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Review Article

Review of Fatigue Assessment Methods for Welded Steel Structures

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Due to high stress concentrations, welded joints represent the most common locations of fatigue crack initiation in steel structures that are prone to fatigue. Welding affects material properties by the process of heating, cooling, and combining basic and additional material. Since welding is the primary process of joining elements in steel structures, it is obvious that fatigue assessment during the design and maintenance process becomes inevitable. There are many fatigue assessment methods of welded joints, but their precision remains questionable. This paper represents a review of the most common fatigue assessment methods used for welded steel joints. As a result of this review, areas that require additional research are highlighted.

1. Introduction

During their lifetime, many steel structures such as road and railway bridges, oil and gas exploitation platforms (offshore platforms), windmills, and so on are subjected to a high number of repetitive cyclic stresses. Over time, those stresses can cause damage, such as cracks, at critical locations. This phenomenon is called "fatigue." It can be defined as a progressive localised process in which damage continuously accumulates in a structure or structural element due to the effect of cyclic loading, which has much less intensity than the static resistance of an observed structure or structural detail. A study by Oehme [1] shows how fatigue takes third place as the cause of failure of fatigue prone steel structures.

Fatigue cracks are usually initiated at locations of a sudden change in the geometry or notch locations [2], where there is a localised increase of stress (stress concentration). The smaller the notch is, the bigger the stress concentration is, and in the end, fatigue life is shorter. The most common locations in steel structures prone to fatigue where fractures are made are welded joints as these are locations of high stress concentrations. Obviously, fatigue assessment becomes inevitable during design and maintenance due to the fact that welding is a primary process of connecting elements in structures that are previously mentioned. Furthermore, in the last few years, high-strength steels are being used more frequently for steel structures due to the decrease in self weight of the structure, and although its use has a positive effect, fatigue becomes a leading ultimate limit state.

This paper presents a review of peculiarities of fatigue-critical welded joints and the most important methods for design and fatigue life assessment of welded steel structures that are prone to fatigue. Areas that require additional research are highlighted as a result of review.

2. Fatigue of Welded Joints

2.1. Fatigue in General. The term "fatigue" was first mentioned in the 19th century to describe the failure of a structure or structural element subjected to cyclic loading. Research of fatigue was first carried out by August Wöhler who investigated the failure of train axles. He detected that structural loading that is well below its static resistance does not cause any damage. However, in the case of repeating the same loading over a prolonged period of time, it can cause failure of the structure or structural element. In the 19th century, fatigue was a mysterious phenomenon because fatigue damage could not be seen, and failure occurred without any warning. In the 20th century, it became known that cyclic (repeated) structural loading initiates the fatigue mechanism and, respectively, crack initiation and propagation. Since this fatigue phenomenon became recognised, much research has been conducted, and significant progress in developing fatigue assessment methods, understanding the mechanism of fatigue of structures and materials, and the designing of fatigue resistant details has been made. However, this phenomenon still requires further investigation [3].

A chronology of fatigue development from 1837 to 1994 is given by Schütz [4], as well as Mann [5] in his collection of 21,075 literature sources in his four books that are concerned with the fatigue problem of materials and structures from 1838 to 1990. A review of fatigue assessment methods from 2002 and the factors that affect fatigue behaviour of structures and materials was made by Cui [6].

An understanding of the fatigue mechanism is a prerequisite when considering different factors that affect fatigue life and choosing appropriate assessment methods. The fatigue life of a structure or structural element is measured from the crack initiation and crack propagation phase. Cracks made by cyclic loading usually occur at the surface of a structural element where fatigue damage comes in the form of microscopic cracks in crystallographic slip planes. This phase is called the "Crack Initiation Phase." Furthermore, cracks propagate from localised plastic strain to macroscopic size in a direction perpendicular to the loading direction, which presents the crack propagation phase [3]. The crack initiation phase also includes crack growth on a microscopic scale, but it still cannot be seen by the naked eye. It is very hard to determine the point between the phases of crack initiation and propagation. In the crack initiation phase, fatigue is a surface phenomenon and depends on material surface characteristics and environmental conditions, while crack propagation depends on the characteristics of the material the crack is spreading through. These two phases were first recognized by Forsyth [7], which is one of the biggest accomplishments in research of fatigue of metals in the 20th century. The mechanism of fatigue in different materials and structures is widely described by Schijve [3] in his book.

Modern fatigue theories separately analysed every phase of the fatigue process. Crack initiation theories are based on the assumption that fatigue cracks appear with local stress or strain concentrations on the surface of a structural element because of different geometrical shapes like holes, notches, discontinuity, and so on. Crack propagation and final fracture (failure) is analysed by fracture mechanics which considers the crack propagation rate in relation to the stress state in crack tip.

2.2. Fatigue Properties of Welded Joints. Steel structures contain a large number of geometrically complex welded details. Welding affects the material properties during the process of heating, cooling, and by connecting base and additional material. This results with inhomogeneity within welds. Welds always contain certain imperfections such as notches, pores, voids, insufficient penetration, and incomplete connection of base and additional material. Impacts of imperfections on fatigue life of welded joints are reviewed by Hobbacher [8]. Maddox worked with the assessment of fatigue life of welds with imperfections [9] and concluded that a fracture mechanics approach is most suitable for those kinds of assessments. Welding represents a sudden change in the geometry of connection, which cause high stress concentrations, as shown in Figure 1.

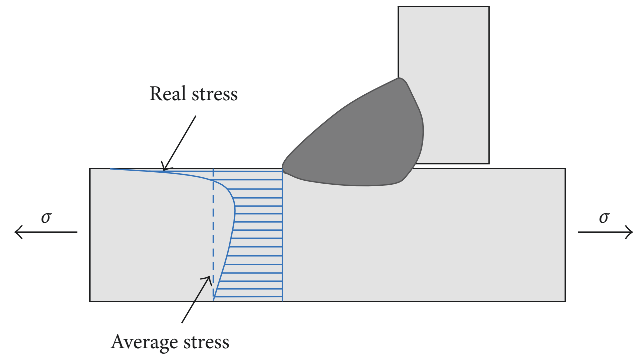


FIGURE 1: Stress concentration in weld location.

Welding is being conducted by melting base and additional material using a concentrated source of heat. The occurrence of residual stresses in a heat-affected zone and distortions of elements due to deformations caused by heating is a result of rapid cooling after welding. Local stress concentrations that are being added to cyclic stresses from external loading are caused by residual stresses on the weld root or toe and in certain cases fatigue life is reduced [10, 11]. Fatigue strength of welded joints is affected by plate thickness of elements that are being connected. Based on experimental results and analysis, Gurney [12] confirmed that an increase in plate thickness results in decreased fatigue strength of welded joints. Residual stresses caused by the welding process are being increased by an increase in plate thickness. In standards, the negative effect of element thickness is considered by the fatigue resistance reduction factor, for example, in European standards EN 1993-1-9, with reduction factor for fatigue stress to account for size effects [13]. It is important to mention that the quality of the base material has a negligible effect on the fatigue strength of welded joints in comparison with the other factors. However, as mentioned in the introduction, use of high-strength steels results in self weight decrease, and there is a negative effect on the loading side which becomes dominant in that case. Consequently, fatigue becomes the leading ultimate limit state in structural design.

As previously mentioned, the two phases in the fatigue process are the crack initiation phase and the propagation phase. For nonwelded details that are prone to fatigue, most of the fatigue life is related to the crack initiation phase, while the crack propagation phase is negligible. Welded joints contain already mentioned imperfections in locations where cracks can begin to propagate with the first loading cycle. Therefore, the crack initiation phase is negligible in welded joints and the fatigue limit of welded details depends on the initial size of the imperfection inside the weld [14]. Already mentioned weld peculiarities show that, in welded details that are prone to fatigue, cracks will always initiate in weld locations rather than in base material. Cracks can initiate in weld root or toe. In case of butt welds with full penetration, fatigue cracks initiate on weld toe and propagate through base material, while in case of incomplete penetration, cracks initiate in weld root and propagate through its thickness [15].

In order to improve welded steel details, it is possible to use postweld treatment methods. Most common are Burr grinding (BG), TIG dressing (TIG), hammer peening, needle peening, and HFMI (High Frequency Mechanical Impact) in order to remove imperfections caused by welding [16, 17]. This provides a smoother transition between weld toe and base material which reduce the stress concentrations that are shown in Figure 1. Moreover, residual stresses are being removed by some of these methods in a way that plastic material deformations (strains) in weld toe area introduce positive compression stresses. The consequence of postweld treatments is an increase in the possible number of cyclic loadings that cause crack initiation. Based on the longer crack initiation phase, the quality of steel now has a role in the increase of fatigue strength [18]. In that way, it is possible to gain welded steel details that are 30%–60% more resistant to fatigue [16]. It is important to mention that weld toe treatment is insignificant if the crack is initiated in the weld root.

Fatigue damage already occurs with relatively small stresses, far from material yielding. That is why within different methods of fatigue assessment, stress assessment based on theory of elasticity is justified. A key role in fatigue resistance assessment of welded components is played by the precise assessment of the loading and geometry effect. That is almost impossible to achieve without use of advanced computer tools based on a finite element method. Examples of calculations of relevant loading within assessment of fatigue life can be found in [15, 19–21]. Development of finite element method results in the occurrence of more advanced methods of fatigue resistance assessment, such as the Hot Spot stress approach, mesh-insensitive structural stress method and master S-N curve approach, effective notch stress or strain approach, and crack propagation analysis with linear elastic fracture mechanics.

An issue of fatigue of welded joints additionally complicates if cyclic stresses in welded details acts in more directions. This phenomenon is called multiaxial fatigue, which is considerably unfavourable for welded joints in relation to uniaxial fatigue [22]. There are many suggested theories in literature for multiaxial fatigue life assessment of welded joints [23–25]. Analysis of 233 experimental results of welded joints that are prone to fatigue is shown in Bäckströms and Marquises paper [26]. Results are analysed by three different methods based on Hot Spot stress which are maximal principal stress amplitude, maximal shear stress amplitude, and critical plane model approach. It is concluded that a critical plane model is best to describe S-N curve. However, it is necessary to additionally develop this method in future to consider residual stresses.

Multiaxial fatigue loading can be proportional, when the direction of principal stresses is constant, and disproportional, when directions of stresses are variable through time. In case of proportional loading, EN 1993-1-9 [13] suggest usage of maximum principal loading as a damage parameter. Disproportional loading causes much greater damage in relation to proportional. In that case, multiaxial fatigue is being disassembled in two components: normal and shear stresses. Using the Miner rule, damages made from each component are being assessed separately and combined by interaction equations. Interaction equations are most suitable in cases of normal and shear stresses acting at the same location and in the same direction. There are experiments that show fatigue life of elements prone to disproportional loading as similar as the fatigue life of elements prone to uniaxial loading [27]. Based on 233 experimental results, the interaction equations that are given in recommendations of European standards EN 1993-1-9 [13], Finnish standards SFS 2378 [28], and IIW recommendations [25] are being compared by Bäckström and Marquis. It is shown that all three expressions have a certain degree of conservatism [29]. The best correlation for proportional and disproportional loadings is given with interaction equations from IIW recommendations which limit a cumulative sum of damage for disproportional loading on 0.5.

Conservatism of interaction equations in EN 1993-1-9 [13] and IIW recommendations [25] is confirmed by Lotsberg in his paper [30]. Connections where the crack is initiated in the weld root due to multiaxial loading have been examined by Bokesjö et al. [31]. Only tests with proportional stresses have been conducted. Results have been analysed by interaction equations from three standards [13, 25, 32]. Multiaxial fatigue assessment models are shown to be suitable for fatigue life when the crack is initiated in the weld root.

Nowadays, advantages of multiaxial fatigue assessment by spectral analysis of stress are more recognized than classical stress time history. Time histories that are used for assessments often show large statistical variations, and every next stress recorded in time is different. Moreover, simulation of longer time history multiaxial stress amplitude can take time. These problems can be solved by the spectral approach and review of multiaxial fatigue assessment methods with the spectral approach given in [33]. It is necessary to conduct additional research to confirm suitability of numerical models in real behaviour. Over the last four decades, much research has been conducted, which has significantly improved the understanding of multiaxial fatigue [34]. However, it is evident that further significant exploration is required in the accurate assessment of time history of elements prone to multiaxial fatigue, with a focus on the development of interaction equations to reduce a degree of conservatism and to enable a simple engineering method for practical assessments. Moreover, it is necessary to investigate the effect of components of normal stress on the damaging process of shear stresses, which would give a better insight in interaction behaviour [29].

3. Fatigue Life Assessment Methods for Welded Joints in General

Fatigue life assessment of welded joints is a very complex and challenging procedure. Welded joints in large steel structures can be subjected to various loading effects, depending on their geometric configuration and degree of complexity. Fatigue assessments explicitly or implicitly include comparison of loading, stresses or strains with their critical values which cause damages, strains, initial crack, or failure. Classical methods for stress state assessment, as well as databases with results of experimental research details, were very limited. Details of designing and modelling in practice were based on experience gained by a trial and error method [35, 36].

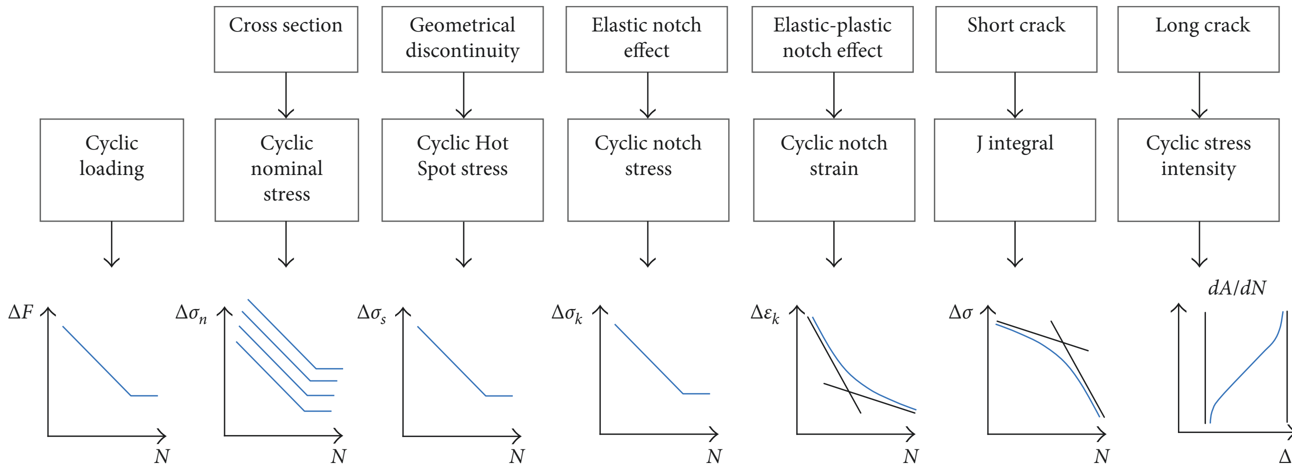


Figure 2: Global and local approaches for fatigue strength and fatigue life assessment [10].

Today there are many approaches for fatigue life assessment, depending on the way local stress concentration is taken into consideration. Global methods result directly from internal forces and moments in critical cross section under the assumption of linear stress distribution. Effects of local concentrations on the loading side are neglected. Local fatigue assessments result from local parameters (local stresses or deformations), taking into consideration effects of local geometry at the observed location. Most used variants of local and global approaches are shown with Figure 2 [10]. Every variant is characterised by particular parameters of loading, stress, or deformation on action side and, in diagrams, on the resistance side.

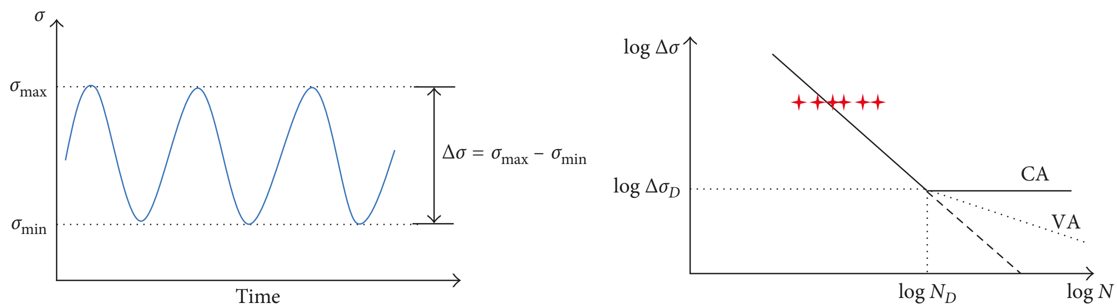
Guidelines and standards for fatigue assessment are mostly based on a nominal stress approach, which is in fact a global concept. However, failure of structural elements due to fatigue is a localized process. Local parameters and geometry have the maximum effect on fatigue strength and fatigue life of structural elements. Comprehensive literature which contains local approaches for nonwelded and welded structures is collected by Radaj [37]. Most used methods based on stresses are nominal stress approach, Hot Spot stress approach, and effective notch stress approach [37, 38]. In the past decade, mesh-insensitive structural stress method and master S-N curve approach [39, 40] have also become widely accepted due to the availability of user-friendly commercial software such as Verity™ in FE-safe™ [41].

To conduct a precise fatigue assessment of welded steel structures, it is necessary to have equally accurate information about loading; even the smallest change in loading value could cause a big difference in the assessment results. Moreover, determination of loading by finite element method is idealization and does not include all the parameters that affect structural behaviour. The only way of getting the precise information about loading is trough field measurement, where real deformations can be measured and noted by different sensors attached to structural elements. In that way, the most precise foundation for fatigue assessment is being gained.

Long-term systems for monitoring structural conditions, the so-called Structural Health Monitoring Systems, are now more widely used and developed [42, 43]. They are intended for early detection of structural damage, for giving information about the state of structure in real time and for obtaining data for further research [44]. Advantages of these kinds of systems are recognized in many countries and implemented in big steel structures all over the world [42, 44–48]. For precise determination of damaged locations on structure, local nondestructive methods are being used, such as visual inspection, ultrasonic inspection, radiographic methods, magnetic particle inspection, and so on. [49, 50]. These methods are often expensive and take a lot of time, but are needed because of structural state assessment after damage [51]. The disadvantage of all these methods is that structural state history represents only a record in a certain time interval and does not have to represent a state in the future. Considering many uncertainties that appear during fatigue assessment procedure, a probabilistic approach represents a rational solution. Sources of uncertainties are mostly categorized as physical uncertainties, measuring uncertainties, statistical uncertainties because of limited number of measurements, and model uncertainties because of imperfections and idealizations. Developing the structural reliability (probabilistic) methods and fatigue damage accumulation method, it became possible during fatigue assessment to take all these uncertainties into consideration. In the late 80's, papers which suggest complete methodology for fatigue assessment with probabilistic methods were published [52]. During that time, these methods have been mostly used for offshore structures and later for fatigue assessments of joints inside steel bridges subjected to traffic loading [53, 54]. A comprehensive review of literature of existing reliability approaches for reassessment of road and railway bridges is available in paper Byers et al. [55].

The first step in the fatigue reliability analysis of structures is the formulation of a mathematical model that would ideally include more variables that affect fatigue behaviour. After that, probability and statistical method analysis are conducted [52].

In fatigue assessment, the two main approaches that are mostly used during the designing phase and the assessment of reliability level are the S-N approaches in combination with the Miner rule and fracture mechanics which is used in



(a)

(b)

Figure 3: Definitions of loadings and S-N curve welded details.

phases of state assessments and assessment of residual fatigue life of structure. In the first instance, the purpose of fatigue analysis is to determine fatigue life of structure or structural element with target reliability or determination of inspection intervals, while in other cases, the aim is to determinate inspection intervals or remaining time to repair.

4. S-N Curves-Based Approaches

4.1. In General. To successfully conduct an evaluation of the fatigue of steel structure, it is necessary to evaluate the fatigue life of every structural component. Detail resistance is represented by the corresponding S-N curve, which is obtained as a result of testing samples subjected to variable stresses of constant and variable amplitudes. It is determined as the relationship between variable stresses, S and the number of stress changes, N. In that way, data about the resistance of each detail with corresponding geometry, quality of performance, environmental influence, and the way of loading are obtained.

If curves are shown in logarithmic scale, lines are gained, Figure 3. Analytical equation for S-N curve is

$$\log \Delta\sigma = \log \Delta\sigma_D + \frac{1}{m} \log \frac{N_D}{N}, \tag{1}$$

where m is the inclination angle of S-N curve, $\Delta\sigma$ is the amplitude value that corresponds to number of stress changes N, and $\Delta\sigma_D$ is the amplitude value that corresponds to number of stress changes N_D.

It can be seen from Figure 3 that fatigue resistance decreases with an increase in the number of stress amplitudes N. The bilinear S-N curve has a certain inclination (usually $m = 3$) to the point that fits the constant amplitude fatigue limit (CA, Figure 3.). It is assumed that fatigue life of a certain detail subjected to constant stress amplitudes lower than this limit is infinite. Today, authors are very sceptical about this claim [56]. If the test is carried out long enough, each element will ultimately fail. This is particularly true in the case of structures which are subjected to a large number of stress cycles. According to Figure 3, it is necessary to modify constant amplitude fatigue limit assumption (CA) if a detail is subjected to stresses with variable amplitudes (VA). In case of variable amplitudes (Figure 3 dotted line), this fatigue limit has to be modified. For example, European standard [13] gives S-N curves with slope changed to $m = 5$ after CA with horizontal line after $N = 10^8$ (cut-off limit). IIW standards in the case of high-cycle fatigue adopt S-N curves with slope of $m = 22$ after CA without cut-off limit. If the constant amplitude fatigue limit is neglected and one line with a constant inclination to the horizontal is adopted, it would be a conservative approach, as indicated by the dashed line.

During fatigue assessment, characteristic details are classified into categories (FAT classes) in a way that one standardized curve represents more details. In standards, detail category represents details of stress range expressed as characteristic fatigue strength in MPa for number of stress cycles $N = 2 \times 10^6$.

As previously mentioned, S-N curves are based on experimental results obtained mostly under constant amplitudes, while in reality, details are subjected to stresses with variable amplitudes. Using a histogram, it is possible to show the variable stress spectrum where every block is defined by stress amplitude, $\Delta\sigma_i$ and the corresponding number of stress variations (Figure 4).

Figure 4 represents a histogram with six blocks of this kind. To convert stresses with variable amplitude (as can be found in reality) into constant amplitude stresses, it is assumed that every stress block causes certain related partial damage (n_i/N_i), during which stress order is neglected.

This procedure is called Palmgren–Miner Hypothesis of Linear damage accumulation, commonly known as the Miner rule [57]. According to the Miner rule, cumulative fatigue damage can be expressed as

$$\sum_{i=1}^{i=j} \frac{n_i}{N_i} \leq 1, \tag{2}$$

where n_i is the number of constant amplitude stress ranges $\Delta\sigma_i$ and N_i is the number of stress ranges $\Delta\sigma_i$ until failure.

Failure occurs when the sum of each partial damage equals one. The Miner rule can also be applied using the concept of equivalent stress range. It represents fictive constant amplitude stress range $\Delta\sigma_e$ which causes the same damage as the Miner sum of stress ranges, if it occurs often enough. Equivalent stress range is compared with a corresponding S-N curve for a given number of stress ranges. Reviews of Miner rule application for welded structures are given by Maddox and Razmjoo [58], Gurney [59], and Sonsino et al. [60, 61].

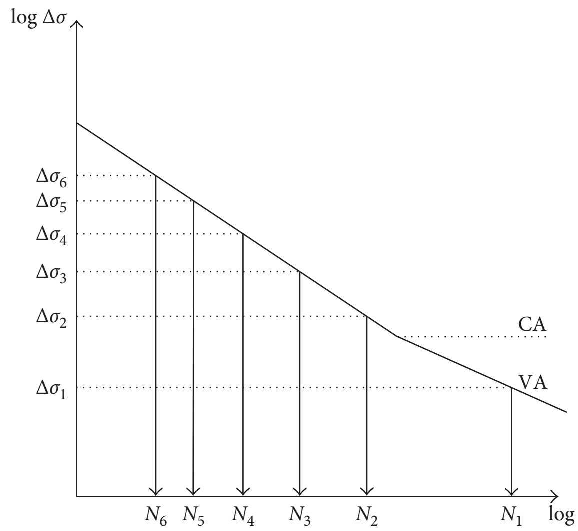


Figure 4: Palmgren–Miner hypothesis of linear damage accumulation.

The fatigue life assessment of a stochastically loaded structure is related to the correlation of the stress spectrum and resistance of the considered detail. Stress spectrum is usually unknown and can be obtained by different measures and simulation. To obtain stress amplitudes from a stress history, it is necessary to use one of the stress range counting methods, such as the reservoir or rain flow method [62]. The reservoir method is more suitable for manual calculations, while the rain flow method is more suitable for programming, and, respectively, computer calculation [63].

S-N approach does not differ from crack initiation and propagation, but considers the overall fatigue life of a structural element. In the case of geometrically complex structure details, where it is not possible to classify into a certain category, it is necessary to use more advanced methods for fatigue assessments (local approaches) which precisely determine stress values in the observed location. Application of local approaches is justified with the fact that even the fatigue process of local character cannot be well described by global approaches. Limit state function is formed by basic variables on a side of resistance and loading. Load model is defined by its own value and frequency of occurrence, while resistance model is obtained by fatigue tests. A review of the most used distribution functions for load and resistant model is given in [53]. There are many probabilistic fatigue damage studies and fatigue life assessments of bridges. A probabilistic model for reliability assessment of steel bridges based on data of long term monitoring is developed by Ni et al. [64]. Distribution of probabilistic stress range in Hot Spot with probabilistic formulation of the Miner rule is integrated in the paper. Recent fatigue assessments of steel bridges by bilinear S-N curve can also be found in [65, 66].

As already mentioned, S-N curve represents the relationship between stress ranges with constant amplitudes and the number of stress ranges until failure. If it is about variable amplitudes, the Miner rule is used. For ergodic processes of stress ranges, stress history scatter can be neglected and damage D_n with n stress ranges can be written as [67]:

$$D_n = E(n)\left[\frac{1}{K}E\left[\Delta\sigma^m\right]\right],$$
$$E\left[\Delta\sigma^m\right]_A^B = \int_A^B s^m f_{\Delta\sigma}(s)\,ds, \qquad (3)$$

where $E[\ldots]$ is expectation, $f_{\Delta\sigma}(s)$ is the probability density function of stress ranges $\Delta\sigma$, and K and m are material parameters that implicitly take into account effects of weld geometry, residual stresses, and through thickness stress variation.

According to this model, failure occurs when D_n equals unity. In most cases, a model with two slopes of S-N curve, which can be found in literature [67], is being used. The effects of weld geometry, residual stresses, and stress variation through plate thickness are implicitly included into values K and m. Effects of factors such as plate thickness, environment, weld notch, postweld treatment, and so on are included through appropriate corrections of basic S-N curves.

In that case, limit state function can be written as

$$g(X,t) = D_{cr} - D_n, \qquad (4)$$

where X is the random variable vector, t is time, D_{cr} is the miner damage sum with failure, and D_n is the damage with n cycles.

Applying structural reliability methods, it is possible to calculate the probability of failure or reliability index for the fatigue life of structural detail which can be used as a foundation for decision-making for maintaining structure.

4.2. Nominal Stress Approach. This is the most used approach for fatigue life assessment of steel structures that are prone to fatigue, and it is also adopted in standards. This approach is based on average stress in the corresponding cross section. The stress has been calculated by classical structural mechanics under the assumption of linear elastic theory. Local effect which causes stress magnification (concentration) is neglected, but it considers geometrical modification that has significant impact on stress variation (e.g., cut out holes). Local effects are implicitly taken into account by S-N curves. Figure 5 represents determination of nominal stress neglecting stress concentration in weld region.

Category of details and corresponding S-N curves based on nominal stresses are available in most design guidelines. Since the category of detail depends on element geometry, loading, and crack location, considered welded detail must be similar to detail that is given in guidelines.

Nominal stress-based approach is not suitable for geometrical complex details which cannot be assigned to corresponding S-N curve or in case that it is impossible to calculate nominal stress. In this case, it is necessary to use approaches that consider local effects (local approaches).

4.3. Hot Spot Stress Approach. Initially, fatigue assessment of welded joints based on Hot Spot stress approach was used for welded joints of tube elements [68]. Later, it began to be used

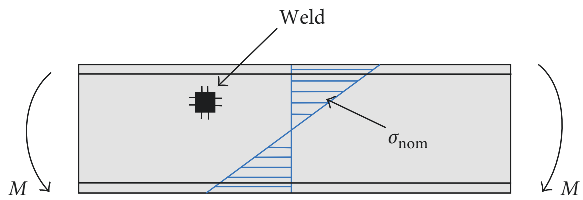


Figure 5: Nominal stress in a beam component.

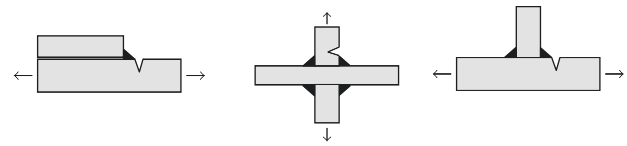


Figure 6: Examples of fatigue crack initiation locations in Hot Spot [25].

for plate elements and finally became a standardized procedure for fatigue life assessment of welded joints prone to fatigue [10, 25]. Hot Spot is the critical location on a weld toe where a crack is expected due to fatigue process. Examples of these crack initiation points can be seen on Figure 6.

As previously mentioned, fatigue strength of every welded detail depends on imperfections inside the weld and local stress concentrations due to the effect of detail geometry or the notch effect inside weld. Total Hot Spot stress consists of components of membrane stresses, plate bending stresses, and the nonlinear stress component due to the notch effect on a weld toe, Figure 7.

The basic idea of the Hot Spot stress approach is to exclude the nonlinear component from a stress calculation since it is impossible to know in advance the actual geometry of the weld. In this approach, S-N curves should cover only those effects that are related to the local stress concentration inside a weld (notch effect) and local weld imperfections. Consequently, a smaller number of S-N curves are needed than that in cases of nominal stress approach. Hot Spot stress approach is mainly used when it is impossible to clearly define nominal stress due to complex geometry or in cases when considered detail cannot be categorized in one of the nominal stress categories given in standards.

In situations when nominal stress can be simply calculated, stress concentration factor K_s which magnifies nominal stress is used. These factors are given only for a limited number of details and can be found in [69]. Hot Spot stress is then defined as

$$\sigma_{hs} = K_s \cdot \sigma_{nom}, \quad (5)$$

where σ_{nom} is the nominal stress in the Hot Spot location.

An example of application of stress concentration factors in calculations of Hot Spot stress in multiaxial fatigue assessment is given in [70].

In most cases, it is impossible to analytically determine Hot Spot stress. Then the Finite Element Method is used [71]. It is also possible to determine stress concentration factors in this way. Calculations are carried out with assumption of linear elastic material behaviour. During modelling, it is necessary to use finite elements that can take into account plate bending. Stress values depend on types and sizes of finite elements, and special attention should be paid to the modelling of weld toe and to the selected location of the Hot Spot. It is necessary to have extensive knowledge and experience to avoid mistakes in modelling and interpreting calculated results. Guidelines for modelling are given in [72].

During the calculations by finite element method, obtained results often deviate from real state. The reason for that is geometrical idealization which neglects geometrical misalignments as a result of the fabrication process. They cause secondary bending moments which should be taken into account in a way to make a finite element model with idealized geometry, and then obtained nominal stress should be modified with factor K_m which take into account geometrical misalignments. This factor is given with parametric formulas and can be found in [72]. Thus, a modified nominal stress is obtained:

$$\sigma_{nom} = K_m \cdot \sigma_{nom,m} + \sigma_{nom,b}, \quad (6)$$

where $\sigma_{nom,m}$ is the membrane component of stress and $\sigma_{nom,b}$ is the bending component.

Hot Spot stresses can be also obtained by measurements on existing structures. Strain is measured in reference points from which extrapolation on the Hot Spot location is conducted, Figure 8. From measured and extrapolated deformation, stresses are calculated. Extrapolation is conducted to exclude nonlinear stress component, and stress should be extrapolated from location where stress distribution is still linear. This area for plate elements starts approximately at a distance of 0.4 t from weld toe, where t is plate thickness. Recommendations for determining reference points and extrapolation can be found in [25, 72].

Hot Spot stress is derived by linearization of stresses outside the weld. According to IIW recommendations [25], linear extrapolation is conducted from stress values in two reference points on specific distances from the weld toe which are related to plate thickness. In cases when the loaded plate element is supported on an elastic stiff support (such as flange above web), linear extrapolation can underestimate Hot Spot stress. In that case, it is necessary to use nonlinear extrapolation from three reference points.

Fatigue assessment with this method follows the same procedure as the nominal stress approach. Hot Spot stress is compared with corresponding S-N curve of a certain structural detail. S-N curves for Hot Spot stresses can be found in [13, 25]. It should be noted that this approach is conducted on the assumption that fatigue crack initiates on the weld toe. Fricke [73] investigated three different extrapolation techniques in his paper. He then compared the resulting stress with S-N curves given in IIW recommendations [25]. He concluded that recommended extrapolation methods can be used with S-N curves that are given in recommendations. Xiao and Yamada [74] suggest a concept which is based on stress calculation in a location 1 mm under the surface on the weld toe, in a direction of crack propagation. It is proved that this method of calculation corresponds with extrapolation techniques.

However, the extrapolation procedures mentioned above lack consistency for general applications [75]. Local stresses

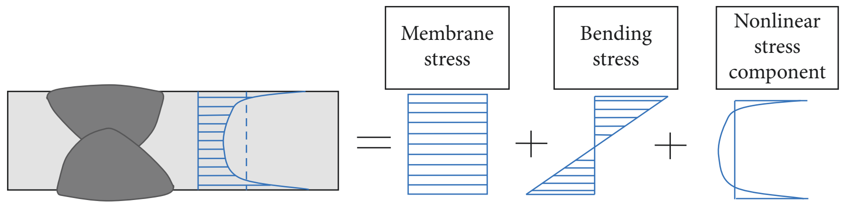


Figure 7: Total stress in Hot Spot.

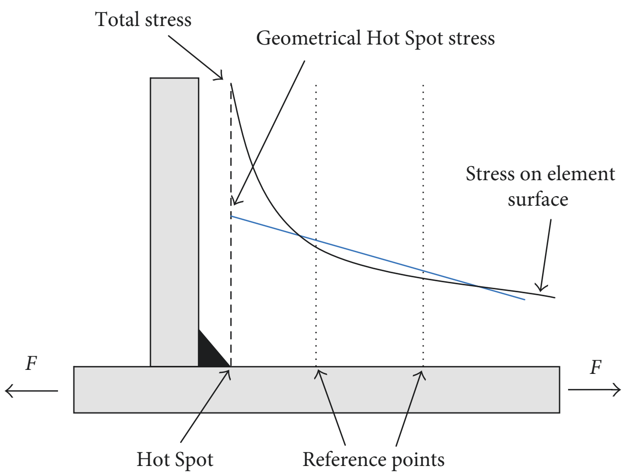


Figure 8: Definition of Hot Spot stress according to [25].

near a notch (weld toe) are nonlinear, and calculations of Hot Spot stresses highly depend on finite element mesh size and element types at weld discontinuities. A majority of the effort has been made on developing effective Hot Spot stress extrapolation procedures [76, 77]. In order to precisely assess fatigue life of a considered welded joint, stress concentration effects must be consistently captured in the stress calculations from FE models. In addition, weld classification besides geometry also depends on dominant loading mode, so choosing a suitable S-N curve could be subjective [39].

4.4. Mesh-Insensitive Structural Stress Method and Master S-N Curve Approach. In order to remove or minimize finite element size effect on stress calculation, the mesh-insensitive structural stress method and master S-N curve approach [39, 40] have been developed. Both of them have been adopted in the 2007 ASME Code and API Standard 579-1/ASME FFS-1 [78, 79]. Mesh-insensitive structural stress method was first brought to light in [39] in its basic concept and simple calculation procedures, and then in general form for applications in complex welded structures such as offshore/marine structures in [80, 81]. It is particularly suited for dealing with ship structures in situations where coarse finite element meshes are highly desirable, particularly in early design stage. The treatment of multiaxial fatigue incorporating both proportional and nonproportional loading effects including arbitrary variable amplitude loading is presented in [82–84]. Example of application of this method in Civil Engineering practice can be found in [85].

Using the mesh-insensitive structural stress method, it is possible to extract structural stress parameter. Stress parameter has an ability to differentiate stress concentration effects with different joint types, which is not always possible with conventional Hot Spot Stress extrapolation. Due to its mesh insensitivity in finite element solutions, it is possible to use conventional finite element models with coarse mesh. The validation of such stress parameter is demonstrated in [39] on a series of existing S-N curves for different joint types.

Structural stress is obtained by introducing equilibrium conditions, which indicate the mesh size insensitivity. Figure 9(a) shows local through thickness stress distribution obtained by finite element method. Figure 9(b) shows a corresponding simple structural stress distribution that is equilibrium equivalent to the local stress distribution [39].

Within this paper, solid model with monotonic distribution will be presented. Definition of other models such as shell models or solid model with nonmonotonic distribution can be found in [39]. Figure 9(a) shows stress distribution with the peak stress occurring at the weld toe. Figure 9(b) shows corresponding statically equivalent structural stress distribution. Cumulative stress is formed of membrane (σ_m) and bending (σ_b) component. The normal structural stress (σ_s) is defined at a location of interest (first reference plane) such as Section A–A at the weld toe in Figure 10 with a plate thickness t [39].

Section B-B is a location where stresses can be obtained from a finite elements solution. By imposing equilibrium conditions between these two sections, structural stress components σ_m and σ_b must satisfy following conditions [39]:

$$\sigma_m = \frac{1}{t}\int_0^t \sigma_x(y)\,dy, \tag{7}$$

$$\sigma_m \cdot \frac{t^2}{2} + \sigma_b \frac{t^2}{6} = \frac{1}{t}\int_0^t \sigma_x(y)\cdot y \cdot dy + \delta \int_0^t \tau_{xy}(y)\cdot dy. \tag{8}$$

Equation (7) represents the force balances in x direction, evaluated along B–B and (8) represents moment balances with respect to Section A–A at $y = 0$. The integral term on the right-hand side of (8) represents the transverse shear force as an important component of the structural stress definition. It then follows that if element size δ is small or transverse shear is negligible, the integral representations of σ_b and σ_m in (7) and (8) can be directly evaluated at Section A–A in Figure 10. Structural stress should serve as an intrinsic stress parameter for a given geometry and boundary conditions, regardless of numerical procedures used [39].

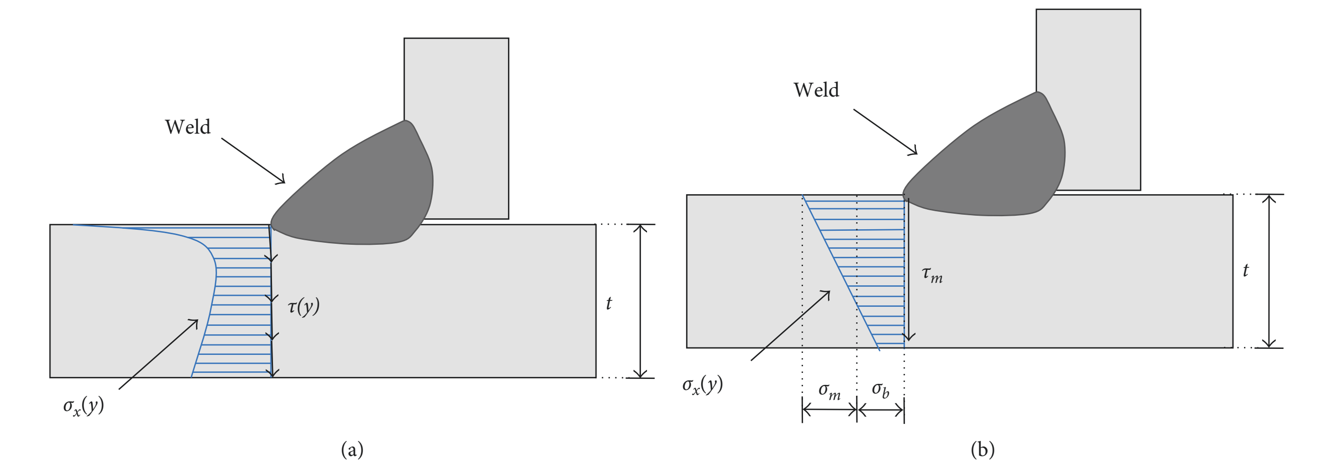


FIGURE 9: (a) Local through thickness stress distribution obtained by finite element method and (b) corresponding simple structural stress distribution [39].

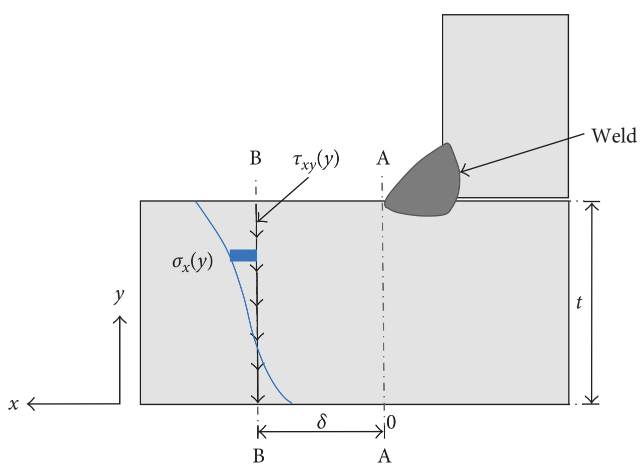


FIGURE 10: Structural stress calculation procedure [39].

In paper [39], structural stress calculations were performed for a collection of existing weld S-N data for various joint types. The results suggest that it is possible to reduce weld classification-based S-N curves into a single master S-N curve. The slope of that curve is then determined by the relative composition of the membrane and bending components of the structural stress parameter [39]. Master S-N curve can be constructed for all joints analysed in paper [39]. A comprehensive documentation on the master S-N curve method and its detailed validation can be found in [40].

4.5. Effective Notch Stress Approach. Today, this approach is increasingly represented in the industry, and the guidelines for fatigue assessment with this approach can be found in the design codes [25]. The basic concept of this approach is to model a weld root or toe with a notch of certain referent radius (Figure 11) [86]. Effective notch stress is the total stress in the root of the weld, which has been given by assuming the linear elastic behaviour of the material. If local stress in the crack initiation point is calculated during fatigue assessment, element strength can only be represented by one S-N curve.

Local stress concentrations are caused by notches and other imperfections inside welded joints, which decreases fatigue life of the welded joint. Stresses inside the weld are a sum of local stresses which are caused by the geometry of details and stresses because of the weld itself. Notch stress (toe or root) of the weld can be very high depending on notch sharpness or radius [10]. For very sharp notches (notch radii weaves zero), the theoretical elastic strain weaves to infinity. However, with that infinite strain, it is not possible to calculate.

In a fatigue assessment approach based on notch stress, there are two most used imaginative radii of 1 mm and 0.05 mm. Every notch in the weld root or toe is being modelled without discontinuity under assumption of linear elastic behaviour of material. Use of a fictive radius of 0.05 mm, which is based on the relation between the stress intensity factor and notch stress [86, 87], has been suggested by Zhang and Richter [88]. This kind of radius is being used for plates under 5 mm and, today, is mostly used in automotive industry [87]. Reference radius of 1 mm is being used for plates thicker than 5 mm, so this method finds its use in structural engineering practice.

The reference radius of 1 mm is a fictive radius derived from microstructural support theory [89, 90]. The fictive radius is added to the actual radius, which is conservatively assumed to be equal to zero (which means crack) [10]. This avoids estimation with theoretical elastic stress. Since notch deformations in weld toe or root cannot be measured, effective notch stress cannot be experimentally determined as is in the case of nominal stress and Hot Spot stress. Therefore, calculation of notch stress amplitude is possible only with the finite element method.

Fatigue assessment based on notch stress follows the same procedure as the nominal stress approach, with consideration of local effective notch stress instead of global stress. Assessment procedure is based on comparison of effective fatigue stress amplitude with certain S-N curve that represents resistance. Those kinds of curves are being

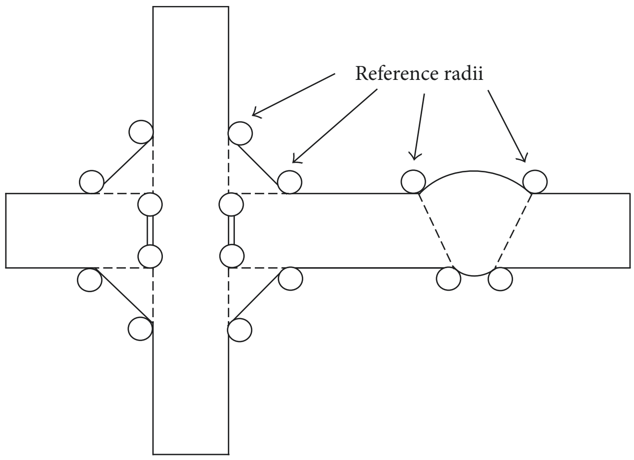


Figure 11: Stress evaluation in notch with referent radii.

suggested in IIW recommendations [25] for plate structures prone to axial load and bending moments. Fatigue strength data based on this approach is gained in perfectly performed samples. Every welded joint has imperfections which cause an increase in stress amplitudes, which is implicitly considered in S-N curve [25]. However, there are imperfections that can have a great impact on the decrease of fatigue joint resistance and are necessary to be considered during calculation [91]. The question arises, in which way secondary effects caused by joint imperfections can affect resistance and how to take them into consideration. Additional stresses from secondary bending moment are caused by those imperfections. During fatigue assessment with the notch stress-based approach, these effects must be taken on the load side. A group of authors detected this problem and showed disagreement of calculation results with S-N curves of considered joint [92].

4.6. Approach Based on Effective Notch Strain. This approach was developed in the 1960s, relating to the estimated time for cracks to initiate inside the element subjected to fatigue. It is being used in cases when strain on the observed spot is not completely elastic, but contains a plastic component. To modulate the crack initiation period, an approach that considers repetitive local yielding is being used [37, 93]. Local elastoplastic deformations are being observed with the Neuber rule of the notch, and the stress-strain curve is being modelled to the Ramber–Osgood relation [94]. This is the way that local elastoplastic maximum, the average stress, and the difference in notch stress are being calculated. These values are then being used for fatigue life assessment, using Coffin–Manson equation with Morrow medium stress correction [27]:

$$\frac{\Delta\varepsilon}{2} = \frac{\left(\sigma_j' - \sigma_{\mathrm{m}}\right)}{E}(2N)^b + \varepsilon_f' (2N)^c, \quad (9)$$

where $\Delta\varepsilon_T$ is the local strain and σ_{m} is the mean local stress in the weld toe. Parameters b and c are strength and ductility exponents, while σ_j' and ε_f' are the appropriate coefficients of fatigue strength and ductility. Examples of application of these methods in welded joints can be found in [10, 95].

Due to all the above-mentioned peculiarities of welded joints, this approach should only be used in consideration of stress-strain cyclic properties of the base material in a welded joint [27].

5. Fracture Mechanics Approach

Crack propagation in material that is prone to fatigue is described by fracture mechanics. This approach was first introduced by Paris et al. [96], which connected crack propagation rate with elastic stress intensity factor inside the top of crack in an element that is prone to cyclic stress. Considering that S-N models cannot describe crack propagation, fracture mechanics becomes an unavoidable tool in situations when cracks are detected. Figure 12 shows the basic difference between fracture mechanics and the S-N approaches. On the left side, there is an S-N curve where stress amplitudes are given in relation to a number of stress variations, and on the right side, the crack size in relation to the number of variations for one testing.

The relationship between geometrical imperfections, material properties, and stresses inside the detail [3] are given by the fatigue assessment method based on fracture mechanics. Fracture mechanics consider stress field and not stress concentration in a weld notch. Stress state inside the top of the crack is described by stress intensity factor:

$$K = Y \cdot \sigma_0 \cdot \sqrt{\pi \cdot a} \quad \left[Nmm^{-3/2}\right], \quad (10)$$

where Y is the correction factor which is in function of crack size, σ_0 is the uniformly distributed stress in element, and a is the crack size.

Fracture mechanics studies the occurrence of initial crack and its propagation to the fracture. Crack growth follows a law known as the Paris–Erdogan law of crack growth [97]:

$$\frac{da}{dN} = D \cdot \Delta K^n, \quad (11)$$

where D is the crack growth constant (material constant), n is the material factor, and ΔK is the difference of stress intensity factor.

Figure 13 shows the typical crack growth curve of a crack according to the mentioned law. The process of crack propagation passes through an area of slow propagation, stable propagation, and rapid crack propagation. Fatigue life of structure or structural element represents a number of loading cycles until the crack grows to a critical value, when failure occurs. Unlike the S-N approach, fracture mechanics is used for a more precise estimation of the remaining fatigue life [52].

Cracks inside the material can propagate in three modes. Mode I (Figure 14(a)) is the most important in the analysis of fatigue of welded joints by this method. It represents the crack propagation in the direction perpendicular to the direction of load. Modes II and III (Figures 14(b) and 14(c)) represent the propagation of fractures under the influence of shear stresses, but these failure modes also have fatigue issues [98].

The total fatigue life of an element that is prone to fatigue can be obtained from the onset of the initiation period and stabile propagation period. In welded joints, the crack

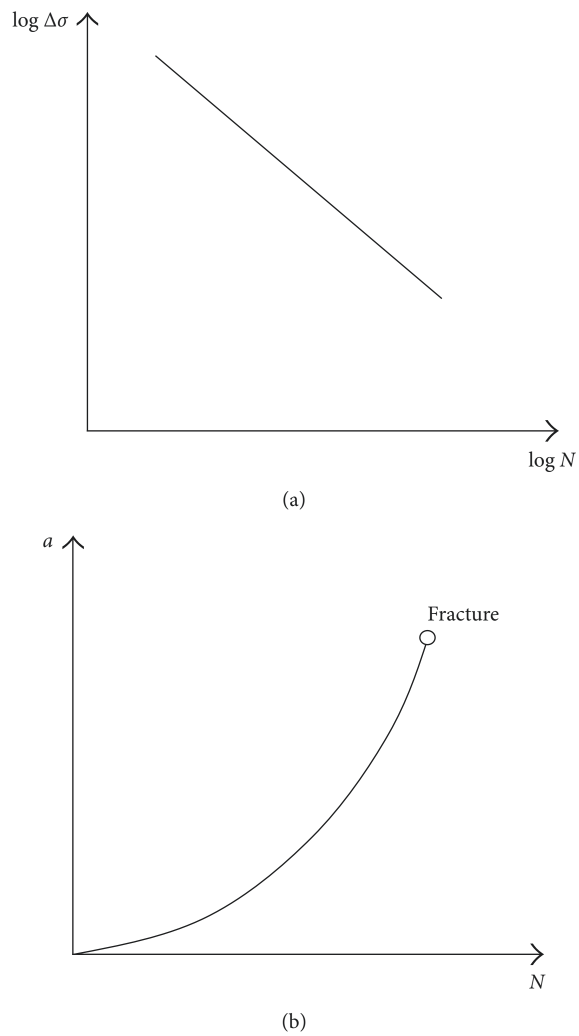


Figure 12: (a) S-N curve with given stress amplitudes in relation to number of stress variations. (b) Crack size in relation to number of variations for one test.

initiation period is quite short, so it can be neglected. Fatigue life of welded joints can be obtained with integration of the Paris–Erdogan law.

$$N_{i,j} = \int_{a_i}^{a_j} dN = \int_{a_i}^{a_j} \frac{1}{D \cdot \Delta K^n} \cdot da, \quad (12)$$

where $N_{i,j}$ is the number of stress cycles from a_i to a_j, and a is the crack size with $a_j > a_i$.

Equation (12) is used with assumption that loading acts in only one direction. Multiaxial fatigue assessment by fracture mechanics is still insufficiently researched and leaves space for further research, especially with multiaxial fatigue assessment and taking into account residual stresses [27]. During fatigue assessment with the Paris–Erdogan law, it is necessary to assume that the initial value of the crack is often very small and immeasurable. If the crack is seen and measured, it is possible to determine if it is going to grow to its critical value or if there is a high consequences of failure for the considered structure. That's when a decision about justification of a repair of a structure is being made, before it

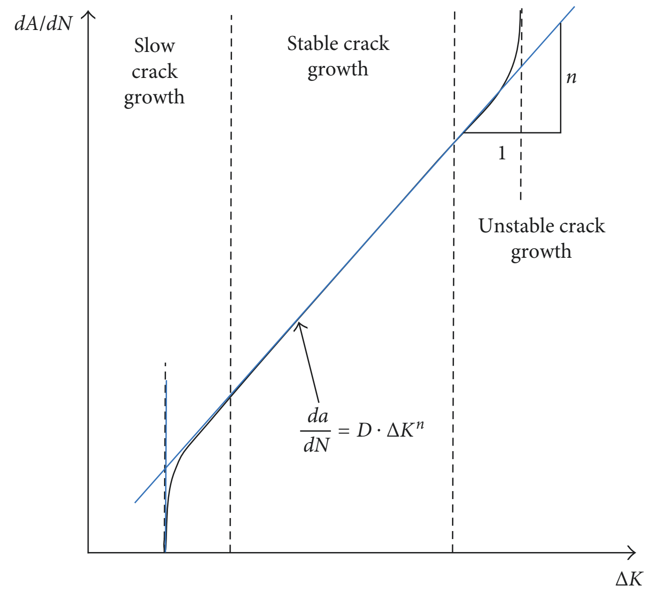


Figure 13: Typical curve of crack growth inside metals.

is sent into further exploitation. Besides the fact that the Paris–Erdogan equation successfully describes fatigue crack propagation, it has some limitations. Fatigue growth curves are phenomenological and cannot be physically described. Parameters of curves contain units which have not got physical meaning [99]. The propagating crack tip always contains some plasticity. If the plastic field is small enough, plastic processes in the crack tip are successfully described by linear elastic parameters, and the stress intensity factor is usually used for fatigue assessments. Yang et al. [100] showed that plastic deformations are changing elastic stress field in crack tip and suggest a new stress intensity coefficient which takes the influence of plasticity into account. When the size of plastic deformation in relation to crack size cannot be neglected, it is necessary to use elastoplastic fracture mechanics, and, respectively, parameters that take into account nonlinear plastic material behaviour. A review of the assessment of these parameters is given in [101]. Antunes et al. show a review of nonlinear parameters in [102]. Basics of nonlinear fracture mechanics are given in [103]. The correlation between nonlinear parameters and crack growth rate using empirical equations and numerical models is given in [104, 105]. However, there is an established physical relation of nonlinear parameters and the crack growth rate [99]. Most used nonlinear parameters are Crack Tip Opening Displacement (CTOD) and J integral.

J integral represents a mathematical description of the energy released during crack growth. It is introduced by Rice in 1968 [106]. The advantage of using J integral as a parameter of fatigue growth is the possibility of explicitly taking into account residual stresses and weld geometry. Fatigue assessment procedure with J integral is presented in [107]. Fatigue life of a structural detail estimated by numerical methods is compared with experimental results, and good agreement of experimental and numerical results are shown. It is concluded that this is a suitable fatigue assessment

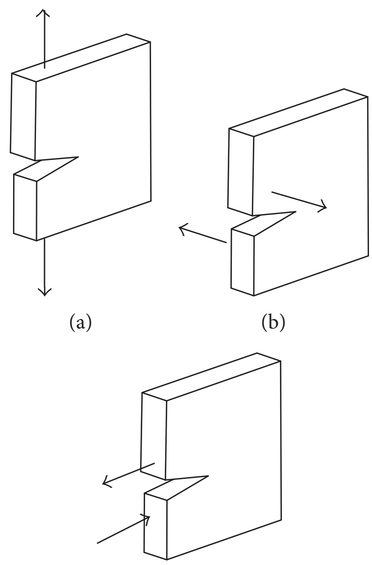


Figure 14: Basic modes of crack propagation. (a) Mode I. (b) Mode II. (c) Mode III.

method. It is also concluded that residual stresses do not have a big influence on bigger stress amplitudes.

CTOD represent the value of the crack separation surface due to plastification [108]. It has a physical meaning and can be measured. For describing crack growth, it uses crack tip blunting during maximum loading and resharpening crack tip during minimum loading [109]. This parameter is still insufficiently investigated and shows great potential, especially with better understanding of fatigue crack growth [99]. Procedure of assessment J integral and CTOD for circumferential welds can be found in [110].

Today, fracture mechanics is one of the basic approaches for fatigue assessment of welded joints. Possible application of the fracture mechanics in fatigue assessments was shown by Hobbacher in his work [111]. The main problem with this approach is that the size of the initial crack is based on assumptions, and it is not always possible to be measured.

There is a number of probabilistic research works on the fatigue of welded steel structures based on the fracture mechanics approach. Based on nondestructive evaluation (NDE) data, fracture mechanics probabilistic model, considering various uncertainties such as the initial crack size, material properties, and number of stress cycles, was proposed by Zhao and Haldar [112]. Probabilistic procedures for fatigue assessments of steel components using the crack propagation model for a welded joint are given by Lukić and Cremona [113]. A study on the application of fracture mechanics to assess the fatigue life of welded joints with initial cracks, assuming a bilinear law of crack propagation, was conducted by Righiniotis and Chryssanthopoulos [114]. Procedure for probabilistic assessment and fatigue reliability update of existing steel bridges is presented by Wang et al. [115]. They used nondestructive inspection techniques and Bayes theorem which is applied to the probabilistic methods of fracture mechanics. According to the approach through fracture mechanics, limit state function can be defined as

$$g(X,t) = a_{cr} - a(t), \tag{13}$$

where X is the vector of random variables, a_{cr} is the limit crack size (e.g., Plate thickness), and $a(t)$ is the crack size after certain amount of time t.

At $t = 0$, crack size has the initial value a_0. Calculation of crack value in time t is not trivial since fatigue stress is a random process. Details of probabilistic methods based on fracture mechanics can be found in the literature [67].

6. Conclusion

Based on the review of fatigue assessment methods of welded details in steel structures, the following conclusions can be drawn:

(i) Fatigue of welded details is still an insufficiently researched phenomenon which is under the influence of many parameters such as load, geometry, material quality, production process, and environmental effect. Because of their imperfections, welded joints additionally complicate the fatigue assessment process.

(ii) Today, global approaches are adopted in the international standards for design and are best suited for engineering evaluations. With the nominal stresses approach, local effects are indirectly considered on the resistance side (S-N curve), and it is necessary just to determine nominal stress in observed location.

(iii) Local approaches consider a bigger number of parameters on the load side, which decreases the necessary number of S-N curves. However, the possibility of a mistake increases, so the precision of an assessment depends on engineer's experience. Local approaches, often unjustified, neglect the influence of residual stresses. In the future, it is necessary to further investigate the correlation between the numerical model and the actual behaviour of elements. The extrapolation procedures in Hot Spot approach lack consistency due to its sensitivity on finite element mesh size and element types at weld discontinuities. One of the solutions for this problem is the mesh-insensitive structural stress method and master S-N curve approach.

(iv) An issue of welded joints is additionally complicated if the elements are subjected to multiaxial fatigue. Today, standards propose a number of interaction terms for the assessment of multiaxial fatigue, but expressions show a certain degree of conservatism. It is necessary to additionally investigate an effect of the components of nominal stress on the shear stress damage process, which could give better insight in interaction behaviour.

(v) Fracture mechanics describes the fatigue crack propagation, but it is still unexplored enough that it leaves space for further research, in particular, with multiaxial fatigue assessment and taking into account residual stresses.

(vi) Regardless of the accuracy of the methods of fatigue assessment of welded details, the essential role remains to the load, whose intensity and frequency are very difficult to assume, particularly in the case of the large infrastructure welded steel structures prone to fatigue.

(vii) Although crack initiation period for welded joints is negligible, it is possible to substantially extend it with variable postwelding treatments and thus increase the overall resistance of the welded joint prone to fatigue.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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