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Recent developments and future challenges in fatigue strength assessment of welded joints

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Abstract
Fatigue is an important design criterion for welded structures subjected to cyclic loading. Several approaches for fatigue strength assessment have been developed which are either based on Woehler S–N curves and damage accumulation rule or on crack propagation law. The paper briefly reviews the different approaches, highlighting their advantages and limitations. In this connection, the problematic distinction between crack initiation and propagation phases is discussed, followed by considerations about some parameters which have large influence on the fatigue behaviour of welded joints but are considered differently in the approaches, such as plate thickness and stress gradient effects, multiaxial stress states, welding-induced distortions and residual stresses. Finally, ways of improving the fatigue behaviour of welded structures, either during design by reducing the stress concentration or during fabrication by improved quality or post-weld treatment or else by special material characteristics, are addressed. Emphasis will be placed on recent developments and challenges for the future from a personal perspective of the author.

Keywords
Fatigue, stress, thin structures, welding technology, finite element analysis, fracture mechanics, high cycle fatigue, numerical analysis

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Introduction

Welding has increased the risk of fatigue failure for various structures due to the introduction of sharp notches and detrimental material effects. Affected are all structures subjected to cyclic loading, in particular those involved in transportation such as ships, railcars, automobiles, trucks and airplanes. But also other structures have experienced fatigue failures at welds, such as offshore structures, bridges, cranes, engines, pressure vessels, etc.

Fatigue assessment is therefore a significant task during structural design. First standards were already introduced in the 1970s, e.g. DIN 15018[1] and BS 5400,[2] which have been applied in various branches. Also international recommendations were created, e.g. the first fatigue design recommendations of the International Institute of Welding in 1982.[3] All these standards and recommendations were based on the nominal stress approach. In the following years, local approaches such as the structural hot-spot stress and the effective notch stress approach as well as the crack propagation approach were additionally introduced into practical application.[4,5]

In this paper, an overview and critical review are given about these and other approaches for the fatigue assessment of welded joints. One major problem associated with them is that fatigue life consists of crack initiation and crack propagation phases which are considered in different ways. The related problems and the consequences will be discussed in the paper. But also other influence factors on fatigue of welded joints are discussed which are considered differently in the approaches and are responsible for diverging results. Regarded as particularly important by the author are the plate thickness and stress gradient effects, multiaxial stress states, welding-induced pre-deformations such as axial and angular misalignment and last but not least residual stresses.

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Finally, measures for improving the fatigue performance will shortly be discussed, where some interesting developments have been observed in the recent years. It should be noted that the following considerations can be neither deep nor complete. The objective is to give a personal overview of some recent developments including relevant references, allowing future challenges to be addressed.

Approaches for fatigue assessment

Most approaches are based on S–N curves obtained from constant-amplitude tests. Variable-amplitude loading is usually considered by an appropriate damage accumulation hypothesis such as the Palmgren-Miner rule. The approaches differ in the type of stress considered, requiring a greater or lesser degree of detail and effort for its determination. In contrast, the crack propagation approach outlined at the end of this chapter uses the crack length as the fatigue parameter. Figure 1 gives an overview of the approaches, the last two focusing on crack propagation (after Radaj et al.[4]).

In addition to the approaches mentioned in the following, the fatigue behaviour can be assessed by specific methods based on experimental findings, such as the *thermographic method* using the increase in temperature of the material due to reversal plastic straining, which is particularly suitable for determining the endurance limit.[6]

Nominal stress approach

The nominal stress approach utilizes the stress σ_n for the fatigue assessment which disregards the local stress increases due to structural discontinuity (e.g. the stiffener termination in Figure 2) and due to the local weld profile. These effects are included in notch cases or detail categories containing structural details which are associated with design S–N curves allowing the fatigue strength to be assessed (also called FAT classes).

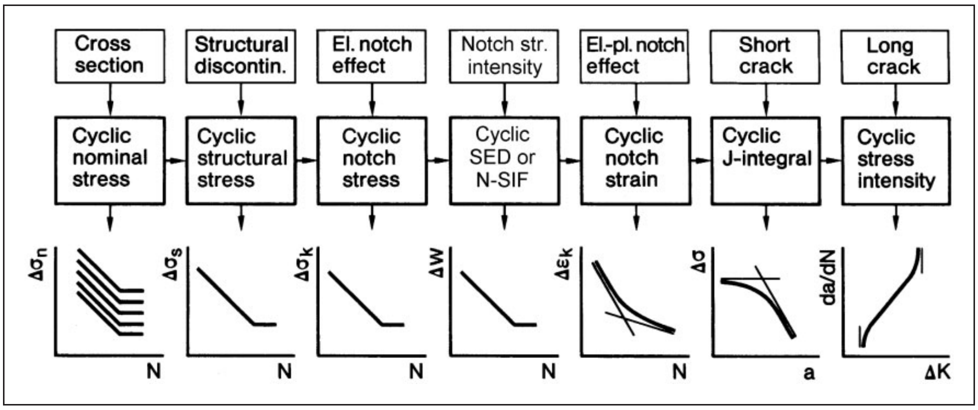

Figure 1. Overview of the fatigue assessment approaches.

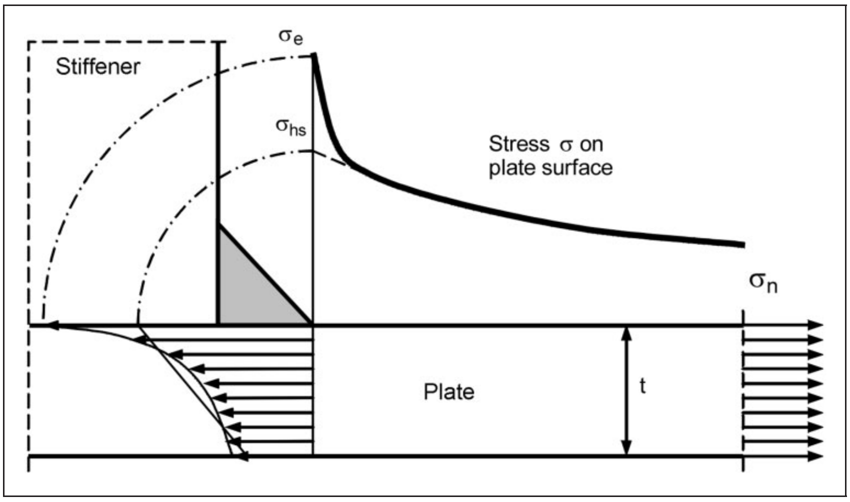

Figure 2. Stress distribution at the end of a stiffener and definition of nominal and local stresses.

In general, the nominal stress approach is the easiest and most frequently applied, requiring only a simplified stress determination. The approach is contained in all fatigue design codes and recommendations. Several influence factors such as quality effects including misalignment as well as residual stresses are implicitly taken into account to a certain extent, whereas others, such as the plate thickness effect, have additionally to be considered. The nominal stress approach should be applied only to the cases and within the limits defined by the fatigue classes described in codes and recommendations. The determination of the nominal stress might be a problem in real structures with complex geometries which differ from the small-scale specimens being the basis of the design S–N curves.

Structural hot-spot stress approach

In contrast to nominal stress, the structural stress includes the stress increase due to structural geometry, e.g. the stress concentration of an attachment or additional plate bending due to significant misalignment effects. The local stress peak by the weld itself, due to its sharp notch at the weld toe, is not considered.

The structural stress is usually determined by extrapolating the surface stress to the hot-spot, termed structural hot-spot stress σ_{hs},[5,7] see Figure 2. Another way of deriving the stress by omitting the local stress peak is stress linearization in the thickness direction, also illustrated in the left part of Figure 2. The fatigue strength is defined for each type of weld and material by one or two S–N curves, the latter to distinguish between load-carrying and non-load-carrying fillet welds. The plate thickness effect has additionally to be taken into account.

Different variants of the approach exist which consider, for example, the effect of the stress gradient in the plate thickness direction and the plate thickness effect,[8] which will be discussed further below. In contrast to the nominal stress approach, the structural stress approach offers the possibility of explicitly considering significant secondary bending stresses due to misalignments.

Several fatigue design codes and recommendations contain the structural hot-spot stress approach. This includes the application to specific structures such as tubular joints in civil and offshore engineering or complex welded structures in ships.

Effective notch stress approach

The effective notch stress approach takes into account the increase in local stress σ_e at the notch formed by the weld toe or the weld root (Figure 2), based on theory of elasticity, i.e. without consideration of elastic-plastic material behaviour. The micro-structural support effect of the material, which considers the effect on fatigue behaviour of the inhomogeneous material structure in a non-constant stress field, may be taken into account by averaging the stress over a substitute structural area as proposed by Neuber.[9] Similarities exist to the alternative critical distance approach proposed by Taylor,[10] where also a reduced stress is considered, but at a point or line in a small material-dependent distance from the notch root.

The effective notch stress approach is mainly used in the form of fictitious notch rounding,[4,5,8,11] using a reference radius of $r_{ref} = 1\,\text{mm}$ as the worst case assumption together with a design S–N curve based on notch stresses determined for the underlying specimens. Approaches exist using smaller notch radii which are obviously better suited to thin-plated joints, especially in case of weld root failure.

Significant secondary bending stresses due to misalignment have to be considered in the stress, whereas the plate thickness effect is naturally included. The main advantage of the effective notch stress approach as well as the critical distance approach over the nominal and structural stress approaches is that the effective stress in the relevant notch is explicitly taken into account so that influence factors such as the actual local geometry including weld throat thickness, flank angle, etc. are considered. However, the weld geometry is usually idealized, so that irregularities and other effects such as residual stresses are only considered by the S–N curve chosen.

The effective notch stress approach is contained in the IIW fatigue design recommendations[5] for already several years. The inclusion in different codes may be expected in the near future.

Notch stress intensity factor approach

The theoretically infinite stress at sharp V-notches can be described by a notch stress intensity factor (N-SIF) in a similar way as for crack tips. The N-SIFs can be directly used to describe the crack initiation at sharp corners. Lazzarin and Tovo[12] developed an N-SIF approach for welded joints and showed that fatigue test results of various welded joints form an S–N curve with reasonable scatter if based on N-SIF. Alternatively, the averaged strain energy density (SED) in a control volume around the sharp notch can be used, offering the application of simplified analysis models and the assessment with a common S–N curve independent of the notch opening angle.[13] Another alternative is to use the relation between the notch strain intensity and the peak stress in a finite element model with defined mesh size and element properties.[14]

Principally, the approach is similar to the effective notch stress approach, thus the same opportunities and restrictions apply. In the case of zero opening angle, i.e. a slit typical of weld roots, the N-SIF becomes the well-known stress intensity factor which can be directly used for fatigue assessment or for crack propagation analyses.

Notch strain approach

A more refined assessment may be offered by the notch strain approach which considers elastic-plastic effects.[4] These may be relevant particularly in the low-cycle fatigue domain which is important for structures in transportation engineering when looking, for example, at the different loading conditions of airplanes on ground and in the air or of ships in ballast and fully loaded. The approach requires the so-called cyclic stress–strain curve of the affected material. In the case of welds, the parent metal, heat-affected zone and weld metal may show different behaviours which complicate the analysis.

The local stress and strain are normally determined by nonlinear finite element analyses or approximation formulae (e.g. Neuber's rule). The fatigue strength is described by strain S–N curves which are derived from material tests with small-scale specimens where crack initiation characterizes the failure. Recently, the effective notch stress approach using the 1 mm reference radius has been extended for application in the low-cycle fatigue regime, using a design S–N curve based on the effective elastic-plastic notch strain range.[15]

The approach is contained in specific codes and recommendations in connection with low-cycle fatigue assessment.

Crack propagation approach

The crack propagation approach allows the number of cycles to be computed for a crack growing from an initial size to a final (critical) size on the basis of the power law by Paris and Erdogan,[16] describing the linear part of the crack growth rate da/dN in relation to the range of the stress intensity factor (SIF) in a double-logarithmic representation, i.e. above the threshold value and below the critical SIF where unstable fracture occurs. Additional effects such as the mean stress and crack closure can be considered. The behaviour of the so-called short cracks occurring under loads below the threshold value is governed by different rules, taking into account the inhomogeneous material structure including plastic deformation, grain boundaries, etc.

Today, the crack propagation approach is mostly applied to the safety assessment of structures containing a defect or crack by computing their remaining life. Associated codes and recommendations have been established. However, the approach is also applied during design to cases where the crack initiation period is short. This is particularly the case for welded joints with incomplete penetration, where the crack may initiate from the weld root. For weld toes, a crack depth between 0.05 and 0.25 mm is usually assumed together with the conventional crack propagation law. Using the so-called equivalent initial flaw-size[17,18] allows predicting the life observed in fatigue tests.

Crack initiation and propagation

Today, improved microscopic devices help to better understand the phenomena of crack initiation in metallic materials. As illustrated in Figure 3, crack initiation depends on whether it is viewed from physical or technical perspective.[4]

The distinction between crack-free and crack propagation phase is problematic and depends on the technical means available. The term 'technical crack', used for crack sizes which can be found by technical devices, loses its significance. A clear distinction between the crack initiation and crack propagation phases is difficult and a reasonable definition of a crack length separating the two phases seems to be arbitrary.

This, added to the fact that fatigue life consists of both phases, is a fundamental problem for the fatigue assessment approaches. Depending on the type of structure and definition of the failure criterion, fatigue life may contain quite different portions of crack initiation and propagation.

Most of the aforementioned S–N approaches, i.e. nominal, structural hot-spot and effective notch stress as well as notch stress intensity approach, utilize fatigue test results of small-scale specimens subject to constant-amplitude loading, where specimen fracture characterized the failure. In most cases, the portion of crack initiation in fatigue life is unknown, but it can vary between, say, 10% and 90%. Only the notch strain approach utilizes S–N results of small material specimens where crack initiation is usually defined by a certain drop in load during the strain-controlled test, corresponding to a crack length below 1 mm. And the crack propagation approach is naturally

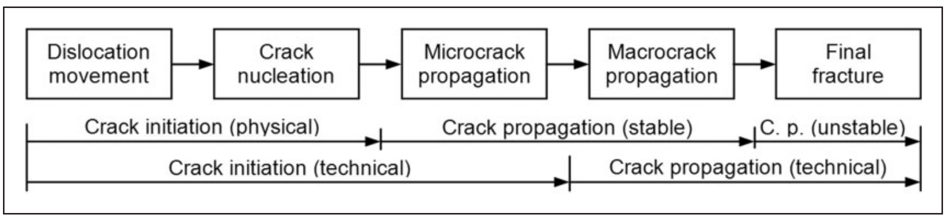

Figure 3. Micro- and macrophenomena of material fatigue.

restricted to the crack propagation phase, assuming an initial crack length, i.e. not considering or even disregarding the crack initiation phase.

The above considerations highlight the problem of a reasonable prediction of fatigue life up to a well-defined failure criterion. Most of the S–N approaches should principally yield similar results, as they are calibrated by fatigue lives of small-scale specimens. Their failure is frequently considered as equivalent to a through-thickness crack in a more complex structural component because afterwards the crack propagation is very fast in small-scale specimens. This is reasonable, but only an assumption. Furthermore, it remains unclear how far the different types of stresses, i.e. nominal or local, are able to correctly capture the crack initiation and propagation phases in view of the fact that only a single stress value at a certain location is considered.

The notch strain approach regarding crack initiation and the crack propagation approach are principally able to predict fatigue life considering both phases as well as a certain failure criterion. However, a clear crack length to distinguish between both phases is missing. Often a crack depth of 0.1–0.25 mm is assumed.[4] However, this is already close to or within the domain of short crack behaviour, requiring different crack propagation laws.

It will be a great challenge in the coming years to overcome the difficulties mentioned. Recent approaches try to consider the damage process in the microstructure and include the crack initiation phase into the crack propagation phase.[19,20] One requirement will be that the approaches must be practical if they are to be widely applied.

Influence factors on fatigue assessment of welded joints

Plate thickness and stress gradient effects

One influence factor which is treated differently in the approaches is the plate thickness effect, meaning that the fatigue strength decreases with increasing plate thickness. It belongs to the size effects and is frequently explained by the increased local stress in thicker structures due to the unfavourable geometry (smaller ratio between notch radius and plate thickness) and by the larger zone of high stresses close to the weld toe increasing the early crack propagation, as illustrated in Figure 4.

A thickness correction factor was introduced for the fatigue strength of welds at plate thickness above a reference thickness of about 25 mm to be applied in the nominal as well as the traditional structural hot-spot stress approach.[5,21] However, the effect is naturally included in all other approaches. The development of the plate thickness effect and associated investigations has recently been reviewed by Lotsberg.[22] One major problem is that not only the local geometry at the weld toe causes an interrelation with plate thickness, but also the structural geometry, e.g., in form of the thickness of a welded transverse attachment. This has resulted in proposals to include also the attachment thickness in the correction factor,[5,22] which has been validated by relatively simple joints. Questions remain how such corrections should be applied in case of more complex structures.

Another influence factor on fatigue strength which has been identified is the stress gradient in the plate thickness direction. Not only the local stress gradient close to the weld toe notch affects the fatigue life as mentioned above, but also the whole stress distribution in the plate being relevant for the crack propagation phase up to a through-thickness crack. Frequently, the stress distribution is linearized in the through-thickness direction, see Figure 4, yielding a structural hot-spot stress σ_{hs} together with a stress gradient which may be used in fatigue assessments.

Compared to a constant linearized stress, the stress gradient displayed in Figure 4 yields a longer fatigue life. This is considered in the crack propagation approach by the so-called M_k factors in the geometry function of the stress intensity factor. But it is also proposed to consider this effect in the structural hot-spot approach. DNV[23] simply suggests considering only 60% of the bending portion of the structural stress. Dong[24,25] proposed to consider the stress gradient together with the plate thickness effect by modifying the structural stress by a factor which he derived from crack propagation analyses.

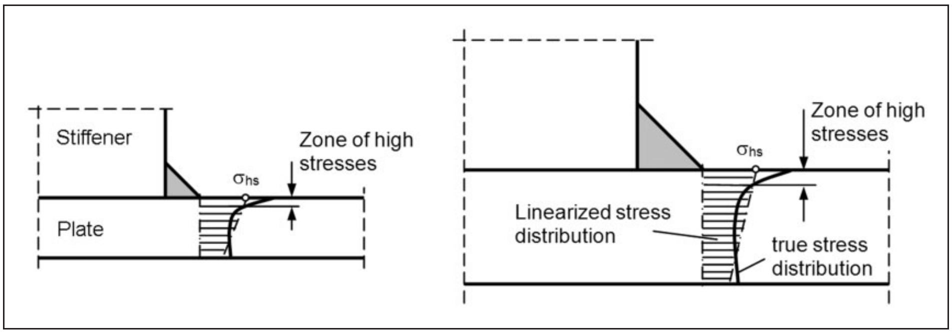

Figure 4. True and linearized stress distribution in plates with different thickness.

This factor becomes rather complex if different crack shapes (semi-elliptical or continuous 2D crack) and load situations (load or displacement controlled) are taken into account.

The stress gradient effect, which has been observed in the structural hot-spot stress approach, should be present also in all other approaches based on a single stress parameter at the weld toe, such as the effective notch stress and the notch stress intensity approaches. This has not yet been recognized, although numerical analyses of complex welded structures as illustrated in Figure 5 yield quite conservative fatigue lives which have been related to this and further effects.[26]

In any case, the stress gradient effect has to be considered in connection with the chosen failure criterion. Thus, its realistic consideration in fatigue assessment is still a challenge for the near future.

Multiaxial stresses

A multiaxial stress state makes the fatigue assessment much more complex. Figure 6 illustrates the situation at the weld toe where three stress components are acting in the fatigue-critical zone close to the surface, i.e. σ_{II} parallel to the weld line, $\sigma_{\perp}$ perpendicular to the weld line and τ_{II} in the horizontal shear plane.

In several cases, a shear stress τ_{II} is present in addition to the normal stress $\sigma_{\perp}$, so that the first principal stress is rotated about the vertical axis. The problem is again that crack initiation and propagation are governed by different mechanisms. The fatigue damage

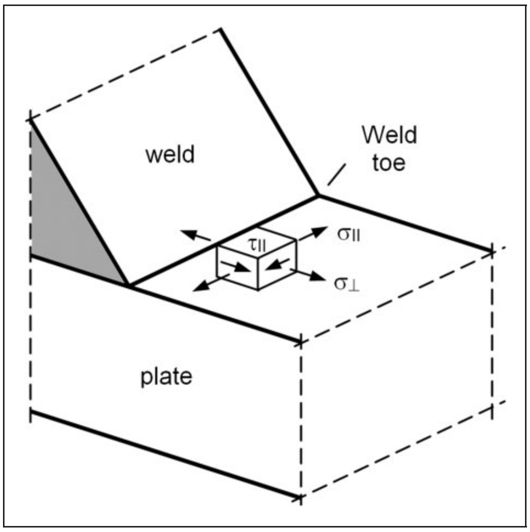

Figure 6. Multiaxial stress state at a welded joint.

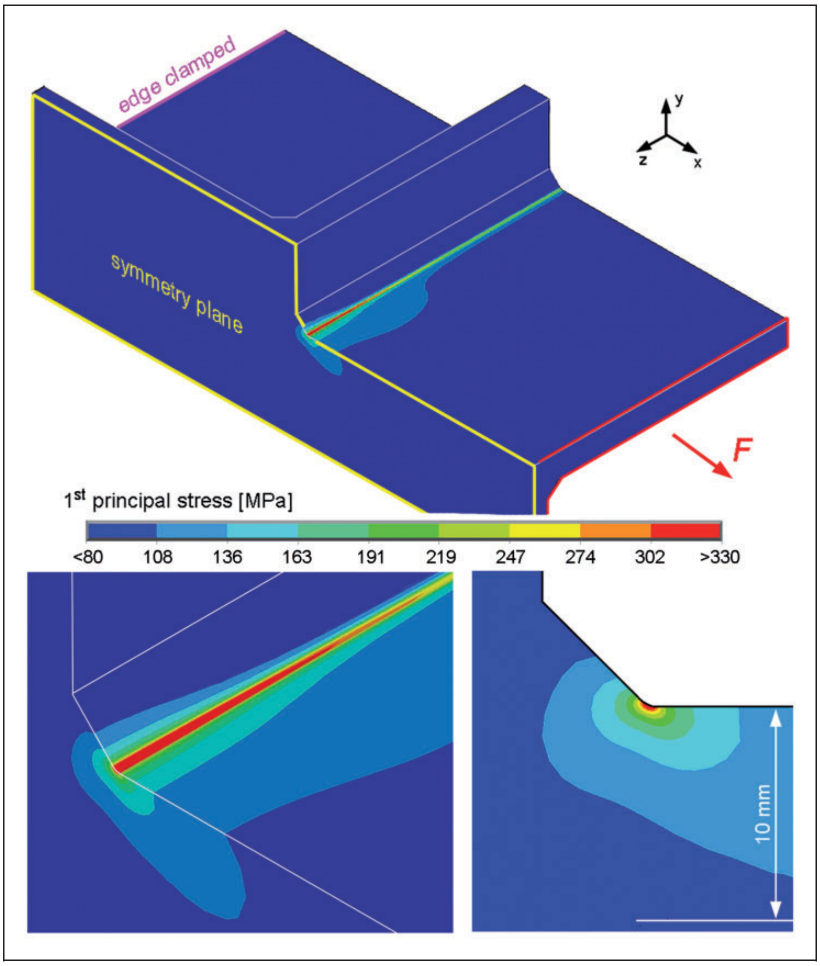

Figure 5. FE model of a complex welded detail.

during crack initiation depends on the ductility of the material. In ductile materials such as structural steels, the fatigue damage is caused by shear stresses in all planes across the material, whereas a critical plane has to be considered in semi-ductile materials, e.g. wrought aluminium and in cast steels, determined by a combination with shear stress.[27] In low-ductile materials, e.g. cast iron, the maximum normal stress determines the failure.

During the crack propagation phase, on the other hand, the first principal stress σ_1 governs the fatigue behaviour. Therefore, this stress component is recommended for the fatigue assessment in several codes and guidelines, e.g. for the nominal, structural hot-spot and effective notch stress approaches.[5,11] A robust alternative for multiaxial stress states, which could also be used when the third stress component σ_{II} is acting, is offered by an interaction curve defining the limits between safe and unsafe for the stress components acting individually (on the axes) and together (by the interaction curve). The Gough–Pollard relationship has been found to be well-suited,[27] i.e. an ellipsis based on a quadratic interaction curve, see the example in Figure 7. The horizontal and vertical axes show the fatigue strengths found for the stress components $\sigma_\perp$ and τ_{II}, respectively.

The assessment becomes even more complex if the stress components are acting with a phase angle δ, e.g. 90° (out-of-phase). Here, the fatigue assessment using the first principal stress is no more appropriate as this stress changes its direction during the load cycle. Sonsino[27] proposed different calculation models to consider the material ductility, i.e. based on the most critical plane for combined normal and shear stresses in case of semi-ductile materials and an integral value of shear stresses over all planes for ductile materials, the latter resulting in an equivalent effective stress. In practical applications, the effects of out-of-phase loading can be assessed by an interaction curve; however, for ductile materials this is reduced by a multiaxial damage parameter $D_{MA} = 0.5$ which shows good agreement with tests as illustrated by Figure 7.

Challenging is still the consideration of variable amplitude loading in connection with multiaxial loading where the stress components are acting in-phase or out-of-phase. Solutions in the literatures[5,27] aim at an assessment using a damage-equivalent stress range. Another procedure has been proposed based on the Critical Distance Theory and a modified Wöhler S–N curve method,[28] using the critical plane with the maximum variance of shear stress,[29] which worked well for a large number of fatigue tests.

Welding-induced distortions

Angular and axial misalignment (Figure 8) in particular may be the reason for large secondary bending stresses at welded joints being subjected to normal stresses perpendicular to the weld line. These secondary bending stresses can be computed by the finite element method or by appropriate formulae for 2D cases, as summarized among others by Niemi et al.[7]

Their effect is included to a certain extent in the fatigue classes of the nominal stress approach, e.g. axial misalignment of butt joints up to 10% of the plate thickness.[5] In all other approaches, the magnification needs principally to be considered in the stress, at least for welded joints showing rather large misalignment effects such as butt joints, cruciform joints and transverse attachments. Stress magnification factors have been proposed for cases where nothing else is specified.

Misalignment effects can be rather large in thin-plated structures. Figure 9 shows the results of fatigue tests for conventionally welded butt joints with 3–8 mm plate thickness and varying axial and angular

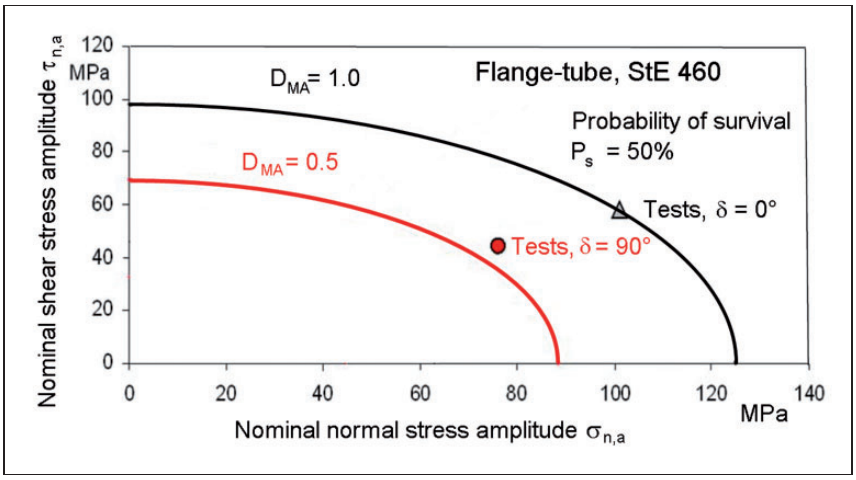

Figure 7. Interaction curve for the fatigue strength of a welded steel component subjected to 10^6 normal and shear stress amplitudes acting in-phase ($\delta = 0^\circ$) and out-of-phase ($\delta = 90^\circ$), after Sonsino.[27]

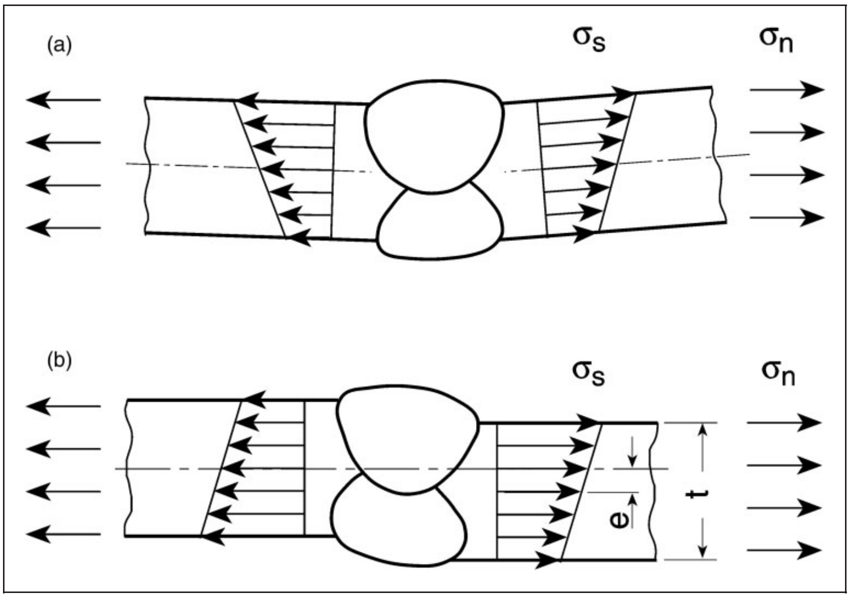

Figure 8. Butt welds with angular and axial misalignment subjected to nominal stress σ_n and increased structural stress σ_s due to secondary bending.

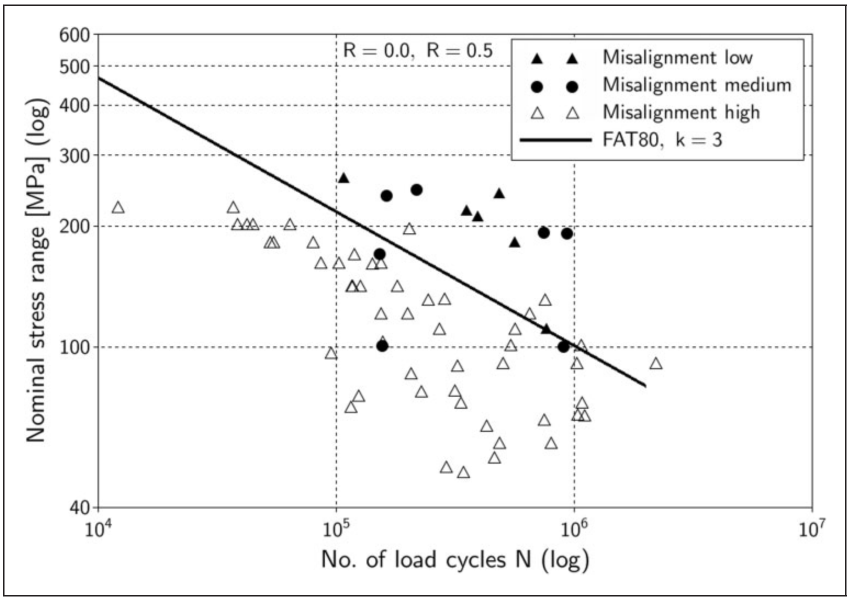

Figure 9. Fatigue test results for 3–8 mm thick butt joints based on nominal stress range.

misalignment.[30] The detrimental effect of the secondary bending stresses is obvious. The fatigue class FAT80, which includes the effect of 10% axial misalignment,[5] is not met by many specimens due to higher misalignments. Figure 10 shows the same results based on the structural hot-spot stress, which includes secondary bending effects having been calculated from the actual misalignments. Now, all results show relatively small scatter and are above the relevant design S–N curve FAT100. It should be noted here that the shape of pre-deformations might affect the stresses particularly in thin-plated test specimens.[31]

The limits for misalignment given in quality standards, e.g. 10% of plate thickness for axial misalignment in butt joints according to quality level B of ISO 5817,[32] create a big problem for thin-plated structures as these cannot be met, e.g., for the erection joints of large structures such as ships. Indeed, the situation is much more complex than the 2D situation occurring in small-scale fatigue tests and calculation formulae mentioned. This is illustrated in the following by a stiffened panel containing a block joint in ships subjected to axial loads.

The 3.2 m wide and 1.6 m long test panel was fabricated by a shipyard as part of a research project,[33]

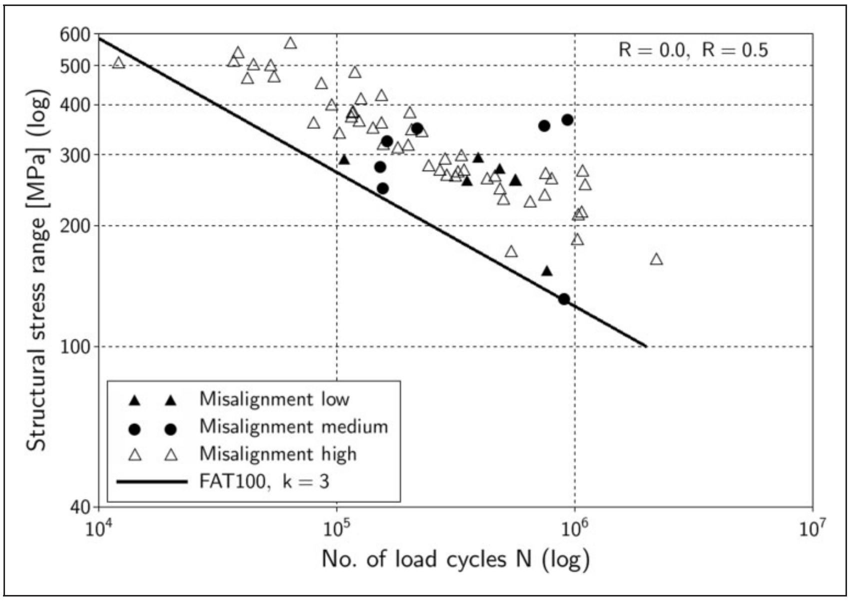

Figure 10. Fatigue test results for 3–8 mm thick butt joints based on structural hot-spot stress range.

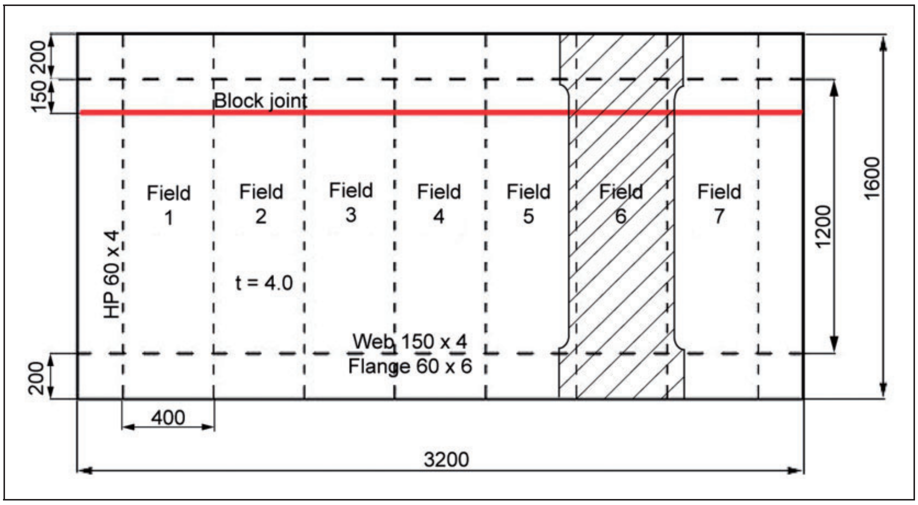

Figure 11. Stiffened panel for investigation of welding-induced deformations.

see Figure 11. The 4 mm thick plate was stiffened by eight longitudinal stiffeners. Two transverse T-shaped beams were arranged close to the ends where also the block joint was arranged. Axial misalignments of up to 2.5 mm and angular misalignments of up to 6° were recorded. No plate fairing was applied to reduce the angular distortion which would be done in practice. Finally, smaller fatigue test models containing only one plate field were cut out as indicated in Figure 11 for plate field 6.

The unevenly distributed misalignment and pre-deformation of the whole panel cause a complex secondary bending stress state if the panel is subjected to axial loading. This can only be calculated by the finite element method, considering the measured pre-deformations. Figure 12 shows the load-induced deformations and the surface stresses in longitudinal (stiffener) direction for compressive nominal stress of −100 MPa acting in the same direction.

The load-induced deformations are magnified in the plot. Figure 12(a) shows the axial (membrane) stress which is reduced in the plate fields due to misalignments, whereas the bending stress in Figure 12(b) reveals increased stresses in particular at the block joint. The sum of axial and bending stress, i.e. the structural stress, has its maximum within the plate field at the block joint. Fatigue tests with the smaller test panels have shown that the structural stress agrees well between measurement and calculation and that it is well-suited to the fatigue assessment of the block joint.[33]

This example illustrates the problems related to the appropriate consideration of misalignments in real thin-plated structures. A practical procedure and

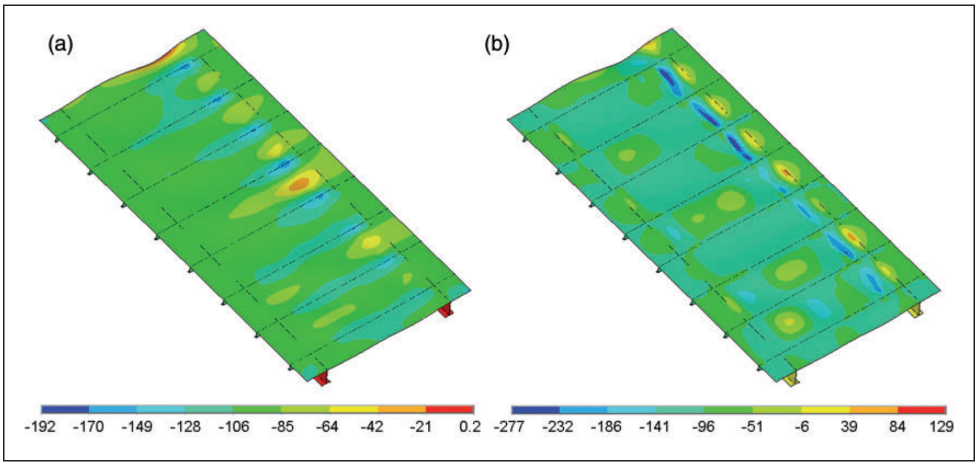

Figure 12. Deformation and longitudinal stresses [MPa] in a pre-deformed stiffened panel: (a) axial and (b) bending stress components (highest compressive stress is blue).

adequate limits in quality standards are not yet available, but urgently needed.

Residual stresses

Another challenge in future will be the realistic consideration of residual stresses in fatigue analyses. It is well known that the welding process in particular may create high residual stresses up to the yield stress, and that high tensile residual stresses at fatigue-critical locations such as the weld toe reduce fatigue strength.

Unfavourable residual stresses up to the yield stress are assumed during fatigue assessment of welded joints if nothing else is known. These residual stresses may act locally, e.g. in the direct vicinity of the weld toe, or in a wider range, which is not further distinguished from each other. Residual stresses in a wider range are caused by the erection process of the structure, e.g. by restraining effects of structural components.

Welding-induced residual stresses can today be determined experimentally or by numerical welding simulation, where the temperature field during welding is computed, serving as input for the subsequent mechanical simulation of the structural response.[34,35] Some aspects of computing the residual stresses and their effect on fatigue are illustrated by the following examples.

The classic example of a welded detail showing high welding-induced residual stresses even in small-scale specimens is the longitudinal stiffener where fatigue cracks usually occur at the toe of the weld around the stiffener end. Several experimental and numerical investigations showed high residual stresses at this location (Figure 13) which were considered responsible for fatigue cracks appearing even if the cyclic stresses were fully compressive.[36] The longitudinal shrinkage of the weld between stiffener and plate is mainly responsible for the tensile residual stresses.

It is interesting to note that recent investigations with refined measurements and corresponding finite element analyses have shown that tensile residual stresses created in front of the stiffener end exhibit a drop towards smaller values close to the weld toe, see Figure 14. The main reason has been found in complex phase transformation processes in this area.[38] Effects on fatigue behaviour still need to be clarified.

Another interesting observation concerns the residual stress at the upper toe of the weld around the stiffener end, where compressive residual stresses have been found in measurements and computations.[39] Figure 15 illustrates the assumed reason by showing the forces between the weld and the stiffener and also the plate, created by the shrinkage of the weld. The horizontal forces would cause in-plane bending of the stiffener, but for compatibility reasons, vertical compressive forces are acting at the end of the stiffener and tensile forces in the middle. This results in compressive residual stresses in the upper weld toe as well as at the adjacent weld root.

The effect on fatigue behaviour is that cyclic loading in the vertical direction is less critical than horizontal loading. This has been verified by special specimens loaded in the vertical direction. Even if an additional stress concentration was acting at the stiffener's end, the fatigue crack occurred in the middle of the connection.[40] Similar observations were made in a typical ship structural detail, where the highest structural hot-spot stresses were found at the upper weld toe, while fatigue cracks which initiated at the lower weld toe were in the less-stressed region.[41]

The computation of welding-induced residual stresses in larger structures is still a problem today because the great numerical effort for the highly nonlinear analysis limits the mesh size. Several simplifications are necessary to perform a welding simulation for larger structures. This is illustrated in the following by the computation of welding-induced residual stresses in a block joint of a ship structure resulting from structural restraints during welding.[42]

The effect of restraints has been investigated by 250 mm wide and 15 mm thick welding specimens

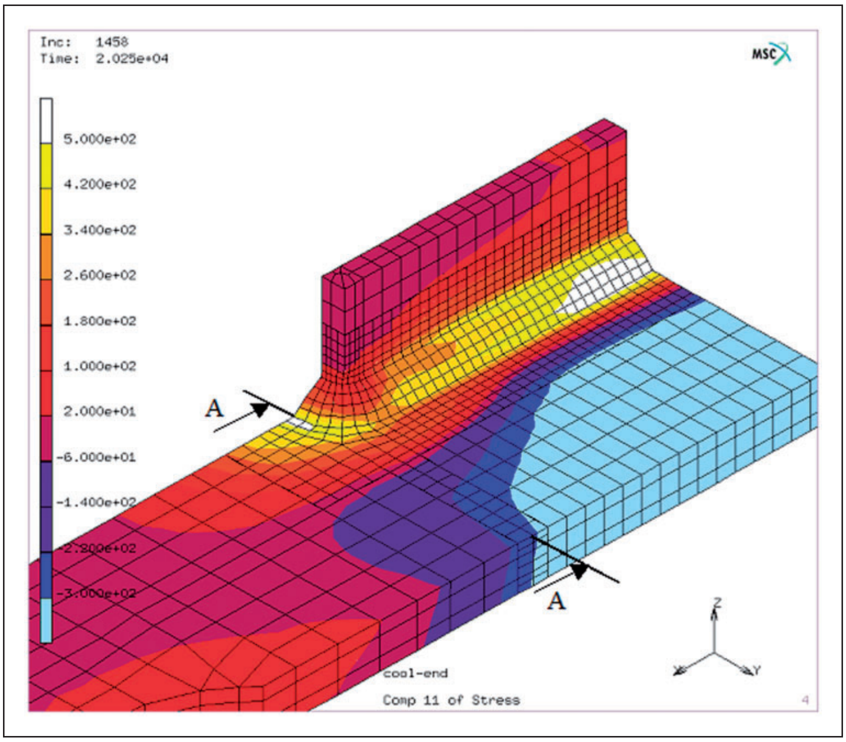

Figure 13. Computed residual stresses in longitudinal direction in a plate with a longitudinal stiffener (quarter model).

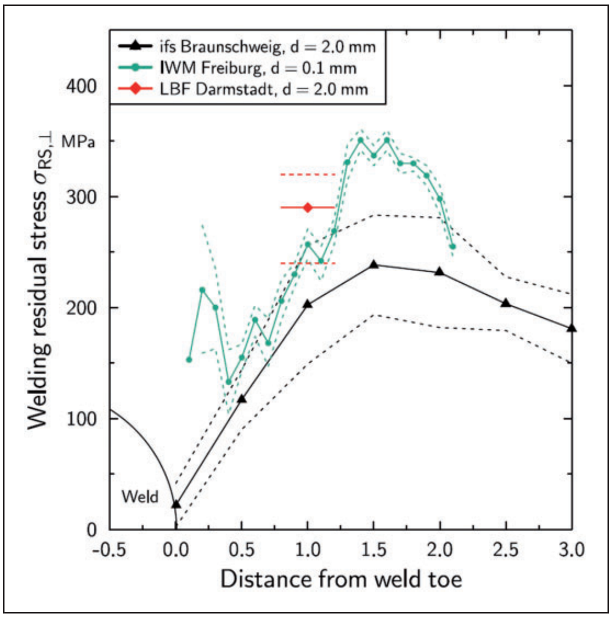

Figure 14. Measured welding-induced residual stresses with confidence intervals in front of a longitudinal stiffener.[37]

containing a butt weld, see Figure 16. The restraint was realized in tests as well as simulations by springs representing a typical situation found at the block joint of a ship before welding. After welding, remaining reaction forces of about 700 kN were found in the tests and also computed during the welding simulation, resulting in a residual stress of 187 MPa on average.[43]

As already mentioned, several simplifications were necessary to simulate the welding of the 22 m long butt joint in the outer shell of the shipbuilding block (Figure 17a). The four original welding passes of the butt weld had to be combined into one pass and a relatively coarse finite element mesh with four elements in thickness direction had to be chosen. A correspondingly coarse model was used for the 250 mm wide welding specimen to calibrate parameters such as the amount and location of the heat input with respect to the reaction forces and distortions remaining after welding.

These simplifications finally allowed the global residual deformations and stresses to be computed. Global means that the residual deformations and stresses in the vicinity of the butt joint are captured, but not in the weld itself due to the relatively coarse finite element mesh.

Figure 17(b) shows the computed distribution of longitudinal residual stresses in the structure. Relatively high stresses occur at points with high restraint due to longitudinal structural components inside the shell, i.e. deck, inner bottom and to a certain extent also longitudinal stiffeners which were already connected before welding the outer shell. The global residual stresses reach values of more than 200 MPa at these points, whereas the stress level is low between the stiffeners and remote from the joint.

The distribution of residual stresses is one significant influence parameter to be considered during the fatigue assessment. But also their redistribution during external cyclic loading is important.

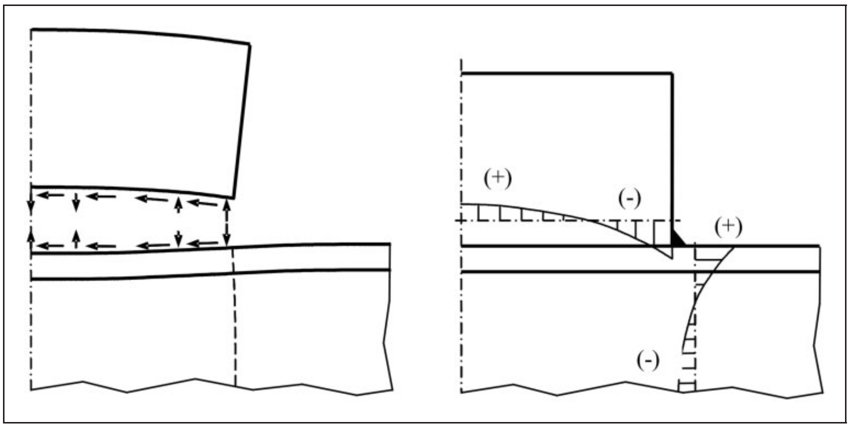

Figure 15. Assumed formation of residual stresses due to longitudinal weld shrinkage.

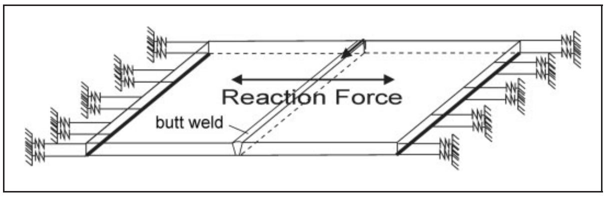

Figure 16. Restrained welding specimen.

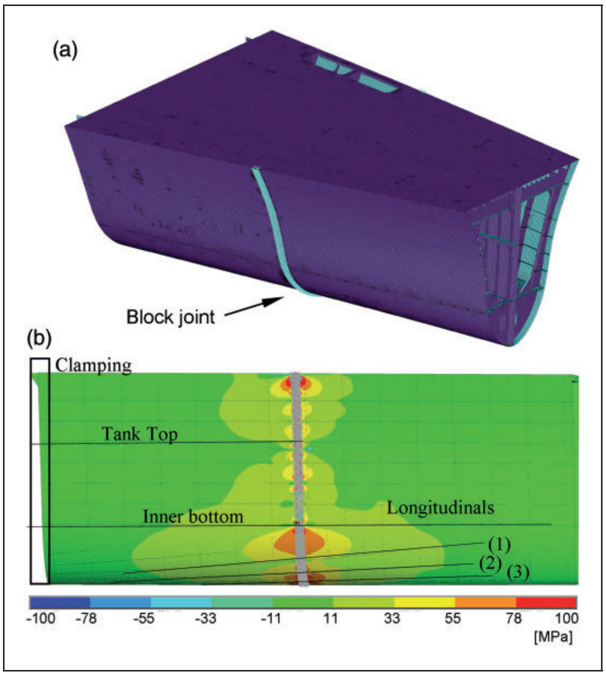

Figure 17. Investigated shipbuilding blocks (a) and global residual stresses in longitudinal direction from simulation of the butt welding in the outer shell (side view b).

This depends, inter alia, on the stress concentration at the location considered.[44] The interaction between the residual stress field and the stress field due to external loads determines the shake-down effect, which still needs more exploration regarding welded structures.

Improvement of fatigue strength

Measures to improve fatigue strength are of great practical interest. Much research and development is currently spent on this aspect.

Reduction of stress concentration

The classic measure is the reduction of the stress concentration so that the peak stress causing local cyclic plastification is decreased. This is possible by improving the weld shape, for example by the arrangement of weld layers to obtain a smoother transition between weld bead and base metal, or else by post-weld treatment which is discussed further below. More potential for improvement is frequently offered by the overall geometrical configuration, i.e. the structural arrangement which determines the force flow. The geometrical configuration including local thicknesses may considerably affect the structural stress concentration. A simple example is an attachment on an axially loaded plate. The structural stress concentration is much smaller if the attachment is oriented transverse to the axial load (transverse stiffener) than if it is in line with it (longitudinal stiffener). Other examples are tubular joints where rather high structural stress concentrations occur, mainly caused by local ovalization of the tubes and bending of the tube walls.

This is a typical case where the effects on the structural stress concentration of geometrical parameters such as the ratio between tube diameters and the relative thicknesses should be investigated in order to improve fatigue strength. Many investigations have been conducted on associated stress concentration factors, e.g. literatures[45,46] or are still ongoing. It is interesting to note that the development of mesh generation tools using CAD data supports the direct computation of local stresses with models, as shown in Figure 18, rather than the application of published stress concentration factors.

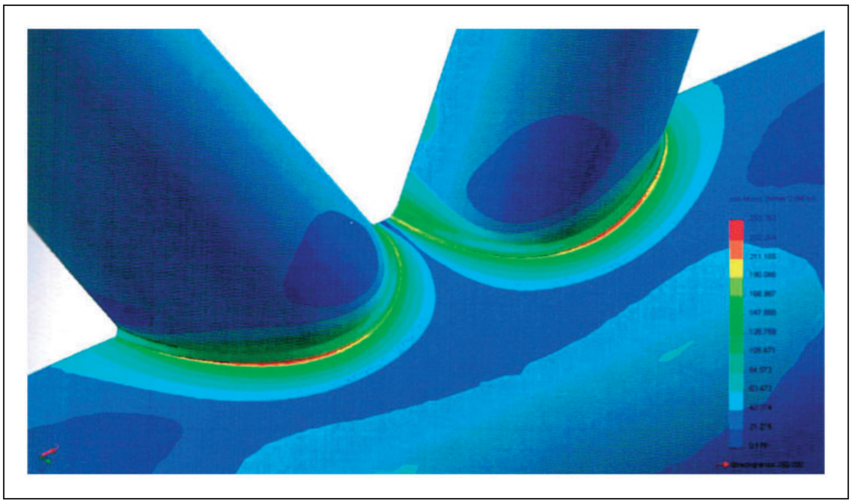

Figure 18. Generated finite element model of a tubular K-node showing von Mises stresses on the tube surfaces.

Improvement of the weld quality

High fatigue strength requires high quality of fabrication, avoiding weld defects and reducing imperfections. The effects of welding-induced distortions have already been highlighted earlier in the text. But also other quality criteria such as weld profile, undercuts, lack of fusion, etc. may have a large influence on fatigue strength.

Weld quality is usually classified according to ISO 5817[32] into quality classes B, C and D. However, there is partly no clear link between the quality classes and the fatigue strength. At present, the correlation of certain quality criteria with fatigue classes is elaborated, helping to rationally consider quality levels in the design of fatigue-resistant structures.[47,48] This should also allow to assess high-quality welds and use their benefits with respect to fatigue.

The local approaches outlined earlier are well suited to consider the effect of quality criteria, in particular the effective notch stress and the crack propagation approach. Various investigations have already been performed in this respect.[49–51]

Post-weld treatment

Another possibility for fatigue strength improvement is post-weld treatment by the following methods:

1. Grinding (of weld toe or whole weld profile)
2. Re-melting of the weld toe (e.g. by TIG-dressing)
3. Hammer and needle peening
4. High-frequency mechanical impact peening
5. Shot-peening.

The objectives of the methods are different. While the first two decrease the stress concentration by improving the weld profile, the others induce compressive residual stresses in the weld toe which increase the fatigue life in comparison to welds with tensile residual stresses. But also the weld shape might be improved by the latter.

The increase in fatigue strength can be significant, in particular in the high-cycle fatigue regime so that the S–N curve becomes flatter. For practical application, bonus factors on the fatigue class in the nominal and structural hot-spot stress approaches have been proposed together with quality requirements.[5,52] It has been found that the improvement of high-strength steels can be rather large so that new design S–N curves (fatigue classes FAT 160 and FAT 180) with shallower slope in comparison with those specified in the recommendations mentioned earlier have been proposed, see Figure 19.

Peening is not only beneficial for structures subject to constant-amplitude loading, but also to variable-amplitude loading as has been shown by Yildirim and Marquis.[54] The increase in fatigue strength might be smaller because extreme loads, in particular those creating compressive stresses, can relax the beneficial compressive residual stresses. The relaxation and redistribution of residual stresses during variable amplitude loading still needs more clarification, but also the behaviour and possible damage of the material being subjected to high impact forces.

Material effects

It is commonly understood that the tensile strength within one material type has a negligible effect on the fatigue strength in the presence of high notch effects. For instance, high-tensile steels exhibit almost the same fatigue strength as mild steel at welded joints. This is related to the notch-sensitivity of high-strength steels. Contributory factors are detrimental residual stresses which increase with steel strength and show less relaxation.

So as also to utilize the high strength with cyclic loads, measures such as high quality and post-weld treatment described earlier may be particularly

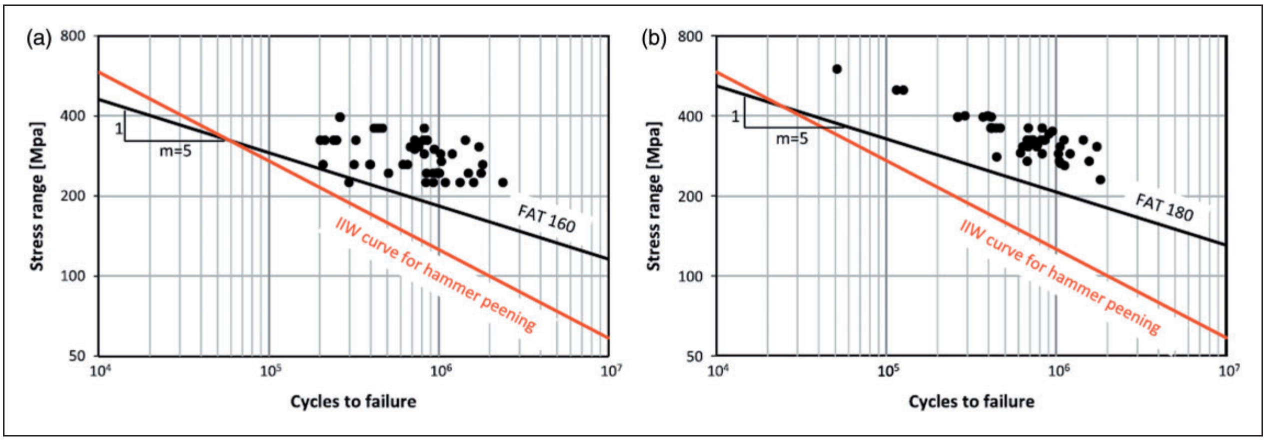

Figure 19. Fatigue test data of butt joints after high-frequency mechanical impact treatment: (a) steels with yield strength up to 550 MPa and (b) above 550 MPa.[53]

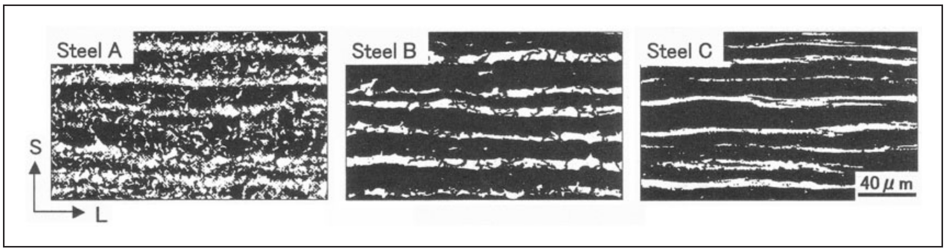

Figure 20. Microstructure of various FMDP steels (black etching phase: ferrite; white etching phase: martensite).[56]

useful for such materials – as may others aiming to reduce the notch severity.

Some developments in the materials field are quite interesting in this context. One concerns low transformation temperature (LTT) weld material, usually with a relatively high nickel content, which is used for the final layer of a weld. Owing to the late martensitic phase transformation during the cooling process, this layer creates compressive residual stresses. Fatigue tests show a significant increase in fatigue strength under constant amplitude loading and less increase under variable amplitude loading.[55]

Another interesting development is fatigue crack arrest (FCA) steels showing an increased fatigue initiation resistance at the heat-affected zone of welds and a decreased crack growth rate in the base material when a fatigue crack passes from a soft phase (ferrite) to a hard phase (bainite) in these new dual phase steels. Another development concerns Ferrite/Martensite Dual-Phase (FMDP) steels, where the martensitic phase is introduced as barrier for fatigue crack propagation. Figure 20 shows FMDP steels with various martensitic morphologies and distributions, where steel C with flattened and banded martensitic microstructure has revealed a significantly improved resistance against crack growth.[56] Recent investigations are summarized by the Committee on Fatigue and Fracture of ISSC,[57,58] showing an increase in fatigue strength by a factor of 1.3.

Concluding remarks

The intention of the paper is to give an overview of recent developments and future challenges in the fatigue strength assessment of welded structures. The approaches are based on different stress parameters, most of them on a certain stress at a specific location. This creates a problem because the fatigue life consists of the crack initiation and the crack propagation phases. A clear distinction between the two phases, which are governed by different laws, is missing in most approaches.

Other aspects which play a major part in the fatigue assessment are treated differently in the fatigue assessment approaches. Those regarded as most important by the author have been reviewed and discussed in the paper, such as the plate thickness and stress gradient effect, multiaxial stress states, misalignment effects and residual stresses. Open questions have to be clarified to arrive at consistent and practical procedures which will be a challenging task for the future.

The main objective of a fatigue assessment should be the improvement and optimization of a welded structure with respect to fatigue. The paper finally reviews some recent developments. Apart from the classic measure, i.e. the reduction of the stress concentration and increase of weld quality, possible methods for post-weld treatment as well as material developments such as LTT weld metals and FCA steels are briefly addressed.

Conflict of interest

None declared.

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