is a summation of membrane and bending stresses. Structural stress components consist of macro-geometric stress concentration effects, i.e., from membrane stress concentration and shell bending stresses. Examples of the macro-geometric stress raisers are presented in Fig. 3.2. The structural discontinuities also induce variation in membrane stress distribution and local secondary bending stresses, see Fig. 3.3.

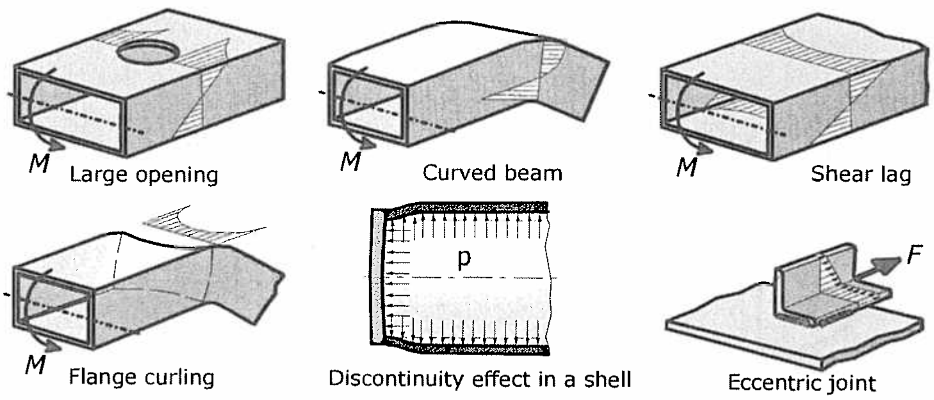


Fig. 3.2 Macro-geometric stress raisers (Niemi 2006).

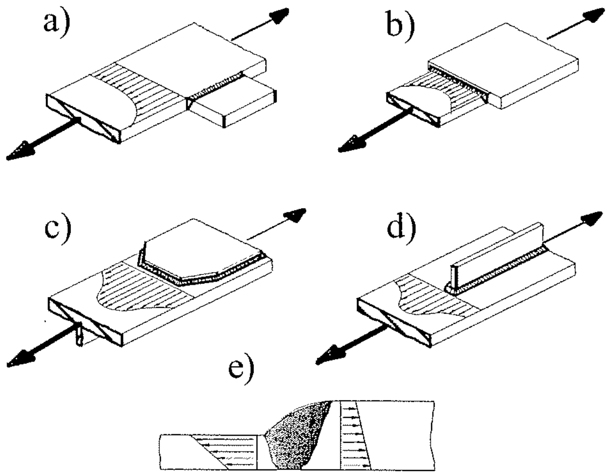


Fig. 3.3 Structural discontinuities (Niemi 1995) .

Plate structures are often so complex that multiple potential fatigue failure locations can be found. Cracks can initiate from the plate surface or the plates edge. With reference to Fig. 3.4, the location is classified as type "a" if the weld toe is in the plate surface and in the attachment end. For the weld toe in the plate edge area hot spot type "b" is introduced. Type "c" location is basically similar as the type "a", but the type "c" can be found from the side weld of the attachment. In Fig. 3.4 Types "a" and "c" are located in the place where stiffener plate is located below the base plate. The fourth type "d" could be designated to weld toes where the stiffener plate is not present.

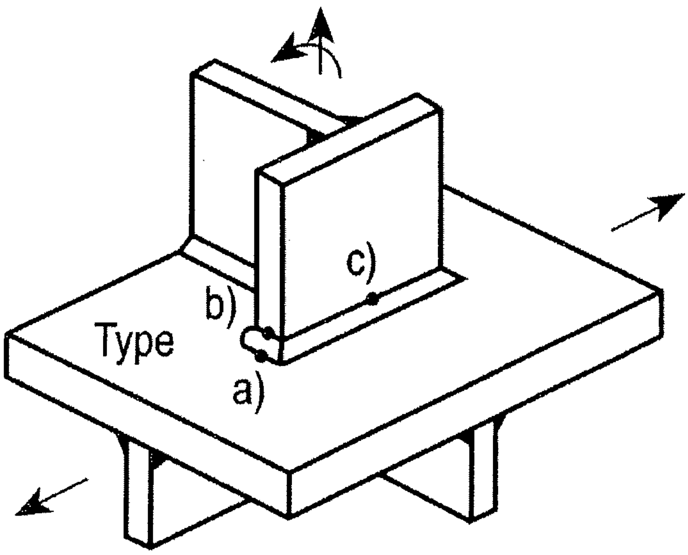


Fig. 3.4 Hot spot types (Doerk et al. 2003).

In general, cracks that initiate in the weld toe tend to grow along the weld toe in the transverse direction. The growth direction is perpendicular to the maximum principal stress. A crack can diverge from the weld toe line if the principal stress direction deviates greatly from the perpendicular direction. The toe line is not ideally straight so the variation of the principal stress direction can be assumed wide. The IIW recommendations (Hobbacher 2005) proposes that the hot spot stress is determined from the principal stress when the maximum deviation is less than ±60° as seen in Fig. 3.5.

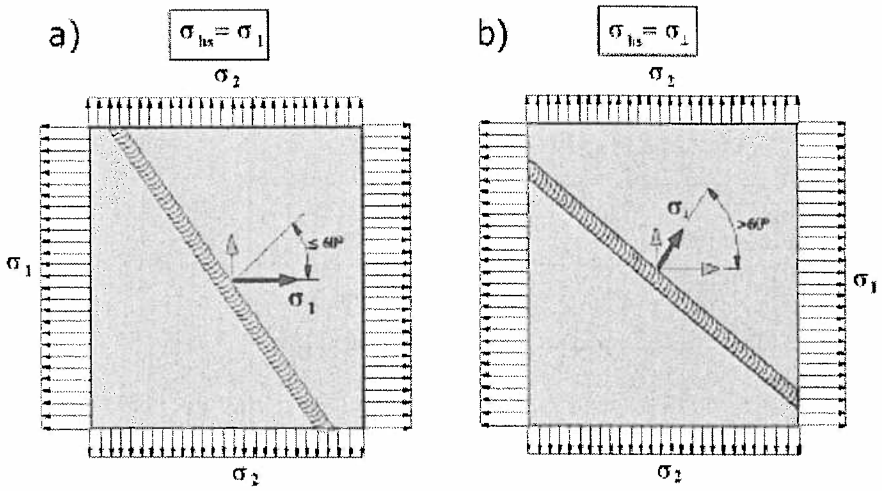


Fig. 3.5 Structural hot spot stress direction (Hobbacher 2005).

3.2 Hot spot design curves

The structural hot spot stress value is related to the fatigue strength of the plate in front of the weld toe. In some cases the value of the structural stress is insensitive to structural configuration behind the weld, i.e., the same structural stress can be obtained in butt welds, non-load carrying and load carrying welds. During fatigue tests, however, it can be observed that these details will have different fatigue strength values. To overcome this problem, alternate hot spot stress design curves are introduced. Niemi (2000) initially proposed four alternate curves from FAT 80 to FAT 112 as seen in Fig. 3.6. This number was later reduced to two (Niemi et al. 2006). IIW recommendations currently include two fillet weld S-N curves, FAT 90 and FAT 100, depending on whether the weld is load carrying or non-load carrying.

Another instances where the different design curves are necessary is to account for alternate materials, e.g., aluminium, post weld treated details and special structural constructions. Maddox (2001) and Partanen and Niemi (1999) have proposed S-N curves for aluminium structures. For the post weld treated structures, Haagensen and Maddox (2004) provided a collection of structural hot spot curves. Curves are introduced for the grinded, TIG- dressed, hammered and needle peened structures both in steel and aluminium.

Because it assumes a linear stress distribution through the thickness, the hot spot method cannot take into account the thickness effect of the base plate. In the hot spot stress method, thick plates must be assessed using a thickness correction factor in the same way as in the nominal stress method. A correction factor $f(t)$ presented by Niemi (2000) is given in Eq.(8). Here, T_{ref} is set to 25 mm and T_{eff} is the thickness of the base plate. If Gurney's thickness correction concept (1991) is adopted T_{eff} can be selected as $L/2$ if $L<2T$, where L is the toe-to-toe length. The exponent n for several detail types is given in Fig.3.6.

$$f(t) = \left(\frac{T_{ref}}{T_{eff}} \right)^{n} \tag{8}$$

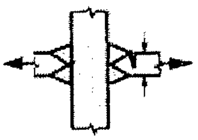
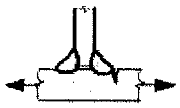
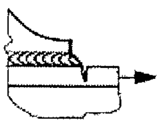
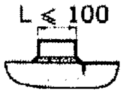
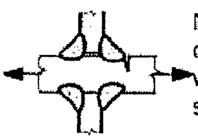
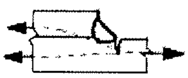
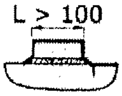
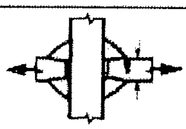
Joint	Quality	FAT	$\Delta\sigma_{R,L}$	n
 Butt joint, special quality		112	83	0.2
 Butt joint, normal quality		100	74	0.3
 Cruciform joint with full penetration K welds  Non-load carrying fillet welds  Bracket end, welds either welded around or not		100	74	0.3
L ≤ 100  Type "b" joint with short attachment		100	74	0.1
 Non-load carrying fillet welds on both sides  Cover plate ends and similar joints		90	66	0.3
L ≥ 100  Type "b" joint with long attachment		90	66	0.1
 Cruciform joint with load-carrying fillet welds		80	59	0.3

Fig.3.6 Hot spot S-N curves suggested by Niemi (2000).

3.3 Structural stress determination

The structural or geometrical stress in a welded plate structure is the sum of the primary and secondary membrane and bending stresses at the weld toe excluding the non-linear peak stress (Hobbacher 2005, Niemi 1995). The structural hot spot stress can be determined using one of the tree methods:

- Experimentally using strain gauges
- Stress analysis using FEM
- Predefined parametric formulas

3.3.1 Experimental determination

The experimental determination procedure is conducted by placing two or more strain gauges in front of the weld toe. The distances are selected so that local stress peak is excluded from the measurement and only the structural stress in the plate is measured. The primary factor influencing this distance selection is the plate thickness. In the case tubular structures, the size of the connecting tubes affects to extrapolation distances (Dijkstra and de Back 1980; Zhao et al. 2001).

In the IIW designer's guide (Niemi et al. 2006) the extrapolation distances are given as 0,4T and 1,0T for the weld toes on plate surface, type "a". For the type "b" plate edge detail three absolute distances are proposed. Distances in this case are 4mm, 8mm and 12mm. In the case of type "a" hot spots with pronounced non-linear structural stress increase, e.g., if the hot spot is above a plate stiffener, three extrapolation points are recommended (0,4T, 0,9T, 1,4T).

If single grid gauges are used, the gauges are placed so that a perpendicular strain component is obtained. In the case of bi-axial stress state the one measured strain component does not provide enough information on the principal stress determination. Before measurements, a stress analysis should be performed if the stress state is otherwise unknown. Another possibility is to use additional transverse gauges or multi-grid gauges.

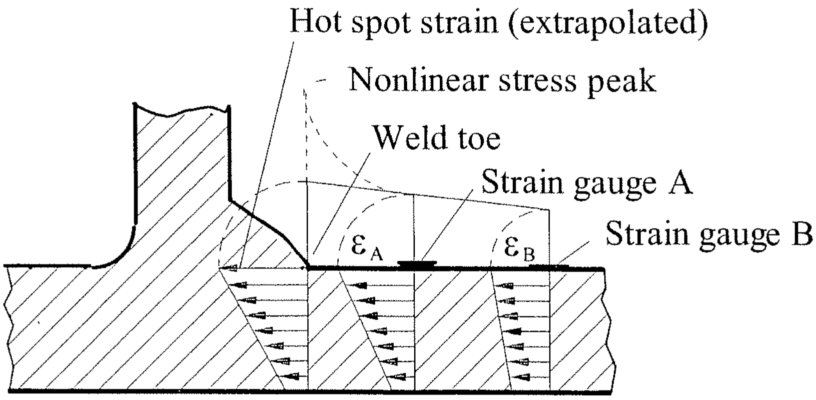


Fig. 3.7 Structural hot spot stress determination using strain gauges.

3.3.2 Stress analysis

The IIW recommendations for determining the structural hot spot stress, SHS, are based in principal of surface extrapolation. Niemi (1995) has proposed distances of 0,4 and 1,0 times plate thickness, *T*, from the weld toe, see Fig. 3.8 and Eq. (9). Also, distances 0,5 and 1,5 times *T* can be used for coarser meshes. In this case Eq. (10) is appropriate. These distances have been selected to be as close as possible to the weld toe but outside the region affected by the weld toe singularity. Similarly, as with the strain gauge based determination, three extrapolation points are used for plates on a stiff foundation (Niemi and Tanskanen 1999). The structural hot spot stress, σ_{shs}, calculation is then given by Eq. (11) for the plate surface and by Eq. (12) for the plate edge. An alternative method for determining the structural stress on a plate edge has been introduced by Tveiten and Moan (2000).

$$\sigma_{shs} = 1.67 \cdot \sigma(0.4T) - 0.67\sigma(1.0T) \tag{9}$$

$$\sigma_{shs} = 1.50 \cdot \sigma(0.5T) - 0.5\sigma(1.5T) \tag{10}$$

$$\sigma_{shs} = 2.52 \cdot \sigma(0.4T) - 2.24 \cdot \sigma(0.9T) + 0.72\sigma(1.4T) \tag{11}$$

$$\sigma_{shs} = 3 \cdot \sigma(4\text{mm}) - 3 \cdot \sigma(8\text{mm}) + \sigma(12\text{mm}) \tag{12}$$

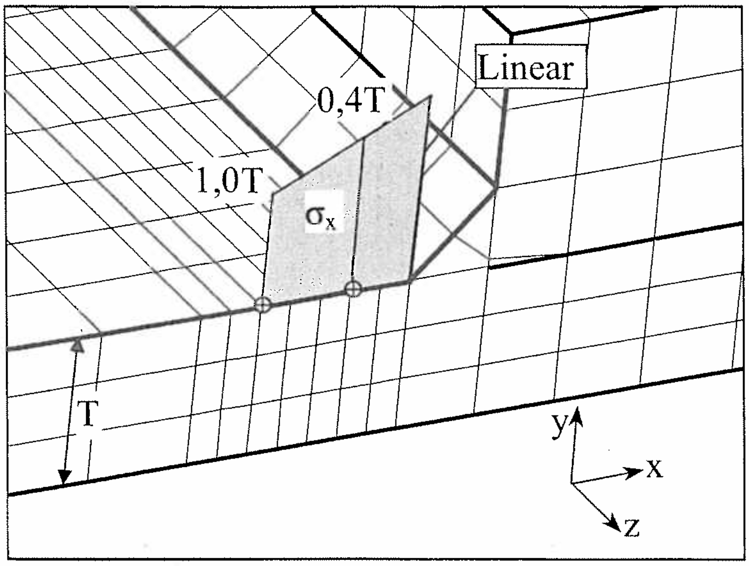


Fig. 3.8 Linear extrapolation on the plate surface.

A second possible procedure for determining SHS is to use through-thickness at the weld toe stress determination, TTWT. According to Radaj (1990), the non-linear peak stresses can be excluded by means of surface extrapolation or by linearization of the through-thickness stress distribution. Linearization is unambiguously defined whereas the surface extrapolation methods vary in the choice of extrapolation distances. Both procedures should result in the same stress value in simple plate structures.

The SHS stress using TTWT determination requires a stress distribution $\sigma_x(y)$ at the weld toe. The SHS stress is calculated using Eq. (13), which is the sum of the structural membrane and bending components of non-linear stress distribution. In the Fig. 3.9 a coarse element mesh is used to obtain the $\sigma_x(y)$ stress distribution. If the stress is plotted straight from the nodes of the weld toe, the mesh should be finer in order to minimize the error caused by the nodal averaging. In the case of Fig. 3.9 the elements in the left side of the weld toe section were allowed to contribute in the averaging (Poutiainen et al. 2004). The SHS stress determination based on stresses does not guarantee that the equilibrium condition in the cross section is satisfied. Equilibrium is achieved, however, if SHS is calculated from the cross section nodal forces (Fricke et al. 2003).

$$\sigma_{shs} = \frac{1}{T}\int_{o}^{T}\sigma_x(y)\cdot dy + \frac{6}{T^2}\int_{o}^{T}\sigma_x(y)\cdot(\frac{T}{2}-y)\cdot dy \qquad (13)$$

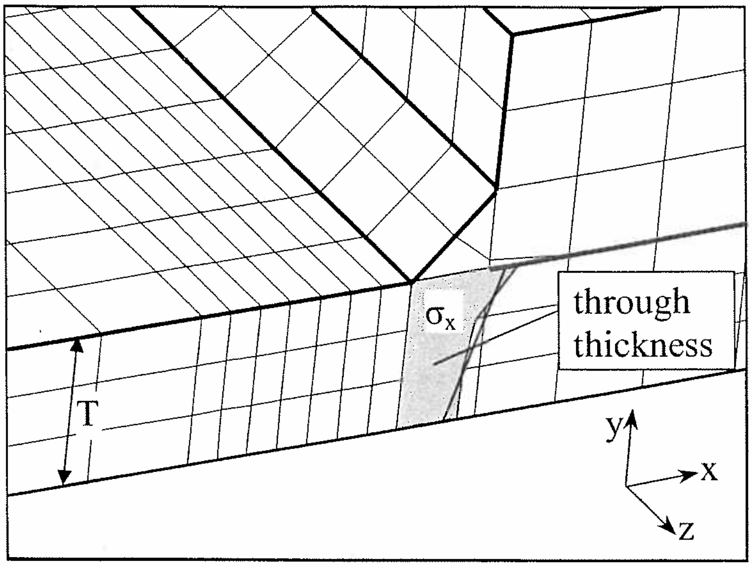


Fig. 3.9 Through-thickness SHS stress determination.

Approximately concurrent to the finalization of the IIW recommendations, Dong et al. (2001) and Dong (2001) published an alternate SHS computation method that combines features of the through-thickness and surface extrapolation procedures. The method is based on nodal force equilibrium and was developed primarily considering shell element models. Structural stress is determined based on the through-thickness stress distribution at some distance, δ, from the weld toe. Additional bending stresses at the weld toe produced by through-thickness shear stresses are then added to the through-thickness structural stress to give total SHS stress. Membrane and bending components of structural stress, σ_m and σ_b, are found from

$$\sigma_m = \frac{1}{T}\int_o^T \sigma_x(y)\cdot dy \tag{14}$$

$$\sigma_m \cdot \frac{T^2}{2} + \sigma_b \cdot \frac{T^2}{6} = \int_o^T \sigma_x(y)\cdot y\cdot dy + \delta\int_o^T \tau_{xy}(y)\cdot dy \tag{15}$$

where T is the plate thickness. Equation (15) represents the equilibrium of the moment about the lower plate surface in location A, shown in Fig. 3.10. This method has been claimed to be a mesh insensitive, i.e., the computed structural stress is independent of the finite element model in front of the weld toe. This has been demonstrated for simple 2D models (Dong 2001). See Fig. 3.10.

In a comparison study using both simple and complex structures, Doerk et al. (2003) investigated the mesh sensitivity/insensitivity using both the Dong method and the two linear surface extrapolation methods outlined in the IIW recommendation. In 2D structures mesh insensitivity was confirmed, but for complex 3D structures the meshing outside the stress evaluation area in front of the weld toe can strongly affect the computed stress distribution within a structure so that mesh insensitivity remains generally questionable for these structures. This is especially the case for relatively coarse meshes. SHS stress variations of ±10% were observed. They emphasized that the analyst should always be aware of the limitations set by the finite element model as well as by the evaluation method of SHS. It was also noted that, for 3D problems, Eq. (15) neglects the influence of element side shear forces shown in Fig. 3.11.

Poutiainen et al. (2003 and 2004) presented also a comparison study of a different SHS stress determination approaches. The traditional linear surface extrapolation, LSE, through-thickness at the weld toe, TTWT, and Dong's proposed method were compared. The 2D structure used in the study is similar as in papers by Doerk et al. (2003) and Dong (2001). The structure was modeled using different element type and mesh configurations. The main conclusion was that the TTWT and the Dong method proved to be mesh insensitive in planar models when a good meshing practice was used. The LSE method results in more scatter when the mesh size is varied. When the dimension of an element is increased in the thickness direction, the number of elements should also be increased in the area between the weld toe and the first extrapolation points (toe area). The use of multiple elements in the thickness direction begins to show the non-linear stress component at the first extrapolation point. In this case "buffer elements" are necessary in the toe area so that the non-linear component is not present at the extrapolation point. LSE provides best results with the minimum meshing configuration, i.e., one element in the thickness direction and one element in the toe area. A 3D longitudinal gusset structure was also analyzed and conclusions were similar to those made by Doerk et al. (2003).

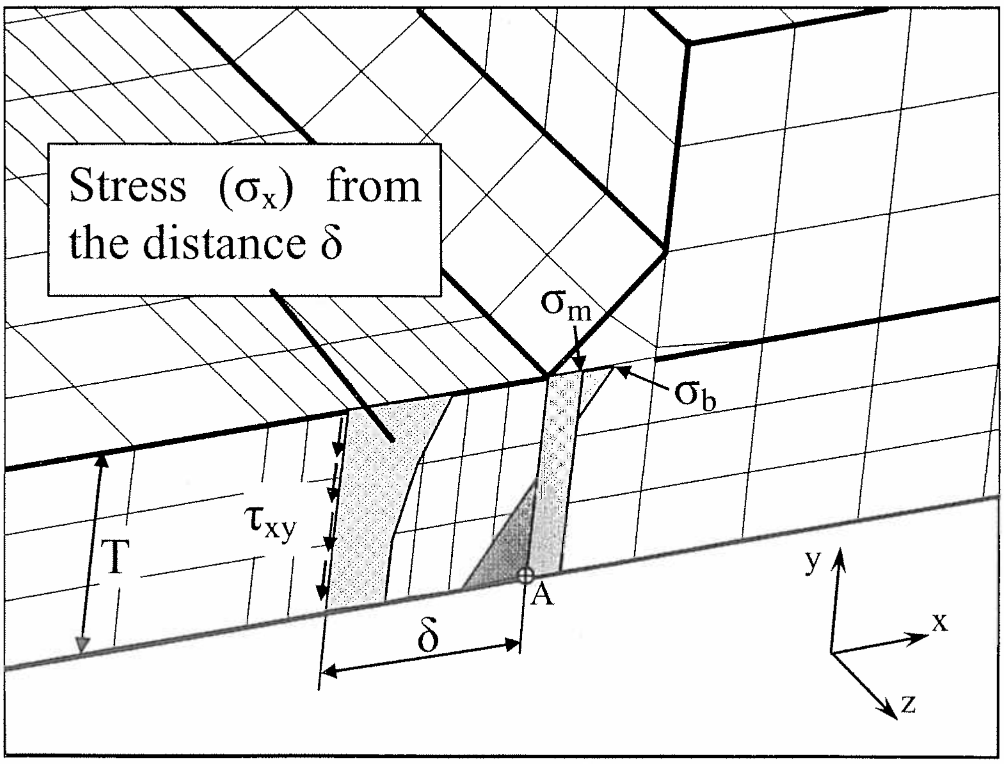


Fig. 3.10 SHS stress determination according to Dong.

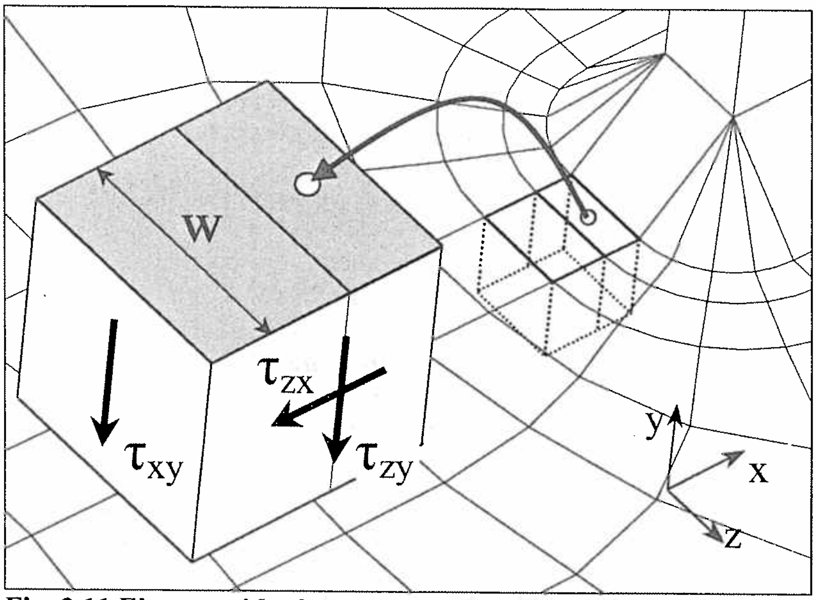


Fig. 3.11 Element side shear stresses omitted by the Dong method.

It can be noted that each of these three procedures seeks to compute the structural stress at the critical location at the weld toe where a fatigue crack can be expected to initiate. Structural stress is the sum of membrane stress and shell bending stress at the plate surface while excluding the non-linear stress peak produced by the weld toe stress concentration. All methods, therefore, are attempting to compute the same stress value and it is reasonable to expect that the same S-N design curve would apply independent of the method used. The choice of SHS method should depend only on the effort involved in applying a certain procedure and the analyst's confidence in the method and the accuracy. To experimentally assess existing structures for which detailed FE analysis is not available, through-thickness techniques, obviously, are not appropriate and only the surface extrapolation methods can be applied.

The linear through-thickness stress determination procedure is ideal for shell element models. Shell elements provide only the linear stress distribution which is the value that is needed according to the definition of SHS stress. The SHS stress determination directly from the weld toe is possible if the nodal averaging issues are considered or the nodal force approach is used. The direct weld toe determination is, however, less used and generally the previously described extrapolation scheme is adopted.

If a solid and shell models are compared some simplifications are necessary. The plates are modelled as shells and the thickness is included in the element properties. The fillets and welds can, in some cases, be excluded from the analysis model. As seen in Fig. 3.12 the mesh of the structure becomes much simpler when thin shell elements are used. The use of the shell models is popular in the analysis of large welded plate structures, e.g., in the ship building and offshore industries.

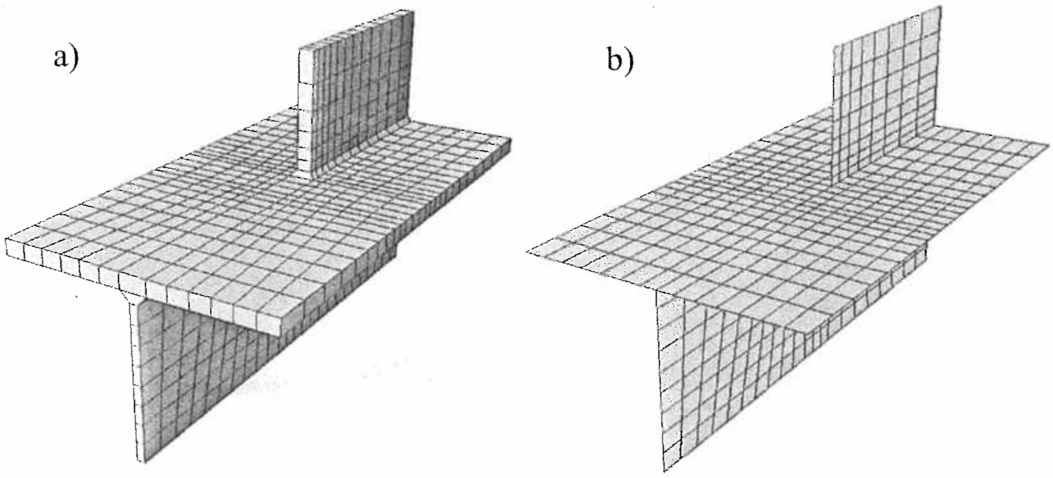


Fig. 3.12 Thin shell idealization (b) of a solid structure (a). (Poutiainen and Niemi 2000).

3.3.3 Parametric formulas

The simplest parametric formulas are those used to account the misalignments of plate-type structures. These formulas are for both axial and angular misalignments and can be included in the analysis. The structural hot spot curves do not include the misalignment of the plates so the separate consideration on these effects can be given using these formulas. The formulas for some cases can be found e.g. in Niemi (2000).

In more complex cases, parametric formulas can be used in design if the corresponding detail exactly matches the detail found in literature. Both the structure and the load case have to be similar as in the analyzed detail. Parametric equations have been specially introduced for the tubular structures (Wardenier 1982 and Zhao et al. 2001).

A project was conducted at Lappeenranta University of Technology in which parametric formulas were determined for several structural details. The details were selected so that they represent the typical structural details used in industry. The collection of typical details is shown in Fig. 3.13. Parametric formulas can be found in the reports by Kilkki et al. (1998, Research reports 22-25), Badger et al (1998) and Poutiainen and Niemi (1998).

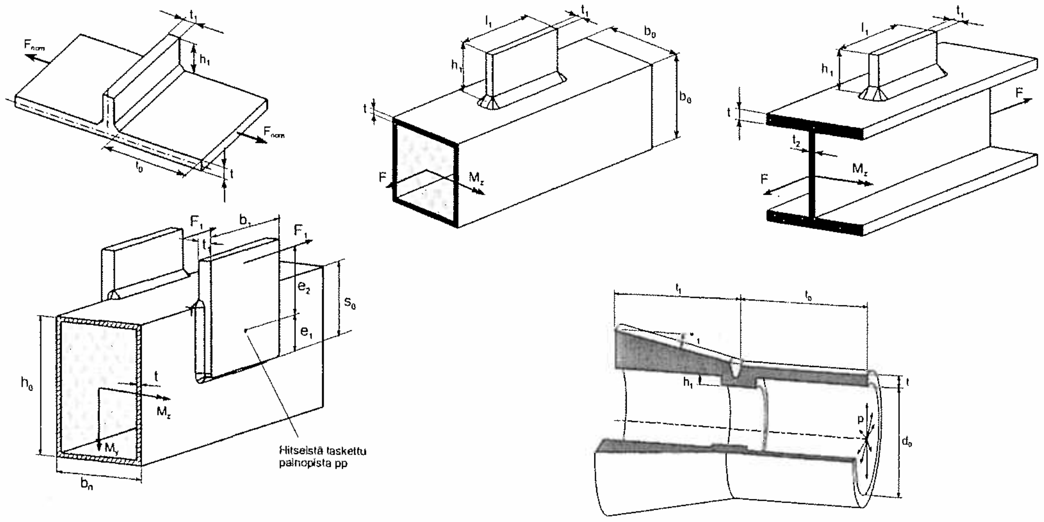


Fig. 3.13 Details with parametric formulas determined at LUT.

4 A MODIFIED STRUCTURAL HOT SPOT STRESS METHOD

4.1 Background

In order for fatigue assessment based solely on the range of SHS stress to be fully successful in correlating fatigue data with minimal scatter, it would be necessary that the stress distribution through the plate thickness below the weld toe to be the same for all joint types. Because this condition is never fully met, different adjustments have been introduced as compensation. For example, different structural hot spot curves are used if the welded joint is load carrying or non-load carrying. The second adjustment is that the apparent thickness approach is included to account variations of the weld toe to toe length (Gurney 1991). Also, a thickness correction factor is used when the thickness of the plate exceeds the reference thickness. The main contribution in thickness effect is the geometrical scaling effect that produces a less steep stress gradient below the weld toe. All of these corrections are needed because the stress distribution shape varies for different joint geometries and a direct comparison of the fatigue strengths based only on the SHS does not distinguish the stress gradient.

In spite of its many benefits, one of the main drawbacks in the SHS stress based fatigue assessment is that the information of the local behaviour of the weld is not included in the analysis. As previously discussed, the local behaviour is assumed constant and fatigue strength is scaled based on the SHS stress. However, this assumption is justified for a broad range of structural details and, with the aid of an appropriate scheme, the SHS stress method can be applied to the majority of the weld toe cases. The fatigue analysis can, of course, be based on more localized parameters. The accuracy is then often better, especially if only the initiation period is sought. The use of local methods is much more demanding from the analyst point of view and this restricts the use of these methods to 2D models and usually only small 3D models. The basic idea behind in the SHS stress modification is to keep the modelling efforts low while still including important features of the local behaviour of the weld toe.

A typical welded structure is presented in Fig. 4.1. This detail was analyzed and parametric SHS stress concentration factor equations were derived by Poutiainen (2002). The critical location is in the front of the cover plate end. The computed SHS stress concentration factor distribution along the transverse weld is presented in Fig. 4.2. The SHS stress was determined in three different ways; traditional LSE using both linear and parabolic extrapolations and also using the TTWT method. The FEA based stress distribution along the weld toe line is also presented in this figure. If the element size in the thickness direction is constant, the stress value can be used to indicate the critical location for fatigue failure even though the stress value itself is not a suitable value for assessing fatigue life. The SHS stress distributions in Fig. 4.2 show that the structural stress is decreasing towards the centre of the I-beam. This is in contrast to the stress at the weld toe which reaches a maximum at the centre of the beam. The web below the flange inhibits plate bending along the beam centreline and, thus, decreases the computed SHS stress value. The weld toe stress values indicate that more force is passing the toe area in the centre region but this does not show in the extrapolation points.

The cover plate is the cause of the stress concentrations on the flange. It is assumed to be welded along all sides using fillet welds. This causes a discontinuity in the I-beam. Some portion of the total load will transfer to cover plate through the fillet welds. In the analysis model it is important that a gap between cover plate and flange is included. In this way the correct stress distribution in the weld is computed. In this case, stress concentration along the weld toe line means that the weld is transmitting more force in those regions of higher stress concentration. Because the weld load can be determined using simple and relatively coarse SHS models, the weld load could be used to give information on the local behaviour of the weld toe.

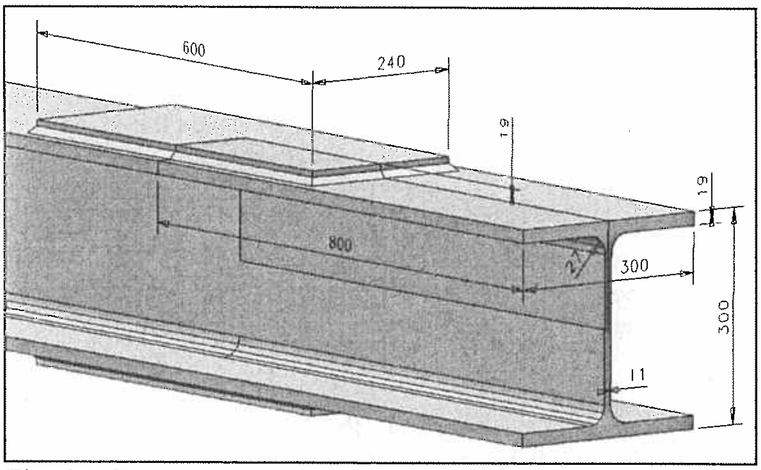


Fig. 4.1 Cover plate on an I-beam.

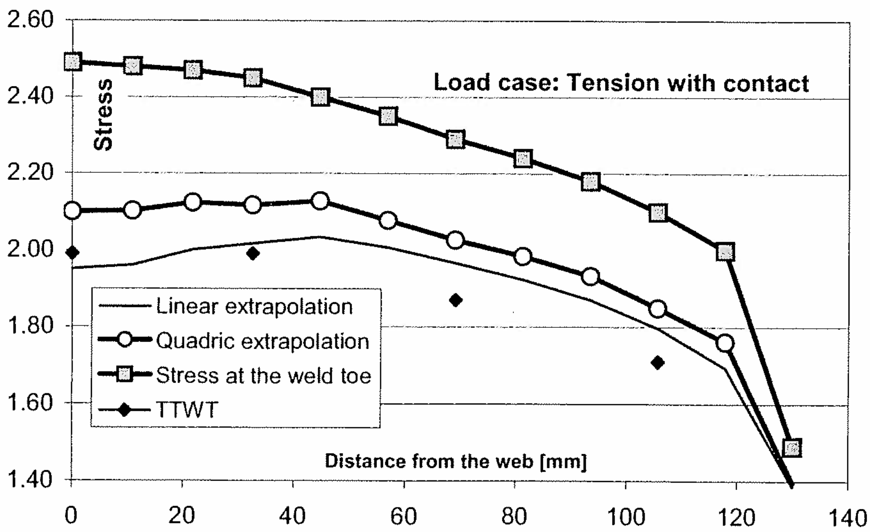


Fig. 4.2 SHS stress distributions along the end of the cover plate.

The effect of the weld load, weld size and plate thickness on stress distribution is presented in Fig. 4.4. This comparison has been illustrated using a symmetric fillet welded detail where the weld size is 5 mm or 30 mm and plate thickness 120 mm or 10 mm, see Fig. 4.3. The weld was either fully load carrying, $2F=T\cdot\sigma_{nom}$, as might occur for a splice plate or the weld load was zero, F=0, as might occur for a small accessory weld. For non-load carrying welds, all the force is assumed to be transmitted by the base plate. It should be noted that for each of the eight cases (four geometries times two load cases / geometry) the SHS stress is equal (σ_{shs} =100 MPa). Fig. 4.4 clearly shows that each of these eight cases have a distinctive effect on the stress distribution in the thickness direction below the weld toe. The differences are most dramatic between non-load carrying and fully load carrying cases for a same geometry.

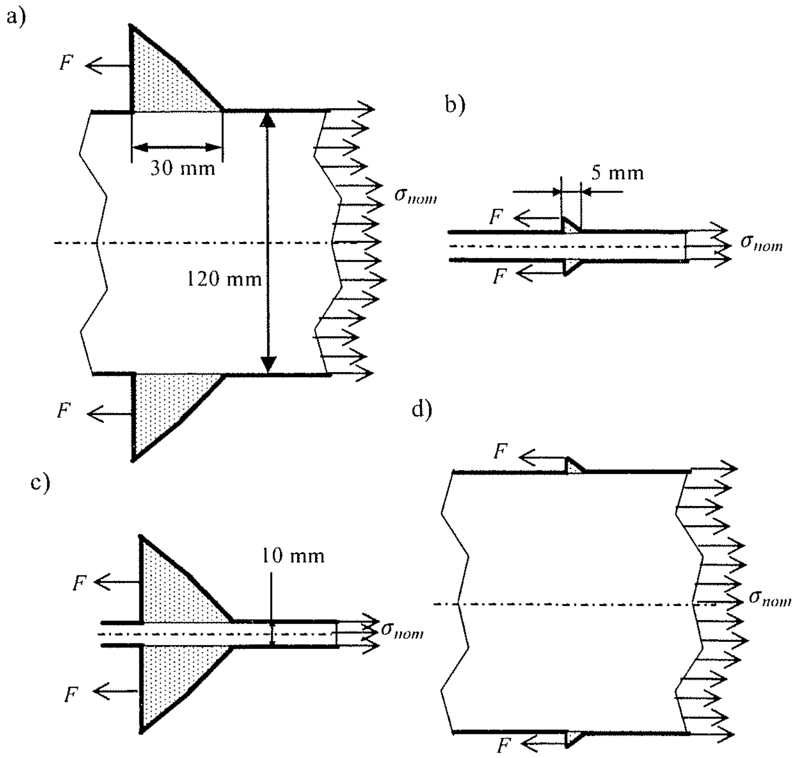


Fig. 4.3 Weld size and load variation for two plate thicknesses and two weld sizes. (l_w = 5 mm or 30 mm; T = 10 mm or 120mm).

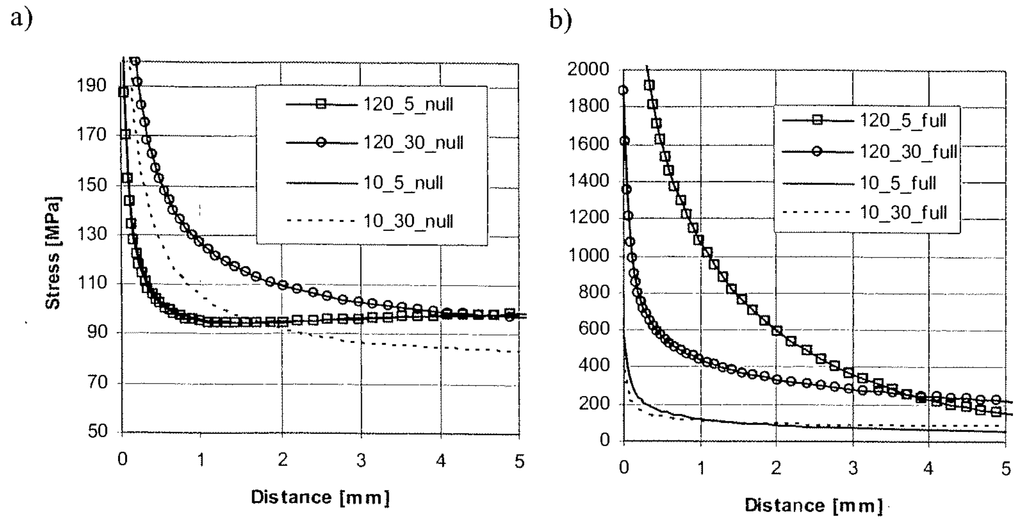


Fig. 4.4 Stress distributions below the weld toe. Non-load carrying (left) and full load-carrying (right).

4.2 A modified structural hot spot stress based on weld stress

4.2.1 Determination of the modified hot spot stress distribution

The stress distribution varies greatly when the weld load, weld size and plate thickness are altered. The use of the SHS stress value alone, e.g., in cases presented in Fig. 4.3, would lead to identical estimated fatigue life in all cases even though the experimental lives would be very different (note: the variations in Fig. 4.3 are intended to be illustrative only and do not necessarily represent good design practice). The basic idea behind the modified structural stress has been to introduce a multi-linear curve that provides a better representation of the actual stress distribution through the plate thickness than does the (by definition) linear structural stress.

The FEA-based non-linear stress distributions obtained using a dense mesh and the corresponding multi-linear distributions of the symmetric fillet welded details in Fig 4.3 are presented in the left hand side of Fig. 4.5. The modified SHS (MSHS) stress is now σ_l. It is proposed that the stress value σ_l should be used during fatigue analysis. The local thickness T_l controls the MSHS stress value. If T_l is assumed to be small the stress is more localized resulting in a higher MSHS value. Poutiainen and Marquis (2004 and 2006C) evaluated different T_l values and compared fatigue life estimates with the resulted MSHS stress and LEFM based calculations. First, an accurate stress distribution was determined using a dense finite element model. Then, two linear curves were calculated and the stress pairs S_1 –S_2 and S_3 –S_4 were determined, see the right side of Fig. 4.5. The stress pair S_1 –S_2 has the same moment and horizontal force equilibrium through the thickness T_l as does the nonlinear stress distribution shown on the left side of Fig. 4.5. Similarly, the stress pair S_3 –S_4 has the same moment and horizontal force equilibrium between depth T_l and the base plate centreline.

The stress values σ_1, σ_2 and σ_3 are determined using the three equilibrium equations, Eqs. (16)-(18). Equation 16 represents the moment balance of the horizontal forces for the stresses to a depth of T_1. Equation 17 represents the equilibrium of the total forces in the horizontal direction. It should be noted that the moment equilibrium between T_1 and the base plate centreline is not necessarily fulfilled using Eqs. (16)-(18). However, the welded joint in this case is symmetric and overall equilibrium is guaranteed. The immediate goal at this point in the development is only to determine a suitable estimate of the turning point for depth T_1, which can then be applied for both symmetric and non-symmetric joints.

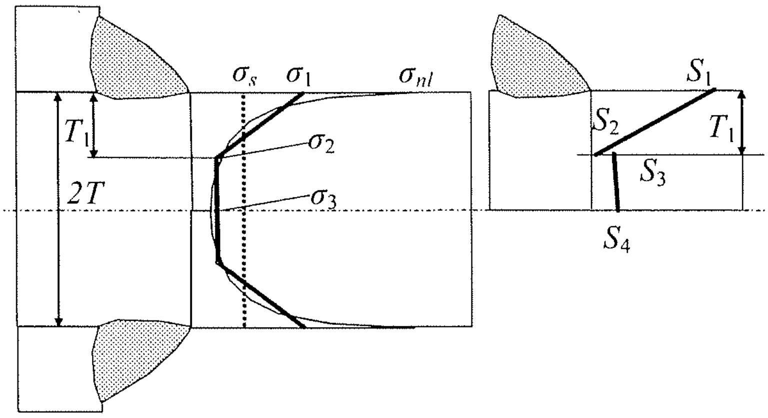


Fig. 4.5 Multi-linear symmetric stress distribution.

$$2S_1 + S_2 = 2\sigma_1 + \sigma_2 \tag{16}$$

$$T_1(S_1 + S_2) + (T - T_1)(S_3 + S_4) = T_1(\sigma_1 + \sigma_2) + (T - T_1)(2\sigma_2) \tag{17}$$

$$\sigma_2 = \sigma_3 \tag{18}$$

Using Eqs.(16)-(18) and varying the turning point distance, T_l, different MSHS stresses (σ_l) can be obtained. This variation for the 40 thick plates is shown in Fig. 4.6. In Fig. 4.7 the multi-linear stress curves are derived for the plate thicknesses 40, 80, 120 and 200 mm. The turning point depth, T_l, was set to 10 mm to produce this figure.

The multi-linear curves were determined based on the stresses obtained using a dense FE - model. An important goal for the MSHS stress method based fatigue analysis has been that the local behaviour should be obtained from more simple FE-models, i.e., models such as would be used for the traditional SHS approach. In the study by Poutiainen and Marquis (2006C), it was concluded that the turning point depth, T_l, should be set equal to weld leg length (T_l = l_w). This value is both easy to define and resulted in fatigue strengths that correlated well with the LEFM based analyses. It was also found that the magnitude of the modification is related to an average weld stress in the weld throat section.

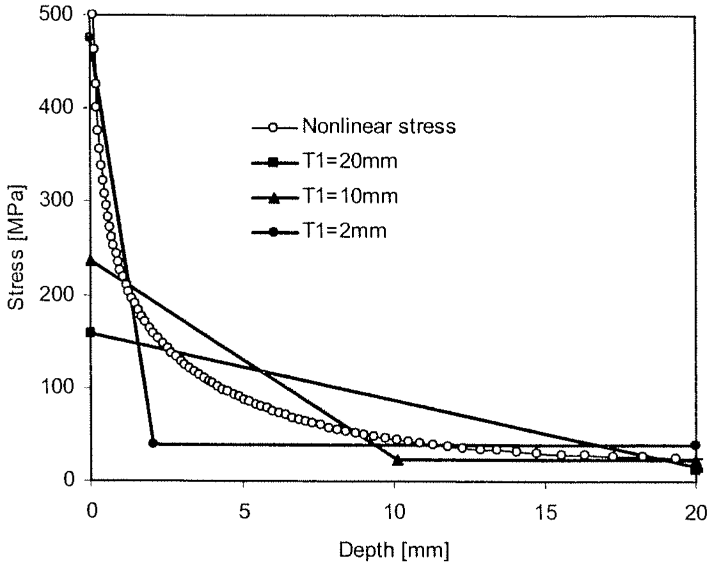


Fig. 4.6 Turning point variation for the 40 mm thick plate.

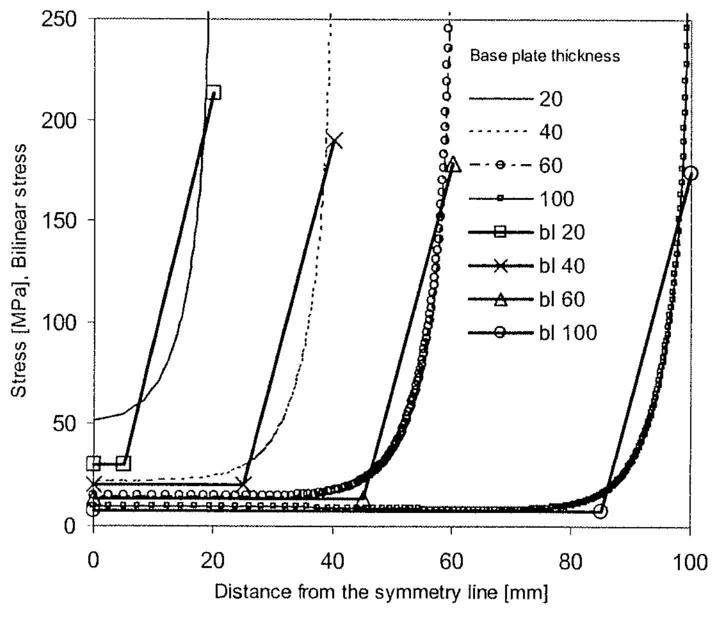


Fig. 4.7 Multi-linear curves for the load carrying fillet welds. Plate thickness 40-200 mm and T_l=10mm.

4.2.2 Definition of the MSHS stress concentration factor

Equations (19) and (20) give the additional stress concentration factor K_{sa}, i.e., the concentration factor for the MSHS stress value. Poutiainen and Marquis (2006A) concluded that the weld load based MSHS approach can be applied to details subject to either axial loading or bending loading. This is particularly important since the SHS stress is, by definition, the combination of membrane and bending stress. It was concluded that the Eqs. (19) and (20) can be used to assess the additional stress concentration factor, K_{sa} as long as σ_{nom} is defined as in Fig. 4.8. The form of the multi-linear stress curves for both axial loading and bending are presented in Fig. 4.8. Equation (19) is used if the weld leg length is less than half thickness of the base plate while Eq. (20) is used for larger welds. The result of Eq. (20) is a bilinear curve. It can be noted that if the l_w/T ratio is high, Eq. (20) is used and the stress value used in fatigue assessment using MSHS approaches the stress needed based on traditional SHS stress assessment. The effect of this transition is illustrated the Fig. 4.9.

With reference to the left hand side of Fig 4.8, the force transmitted through the weld, F_1, and the weld size, l_w, control the size and shape of region 1. The horizontal force component of region 1 is $F_1 / 2$. The horizontal force component of region 2 then becomes $(F_1 + F_2) / 2$.

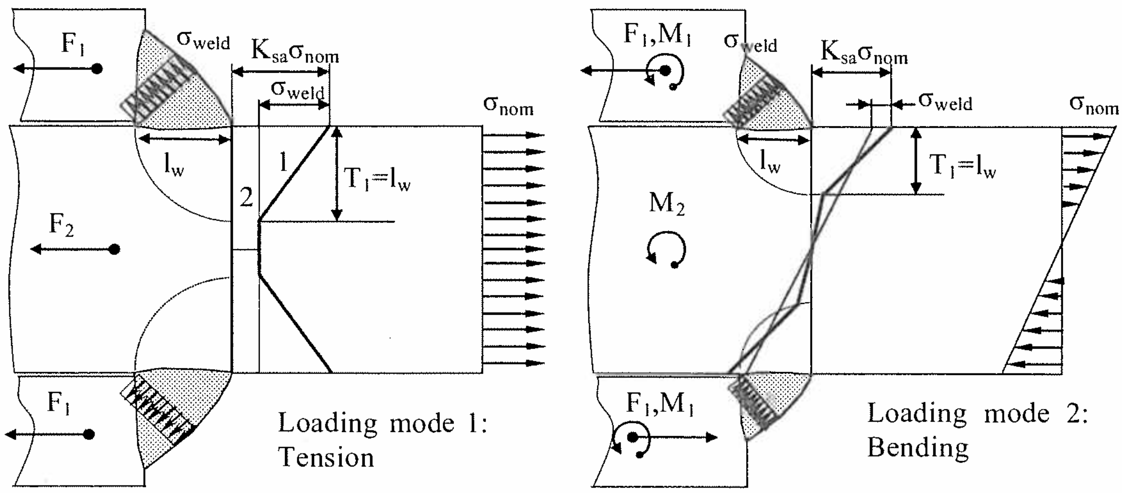


Fig. 4.8 Definition of the multi-linear stress curve based on the weld stress level.

$$K_{sa} = 1 + \frac{\sigma_{weld}}{\sigma_{nom}}\left(1 - \frac{l_w}{T}\right) \quad , \quad l_w \leq \frac{T}{2} \tag{19}$$

$$K_{sa} = 1 + \frac{\sigma_{weld}}{\sigma_{nom}}\left(\frac{T}{4l_w}\right) \quad , \quad l_w \geq \frac{T}{2} \tag{20}$$

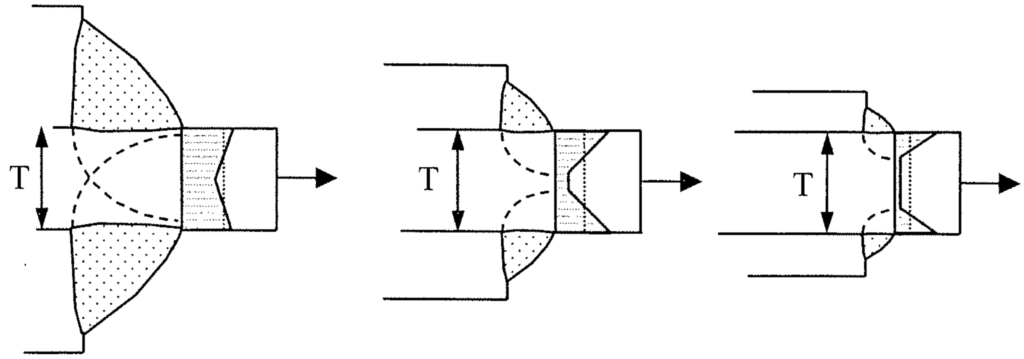


Fig. 4.9 Multi-linear stress curves with different weld sizes according to eqs. (19) and (20).

4.2.3 Computing the MSHS fatigue strength

The modified structural stress method takes into account both the weld size and the stress in the weld. If the weld is non-load carrying, the fatigue life decreases with weld size. During fatigue assessment, the fatigue strength of the detail is first computed assuming that the weld is free of stress. The fatigue strength in the load-free case will vary depending on if the structure is loaded in tension or bending. Estimates for the load-free fatigue class can be determined from the Eq. (21) in the case of tension only loading, FAT_{0T}, and Eq. (22) for the case of bending only loading, FAT_{0B}. Equations (21) and (22) were derived from analysis results previously developed by Poutiainen and Marquis (2006A). These equations take into account the influence of stress gradient through the plate thickness as a function of weld size and plate thickness. The reference thickness T_{ref}= 1 mm. Eqs (21) and (22) are determined for the weld leg length (l_w) ranging between 5-30 mm and base plate thickness (T) ranging between 10-120mm.

$$FAT_{0T} = 314.4 - 0.032 \cdot \left[\frac{T}{T_{ref}}\right] + 1.43 \cdot \left[\frac{l_w}{T}\right]^2 - 135.5 \cdot \left[\frac{l_w}{T_{ref}}\right]^{0.06} - 77.93 \cdot \left[\frac{l_w}{T}\right]^{0.08} \tag{21}$$

$$FAT_{0B} = 1016 - 0.0078 \cdot \left[\frac{T}{T_{ref}}\right] + 3.0 \cdot \left[\frac{l_w}{T}\right]^{1,9} - 899 \cdot \left[\frac{l_w}{T_{ref}}\right]^{0.013} \tag{22}$$

Most welds are loaded with some combination of tension and bending loading, so the zero-load fatigue strength, FAT_0, is computed using Eq. (23). The degree of bending, δ_b, in Eq. (23) is expressed as the ratio of the structural stress due to bending divided by the total structural stress. If the structural stress is determined using surface extrapolation methods, the influence of bending stress will be exaggerated and may lead to an overly conservative fatigue life estimate in those structures where the structural stress is predominantly due to bending. This definition of degree of bending has been used, e.g., by Dong (2006). Surface extrapolation does not directly indicate the portion of stress due to bending. If applicable, a through-thickness determination procedure could be used (Poutiainen et al., 2004).

$$FAT_0 = FAT_{0T} \cdot (1-\delta_b) + FAT_{0B} \cdot \delta_b \tag{23}$$

Fatigue strength of a welded detail is calculated by dividing FAT_0 by the stress concentration factor K_{sa} from Eqs. (19) or (20), see Eq. (24).

$$FAT = \frac{FAT_0}{K_{sa}} \tag{24}$$

4.2.4 Re-assessment of experimental results

A large experimental database found in literature was re-analyzed based on MSHS stress (Poutiainen and Marquis, 2006A). Tests reported by Maddox (1987) and Gurney (1991) were selected since they included comprehensive variations of plate thicknesses and weld sizes. Also, variations in reported attachment sizes produced significant variations in the weld stresses. Test specimens were analyzed using simple FE-analysis models from which weld stresses could be determined.

All the fatigue test results of Maddox (1987) and Gurney (1991) are presented in Fig. 4.10 in terms of nominal stress. The corresponding results correlated using MSHS stress are presented in the Fig. 4.11. The empirical thickness correction factor used in the IIW hot spot assessment method was not needed when using the MSHS method even though several of the data points represent plate thicknesses up to 100 mm. The thickness correction is included in Eqs (21) and (22). The proposed MSHS method was also tested against other local methods (Poutiainen and Marquis 2006B). In addition to this method, an effective notch method and the 1 mm geometric stress method were compared in this study. The structural detail in this study was that reported by Poutiainen (2002), i.e., a cover plate on an I-beam. This model was chosen because the traditional SHS stress method gave inconsistent results. All the local methods predicted failure location in the same region, but the predicted fatigue strength estimations had some irregularities. This can be expected since all the methods have different theoretical background.

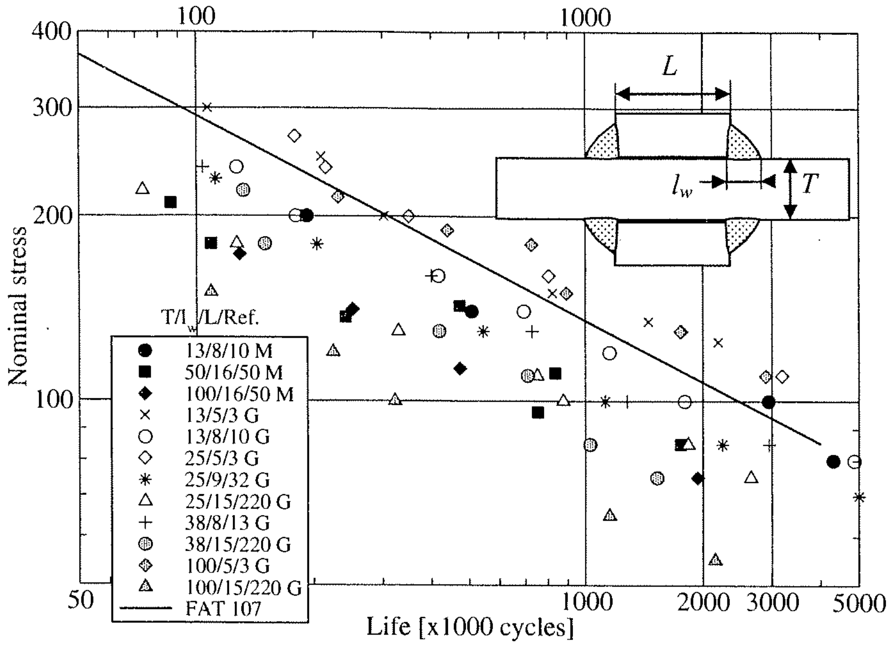


Fig. 4.10 Fatigue test results based on the nominal stress method.

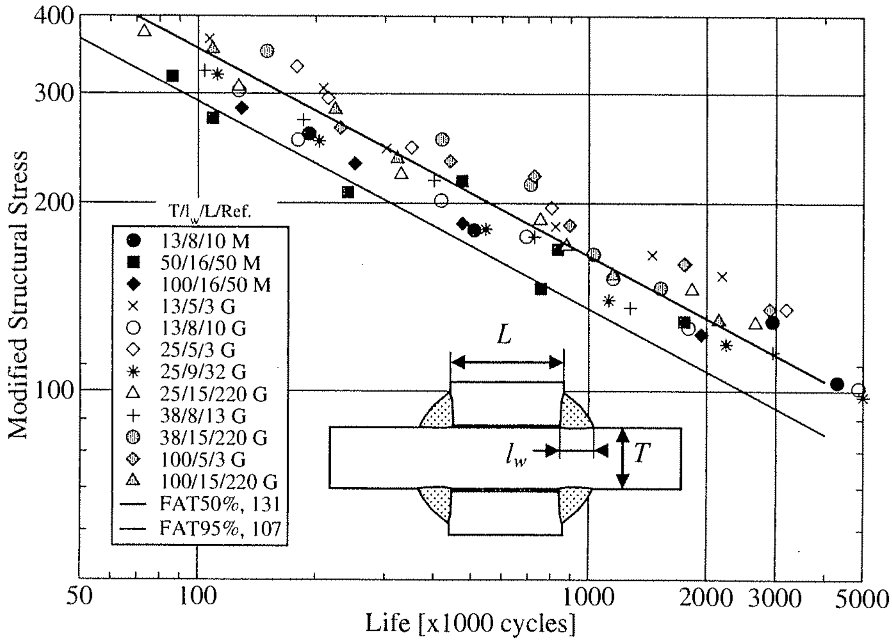


Fig. 4.11 Fatigue test results recalculated and presented using modified structural stress.

4.3 Weld stress in MSHS method

Weld stress is one of the key parameters that must be determined when applying the MSHS method proposed in this thesis. Fatigue assessment based on a modified structural stress that is higher than the conventional structural stresses is explained based on the stress in a fillet weld. This proposed approach is valid only for welds attached along the plate surface, in this case fillet welds. The approach could be extended to include, e.g., lap joints assembled with spot welds or laser keyhole welds. The weld stress parameter is influenced by both the force transmitted by the weld load and the weld size. These combine to give valuable information on the stress state in the critical weld toe area.

4.3.1 Definition

Weld stress in the present method is the average normal stress in the cross section a-a, shown in Fig. 4.12 . This section was selected because it represents the exact same section used for the static strength evaluation of a fillet weld. Fig. 4.12 shows a general example of structural stress distributions in a weld along section a-a, along the fusion line between weld and base metal, section a-c, and along the fusion line between weld and attachment surface, section a-b. The MSHS method uses only the average stress in the throat section a-a. In order to compute average stress, it is sufficient to know only the weld load and the weld throat thickness. Even though a bending stress component may be present, this has no significant effect on the average normal weld toe stresses.

The MSHS method has been derived based on the simplifying assumption that the magnitude of the perpendicular shear stress, $\tau_{\perp}$, at the weld throat is equal to the normal weld stress. It has also been assumed that the stresses in section a-a are produced by stresses in the leg section a-b, and not by the shear stress, τ_y. Force in the y-direction is assumed to be zero with the result that the shear stress, τ_y, is also zero. Vertical force does not influence the horizontal stress in the weld toe of the base plate. Thus, it is proposed that if there are doubts as to how the weld stresses are developed, the weld stress can be assumed to be the same as the average normal stress in section a-b. Based on equilibrium, the average normal stress in this section is equal to the average normal weld stress in the throat section a-a.

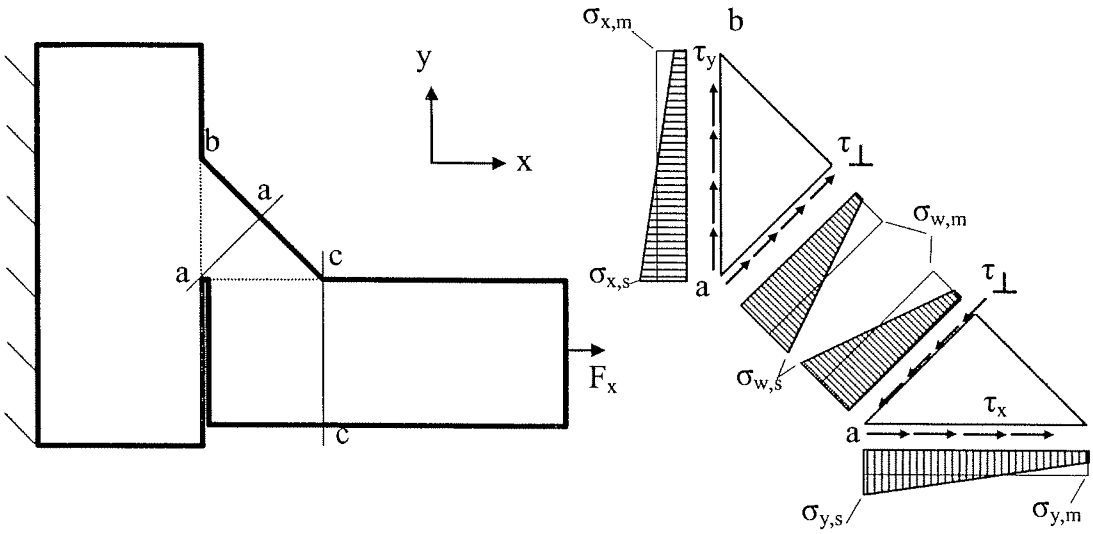


Fig. 4.12 Weld stresses in the fillet welded detail.

4.3.2 Determination

In most cases weld stress is determined based on finite element analysis. When properly applied, FE- analysis gives a good overall view of the stress state in the structure. Problems may arise, however, when a designer tries to extract only a specific stress component in a single detail. It is often easier to obtain peak stresses rather than some lower order stress component. The peak stress has no relevance in the analysis of welded details if the toe is modelled as having zero radius. The sharp notch problem can be solved using local methods with artificial rounded notches. A linear stress distribution could be calculated from the actual stress distribution, but the element mesh needs to be sufficiently dense. In the case of a coarse element mesh, the linear stress distribution in the toe section c-c in Fig. 4.12, can be determined directly from nodal point stress values. This requires that the stress values from the weld are excluded from the stress averaging.

The most accurate means for assessing weld stress is based on nodal forces. The forces can be determined along any of the three weld sections presented in Fig. 4.12. It is recommended, however, that the forces are determined in section a-b where the resulting weld stress component can be directly used in the analysis. If a shell element model is constructed, the welds can be modelled using any of several approaches. In these models the nodal force approach also applies. In shell element modelling, careful attention must be given to the weld elements so that the modelled weld stiffness correlates to the weld stiffness in the actual structure. The approach of mid-plane modelling combined with a single shell element for weld produces a connection with too much flexibility with the result that the computed weld force distribution is erroneous.

4.3.3 Limitations

The weld stress based approach has been derived for the fillet welds with an assumed flank angle of 135° (see Fig. 2.4) and with zero penetration. If the flank angle is increased while keeping the horizontal leg length constant, the weld stress increases with an expected decrease in fatigue strength. In reality such a weld would probably have increased fatigue strength. In such a case, a better assessment method would be to compute the weld stress assuming that both weld legs are equal to the smaller (vertical) leg length. The horizontal leg length would then be set to the desired value for computing the structural stress at the weld toe. In this way, the depth at which the stress gradient is assumed to change slope, T_1 in Fig. 4.8, would increase and the resulting K_{sa} would be lower. It can also be recognized that the weld stress could also be determined base on the shear force along section a-c in Fig 4.12. It is possible that this should be adopted for flank angles significantly different from 135°. However, flank angle variation has not been specifically included in the current study and remains for future work.

A fabrication process that produces full or partial penetration will normally improve that fatigue strength of a joint. In its present form the MSHS method does not take into account the beneficial effect of *vertical* penetration for a joint like that shown in Fig 4.12. The benefit of *longitudinal* penetration that might occur for a joint like that shown in Fig 4.11 can be considered directly. In addition to these cases, welded details like gusset ends produce complex 3D stress concentrations. In such cases 2D based solutions will not necessarily work.

5 CONCLUSIONS

The structural hot spot (SHS) method is frequently used in the fatigue life assessment of welded structures. When compared to the simpler nominal stress method, the SHS method provides more flexibility in structural design. The effects of dimensional variations and structural solutions can be considered without the restrictions of geometries available in predefined joint catalogues. The SHS stress used in fatigue analysis is relatively easy to obtain from the FE analysis. Some concerns still remain regarding the stress determination and resulting accuracy in some special situations.

The problems associated with SHS stress methods are linked to variations in the stress distributions for different joint types. This was demonstrated in the case of an I-beam cover plate detail where the plate stiffness varied along the weld toe. The SHS stress method failed to predict the critical location for fatigue failure. In this case, the life prediction could have been corrected by using higher order extrapolation methods. However, the transition between the stiffened and non-stiffened plate is not well defined and implementing a non-linear extrapolation scheme is more challenging. Weld size variation also produced inconsistent results. Smaller welds showed higher local stresses and lower fatigue strengths based on LEFM simulations. The SHS stress based approach showed the opposite effect. Another problem with the SHS stress method is the plate thickness effect. The SHS stress method is only valid for a specific range of plate thicknesses. For thicker plates, a semi-empirical correction term must be introduced. This is also a feature of some other common assessment methods.

SHS stress determination using surface extrapolation methods can result in variations in the results depending on the FE mesh in the weld toe region, i.e., the method is not mesh insensitive. Care must be taken when meshing so that the extrapolation point closest to the weld toe does not include components of the non-linear stress. This can be achieved using a coarse element mesh where only one element in the thickness direction is used. Thin shell elements for this purpose are also very useful. The mesh insensitivity requirement can be more easily fulfilled by determining the structural stress via a through-thickness at the weld toe (TTWT) procedure or Dong's SHS stress assessment procedure.

To improve the SHS stress method, a bilinear stress distribution through the thickness of a plate in the plane of the weld toe has been proposed in this thesis. The method is based on force equilibrium in the structure and is also suited for load carrying welds in relatively thick plates. Simple equations have been developed to compute the bilinear stress at the plate surface. This bilinear stress at the plate surface can be considered as a local structural stress which is used in the same way as the traditional structural stress in fatigue assessment. This stress value is used to assess fatigue strength using design curves for non-load carrying welds previously developed within the IIW. This new assessment method will allow all welds, non-loaded, partially loaded or fully load-carrying welds, to be evaluated using a single S-N design curve. Using this method, fatigue assessments for a symmetric splice plate were in good agreement with fracture mechanics based predictions. The method also correlated published experimental data from a large variety of welded double sided cover plate structures.

Weld stress determination can be performed using finite element calculations with relatively simple meshes. This stress value is also useful when the root cracks are included in the fatigue analysis. Fatigue assessment for the root side using the structural stress in the weld has been proposed by Fricke et al. (2005). While the fracture mechanics based fatigue assessment or other local methods require very fine FE meshes, the proposed method is also suitable for coarse meshes. Coarse meshes are preferred when large or complex structures are evaluated.

The advantage of the current method is that only one structural stress fatigue class is needed and FE analysis requires only relatively coarse solid, plane or thin shell element models. A semi-empirical thickness correction, such as that used in the traditional structural stress method or nominal stress method, is not needed. A wide range of plate thicknesses and weld sizes have been examined. Good agreement was found between fatigue assessment based on the proposed modified structural stress and fracture mechanics based results and also with published experimental data.

The proposed method was tested in junction with two local approaches (effective notch method and geometric stress at 1mm method). Fatigue strength of welded structure was determined using all of these three methods. All methods predicted the fatigue strength behaviour in the similar manner. The weld size effect was most noticeable with effective notch method whereas the 1 mm stress method showed less influence of weld size. The modified SHS method also showed a clear variation in stress with different weld size.

6 RECOMMENDATIONS FOR FUTURE WORK

Several SHS stress determination procedures are available and they all can provide good stress estimates for the purpose of fatigue design. Some problems still exist related to the use of shell elements and modelling strategies for the weld beads and some welded connections. The relatively simple longitudinal gusset on a plate remains a challenging construction for shell elements and great variations in fatigue assessment results are often observed. In many industries, "in house" recommendations are available, but the results do not necessary coincide with the true SHS stress value.

The weld stress based correction for the SHS stress provided information on the local behaviour of the weld toe. The average stress was used in this study. Fricke et al. (2005) used a linear stress distribution in the weld for assessing root cracking. Since the cracks tend to initiate from the welds, toe or root, the information obtained from the structural stress of the welds is important. The connection between these methods should be further studied.

The MSHS has been shown to be effective when assessing load carrying welded details. Recalculation of experimental fatigue test data based on the MSHS stress gave consistent estimates, but the comparison to other local methods showed more variation. The fundamental differences between local methods should be clarified and S-N curve for the MSHS stress method introduced. The method presented here has been applied only to symmetric fully load carrying welds under tension and bending load. Future work should be expanded to also include verification of non-symmetric welds.

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