FATIGUE DESIGN OF WELDED COMPONENTS AND STRUCTURES: AN OVERVIEW OF WORK DONE WITHIN THE INTERNATIONAL INSTITUTE OF WELDING

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Abstract. Design decisions for welded structures are rarely made based solely on technical grounds. Safety requirements, cost restrictions, structural performance demands and, increasingly, environmental pressures, all contribute to the decision-making process. The importance of raw materials and energy efficiency is constantly growing and has motivated many industries to perform total lifecycle cost assessment and environmental footprint computations, both of which now integrally influence design and purchasing decisions. As materials and fabrication technologies for welded structures evolve and develop, new challenges and opportunities with respect to the Fatigue Design of Welded Components and Structures arise.
Advanced design solutions, incorporating weldable steel plate and strip products with yield strengths from 400 MPa to over 1100 MPa, provide considerable potential for raw materials and energy savings and for decreasing CO2 emissions over the lifetime of cars and trucks, heavy duty vehicles and other mechanical equipment and machinery. Increased performance characteristics, in terms of improved payload-to-weight ratio, amplified boom extension or enhanced vehicle manoeuvrability, are additional benefits when high-strength steels (HSS) or ultra-high strength steels (UHSS) are incorporated into lifting, hoisting or transport equipment.
This presentation attempts to provide a brief overview of select research topics and recent technological developments related to fatigue assessment for welded structures. Much of the work has been performed and reported within the scope of the International Institute of Welding (IIW), but other groups and individuals have also made important contributions. While many themes could have been selected, this paper provides brief discussions on several active research topics: the relationship between weld quality and fatigue performance for welded structures, advanced high strength steel for welded structures, high frequency mechanical impact treatment methods for fatigue improvement and developments in finite element-based fatigue assessment procedures.

1 INTRODUCTION

In current industrial practice, welds and welded joints are an integral part of many complex load-carrying structures. Experience has shown, however, that welds are commonly the weakest portions of these structures and that the welding process has significant influence on the integrity of a structure. This presentation attempts to provide a selected overview of current research topics and recent technological developments related to fatigue and fatigue assessment for welded structures. Much of the work has been performed and reported within the scope of the IIW Commission XIII: Fatigue of Welded Components and Structures, but other groups and individuals have also made important contributions, e.g., the ISSC [1]. The experts that contribute to Commission XIII come from world-leading companies, universities and research institutes. The Commission typically meets twice per year to present and discuss new scientific results and the application of new technologies to avoid fatigue failures in welded structures. The objective is to develop expertise and provide science-based guidelines that can be applied to challenging design and life extension cases.

Industries that benefit from Commission XIII publications include ship building, automotive, transportation, bridge and infrastructure, offshore, mechanical engineering and process equipment. Primary topics of research and development include 1) fatigue testing and evaluation of data for design, 2) techniques for improving the fatigue strength of welded joints, 3) stress analysis for fatigue design, 4) the influence of weld defects in fatigue-loaded structures, 5) life extension of welded structures by repair, retrofitting and structural monitoring, 6) fatigue design methods and rules and 7) the influence of residual stress on fatigue strength.

2 WELD QUALITY

Even a casual examination of background data which was used to develop documents like the new IIW Recommendations for Fatigue Design of Welded Joints and Components [2] reveals that, for a given applied nominal stress range, the difference in fatigue life between the "weakest" and the "strongest" component is frequently one decade or more even for nominally identical test pieces. It is well established that these differences are the result of local geometric features of the weld bead, microscopic features of the weld toe, test piece misalignment and residual stresses. In recent years, Commission XIII of the International Institute of Welding has been promoting research and developing the technical background needed to develop a weld quality recommendation which *quantitatively* relates fatigue performance and geometric features of the weld. The logic has been that, if one can reliability identify and eliminate those welds toward the lower end of the scatter band, new weld classes will emerge with increased characteristic fatigue strength (the characteristic fatigue strength indicates 97.7% survival probability based on a 75% two-sided confidence level of the mean).

Quality systems for welds are described in so-called 'weld class systems', such as ISO 5817 [3] or Volvo's Standard 5605 [4], where acceptance limits are given for different quality levels. The problem with these systems is that they were initially developed as a measure of workmanship with respect to fabrication. Logically, good workmanship has been assumed to correspond to good performance but, a quantitative relationship was not established. The ISO 5817 system divides welds into quality classes B, C and D. Classification is ultimately based on the worst characteristic of the weld out of a long list of potential characteristics. Some of the characteristics in the ISO system have little or no influence on weld strength while some important characteristics are omitted. Karlsson and Lenander [5] have used fracture mechanics to compute the fatigue life for different acceptance limits within ISO 5817 and Volvo STD 5605. In was shown that there is an inconsistent relation between fatigue life and weld class. For a certain quality level the fatigue life can vary by one or two decades depending on the imperfection type. Additionally, with existing systems, raising quality from, e.g., D to C, does not guarantee that fatigue strength will be increased.

Hobbacher and Kassner [6], have considered the relationship between ISO 5817 and the current IIW Recommendations [2]. For *fillet welds* of "standard" quality, i.e., with fatigue strength consistent with the IIW Recommendations, ISO quality D would be sufficient for most weld imperfections while other features would require quality level C or B. For *butt welds* similar results were found but many more of the features would need to be qualified as quality level B. For two features even quality level B would be insufficient to achieve the fatigue strength in the IIW Recommendations. These results clearly indicate that the *type* of defect often plays a bigger role than the acceptance criterion itself. It also demonstrates that some defects or imperfection types in the existing quality systems are very important with respect to fatigue while others are not.

Due to the inconsistent relationship between weld quality class and fatigue strength, Volvo has developed a new system of acceptance limits for the weld classes [7]. The classes are summarized in Table 1. The first important principle used in developing this system is that, for all imperfection types in one weld quality class level, the same fatigue life should be attained. In this way the quality designation on the engineering drawing (weld class level) will be a direct indication of the fatigue strength of the joint. Secondly, a shift from one weld class level to the next weld class level should reflect a 25% increase in fatigue strength which is approximately equivalent to a factor-of-two increase in fatigue life. Thirdly, only imperfection types which have an influence on fatigue strength are defined in the different classes. Other types of imperfections have the same limit for all classes [8].

Table 1 Acceptance limits in the new weld class system (7).

Discontinuity type	**VD (as welded normal quality)**	**VC (as welded high quality)**	**VB (post treated)**
Cold lap	a < 0,5 mm	a < 0,1 mm	Not allowed
Inner lack of fusion	Not allowed	Not allowed	Not allowed
Transition radius	R > 0,25 mm	R > 1 mm	R > 4 mm
Undercut	d < 0,05t [max 1,0 mm]	d < 0,025t [max 0,5 mm]	Not allowed
Throat deviation	< -0,2a [max 2 mm] (bigger OK)	Not allowed (bigger OK)	Not allowed (bigger OK)
Misalignment	a < 0,1t [max 2 mm]	Not allowed	Not allowed
One pore inner / outer	0,4t [max 4] / 0,3t [max 3]	0,3t [max 3] / 0,2t [max 2]	0,2t [max 2] / 0,1t [max 1]
Clustered pores (inner / outer)	6% / 3%	4% / 2%	2% / 1%

The new weld class system makes an important distinction between toe side and root side fatigue initiation locations. These potential failure modes are separated and the root side is fully outside the weld class system. If a full penetration weld is not designated, the root side lack of penetration may serve as a well-defined initial crack. These design cracks may be very large. If the root side is critical, a larger design crack will lead to shorter fatigue life and vice versa. Designing against fatigue is thus strongly dependent on the needed weld penetration. For this reason the root side is outside the weld class system. Instead, the root side penetration is specified as a minimum requirement on the design drawing. This value can be determined by analysis using the effective notch method or fracture mechanics and it must be controlled during production. Consequently, there are no acceptance limits defined for the root side in any of the weld classes. With respect to toe-side fatigue failures of a weld, the transition region between weld metal and base material is the most significant. Here the local geometry, with its statistical distribution, is the most important factor especially in form of a too small radius or other defects. This is, therefore, the main focus of the new weld class system, i.e., to define acceptance limits for radius, cold laps and undercuts, etc., which can be related to the expected fatigue life. Imperfection types inside the material, such as pores, are also treated in the weld class system since they may serve as starting point for fatigue failures.

3 HIGH FREQUENCY MECHANICL IMPACT TREATMENT METHODS

Post-weld improvement is frequently specified during the repair of existing structures and, more recently, for new structures. There has been increasing interest in high frequency treatment technologies. In terms of the mechanics of the improvement, high frequency treatment devices have similar features as compared to needle or hammer peening. However, the high frequency impact is generally more user-friendly and helps to achieve a very regular treatment region with excellent repeatability. The technology for high frequency ultrasonic impact treatment was developed at the Northern Scientific and Technological Foundation in Severodvinsk, Russia in association with Paton Welding Institute in Kiev, Ukraine [8]. The past decade has seen steady increase in the number of high frequency peening equipment manufacturers and service providers. Numerous technologies are employed, e.g., ultrasonic piezoelectric elements, ultrasonic magnetostrictive elements or compressed air. In all cases, however, the working principal is identical: cylindrical indenters are accelerated against a work piece with high frequency. The impacted material is plastically deformed causing both a change in the local geometry and residual stress state in the region of impact. In comparison to hammer peening, the operation is more user-friendly and the spacing between alternate impacts on the work piece is very small resulting in a finer surface finish. The indenters are high strength steel cylinders and manufacturers have customized the effectiveness of their own tools by using indenters with different diameters, tip geometries or multiple indenter configurations. Devices are known by the names: ultrasonic impact treatment (UIT) [9], ultrasonic peening (UP) [10], ultrasonic peening treatment (UPT) [11-12], high frequency impact treatment (HiFiT) [13], pneumatic impact treatment (PIT) [14] and ultrasonic needle peening (UNP) [15-16]. These devices employ various technologies to vibrate cylindrical indenters against a work-piece with high frequency. Magnetostrictive elements, piezoelectric transducers, or pneumatic drives are variously used and some of the equipment may have sophisticated control and feedback monitoring features. The area being treated is highly plastically deformed which has the effect of work-hardening the material, introducing favourable compressive residual stresses and reducing the normally high stress concentration at the weld toe. Figure 1 shows a typical weld toe profile in the as-welded condition and following UIT treatment [17]. The dramatic change in the weld toe geometry is clearly visible.

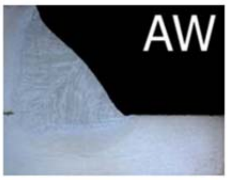


Figure 1: Typical weld toe profile in the as-welded condition and following UIT treatment [17]

Yildirim and Marquis have collected all published fatigue data for welded specimens improved using high frequency treatment methods [18]. Data for more than 400 fatigue tests are available. Figure 2 shows data for 122 longitudinal non-load carrying fillet weld components subjected to R=0.1 constant amplitude loading. Plate thickness was from 8 to 16 mm and the materials' yield strengths ranged from about 260 to almost 1000 MPa. Figure 2 also shows the as-welded design curve for this welded detail (FAT 71) based on IIW Recommendations [2]. The SN slope m=5 provides a good fit for the experimental data and the mean minus two standard deviations line is FAT 142. This represents a 100% improvement in fatigue strength at $N_f = 2x10^6$. Of course, because the slope of this line is different from the slope of the line for as-welded components, the degree of improvement changes depending on the life regime of interest. For example at $N_f = 5x10^4$ the improvement is only 22% while at $N_f = 5x10^6$ the improvement is 225%. Yildirim and Marquis reach the preliminary conclusion that the degree of improvement also increases with material yield strength so that at $N_f = 2x10^6$, the improvement is $40+(f_y-355)*0.08$ (%). This aspect continues to be studied as is the stability of the induced compressive for different type of loading.

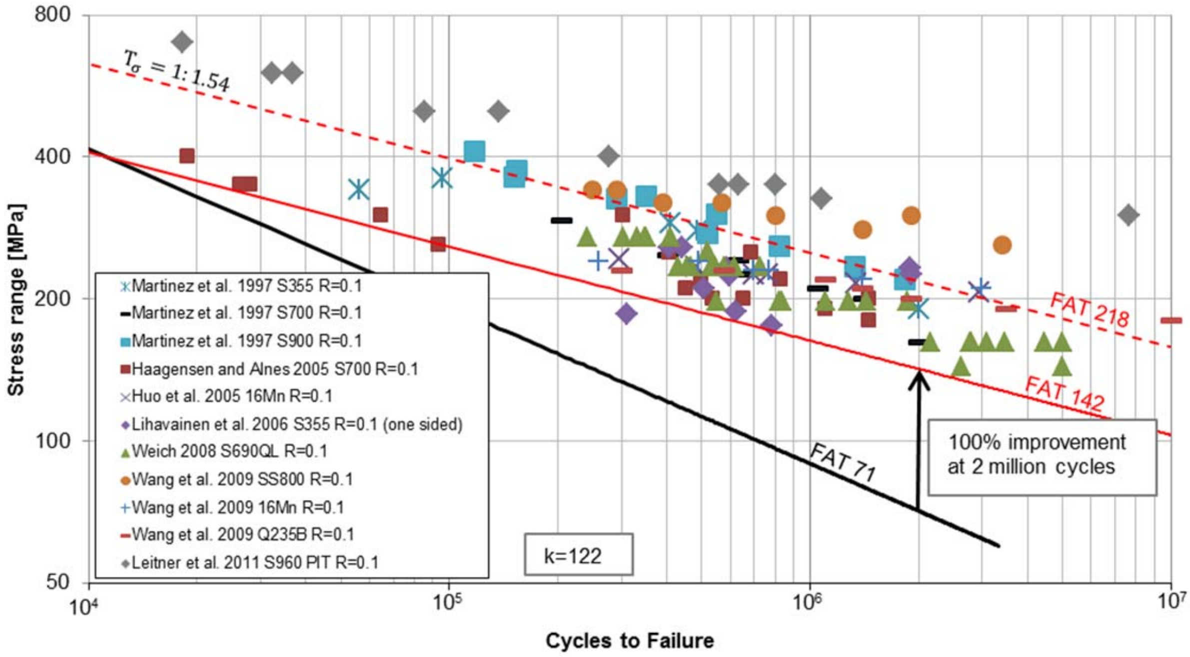


Figure 2: Fatigue data collected from a number of studies where high frequency treatment methods were applied to longitudinal non-load carrying fillet weld components

4 HIGH STRENGTH STEELS

Many factors influence the decision as to what material should be chosen for any application. Safety of the final design, material and fabrication costs, structural performance and the computed environmental footprint, all contribute to the final decision. The importance of raw material costs and energy efficiency are constantly growing and has motivated many industries to perform total lifecycle cost assessment and environmental footprint computations. Advanced design solutions, incorporating weldable steel plate and strip products with yield strengths from 400 MPa to over 1100 MPa, can provide considerable potential for raw materials and energy savings and for decreasing CO_2 emissions over the lifetime of cars and trucks, heavy duty vehicles and other mechanical equipment and machinery. Increased performance characteristics, in terms of improved payload-to-weight ratio, amplified boom extension or enhanced vehicle manoeuvrability, are additional benefits when high-strength steels (HSS) or ultra-high strength steels (UHSS) are incorporated into lifting, hoisting or transport equipment.

Automobiles, offshore structures, mobile cranes and bridges are examples of applications which have progressively embraced higher-strength materials. In shipbuilding, thinner steel plates with strengths of up to 700 MPa have been introduced in some new vessels for above-water structures. Long distance transportation of natural gas in high-strength pipelines is more economical than the transport of liquified and compressed natural gas. For many applications, acceptance of HSS/UHSS will only become widespread as and when standards and design guidance documents are developed. Many standards for steel construction do not yet include requirements for ultra-high strength steels. Eurocode EN1993-1-12, for example, specifies ductility requirements for steels with yield strengths of up to 700 MPa, but does not extend to grades. Standards for rail freight wagons and cranes incorporate higher-strength materials, as long as strict ductility conditions are met. However, there are no generally-accepted design rules which apply to the static strength of steel grades over 700 MPa.

The advantages of HSS or UHSS can rarely be appreciated by the simple substitution of higher-strength steel for one of lower strength. Weight savings can be attained by reducing plate thickness to take advantage of a material's higher strength. But in order to fully take advantage of high-strength material, a design must focus extra attention on considerations of joint design, buckling, component stiffness and fatigue. Extensive research projects in the Nordic countries over the past two decades have shown that innovative products incorporating high-performance ultra-high strength steels are best achieved when research and development for design, fabrication and materials production progress hand in hand. For example, the development of new HSS welded components with excellent fatigue strength can only be achieved with the concurrent development and understanding of welding, cutting and forming processes, suitable for those materials. High-strength materials are more expensive per kilogram than more traditional steel grades. However, the increased cost is partially offset since less material will ultimately be needed. Additional cost savings can be realized at all stages of the fabrication process. With reduced plate thickness, costs for materials handling and filler metals are reduced. The time required for plate cutting, joint preparation and welding are all decreased, so that overall costs for the manufacturer may be less than for a comparable product fabricated with low-strength steel.

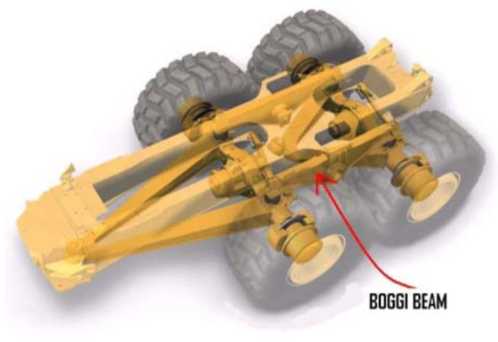
The high-strength, high-ductility characteristics of HSS/UHSS are due to their unique microstructures. Where traditional steels have primarily one microstructural phase, UHSS typically have a combination of martensite, bainite and ferrite phases. High strength is normally associated with increased amounts of alloying elements which result in higher hardenability. However, this may also lead to an increased risk of brittle fracture and hydrogen-induced cracking in welded constructions or pipelines. Most HSS/UHSS steels are produced using a quenching process followed by tempering. Some modern steels, however, make use of sophisticated and highly-controlled direct-quenching processes which allow for a higher strength to be attained with a reduced carbon and alloy element content. Such advanced UHSS have excellent weldability and reduced susceptibility to hydrogen cracking. As a result of the unique material properties which arise from closely-controlled thermal and mechanical production processes, welding can potentially reduce or destroy the high strength and ductility. Too much heat input during welding can result in a large heat-affected zone which ultimately reduces the strength of a joint. Too little heat input can result in rapid cooling which may lead to cracking or regions with low toughness.

Jonsson [19] presents and excellent example of the design procedures that must go into the development of fatigue resistant products using high strength steel. The component in question is a bogie beam used in an earth moving vehicle, see figure 3a. The old design was fully in S350 steel. A new design incorporating reduced-thickness S460 and S600 plates had approximately 22% less weight. The structure could be welded using standard production processes but several regions on the weld needed to be inspected to ensure proper weld profile. Due to higher stresses the region around the bearing weld, single bevel edge preparation and partial penetration welding was needed followed by TIG re-melting.

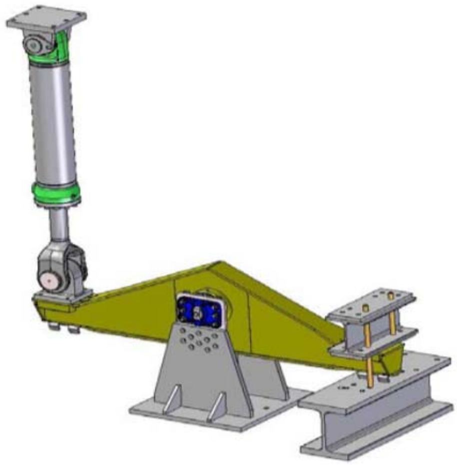
In order to properly identify the high stress regions, advanced fatigue assessment methods needed to be employed. The product was further developed and verified by fatigue testing, see figure 3b. In spite of the additional production steps, i.e., edge preparation and TIG re-melting of one weld, the welding time and total production cost of the structure was reduced with respect to the old design from S350 steel because of the thinner plates. Thus the design steps were:

a) develop a new lighter-weight design incorporating higher strength steel and thinner sections,
b) properly use advanced finite element-based fatigue assessment methods to verify the design and identify high stressed regions,
c) bevelling and extra weld penetration in regions with high weld root stresses,
d) post-weld treatments in regions of with high weld toe stresses,
e) carefully defined WPS and inspection procedures, and
f) fatigue testing to further refine and verify the design

It should be emphasised that steps c) and d) can usually be limited to a very small percentage of the total weld seams in a structure. These locations are identified in step b). The effect of these steps on total welding cost is small and, in this case, was more than offset by faster production time and lower material handling costs. The new lightweight welded component cost 8% less than the component it replaced.



a)



b)

Figure 3: a) The hauler bogie beam that was re-designed in high strength steel and b) the new beam being tested.

5 FATIGUE ASSESSMENT METHODS

Numerous fatigue assessment methods have been introduced to assess the durability of metal structures under dynamic loading. Finite element (FE) modelling is an integral part of most design and analysis work and methods have evolved as the analysis possibilities have become more sophisticated and computers have increased in speed and memory capacity. Fatigue assessment places two conflicting demands on the analysts. The fatigue damage process itself is highly local, thus requiring a fine FE mesh. On the other hand, welded structures are frequently large, geometrically complex, have many load points and boundary conditions which may be difficult to define. These demands are best satisfied with a large FE model. Because of this conflict, fatigue assessment is frequently the slowest link in the design process of fabricated structures.

The most common fatigue assessment methods are based on nominal stress, structural hot spot stress, effective notch stress, notch strain or the stress intensity factor, i.e., linear elastic fracture mechanics (LEFM) [2]. These classes of methods have naturally been developed and verified primarily based on tests of small-scale specimens. A qualitative comparison of these common methods is illustrated qualitatively in figure 4. In this graph the horizontal axis represents the complexity of the structure being evaluated. Complexity may be with respect to the number and types of connections, boundary conditions, the number of load inputs, etc. The vertical axis qualitatively represents the accuracy of the fatigue analysis. The nominal stress method, upon which many design guidance documents for fatigue assessment are based, requires the least amount of computational effort but also decreases rapidly in accuracy as structural complexity increases. The structural hot spot stress approach is well documented [20] and promising for many design situations, but tools for establishing the structural hot spot stress based on FE modelling results are not widely available. LEFM and the effective notch stress or strain based approaches are potentially highly accurate even for complex structures, but the computational effort is increased. The amount of effort required both to develop the FE model and perform the analysis increases rapidly in moving from the nominal stress to the LEFM analyses. This is partially reflected in the element density required in the critical regions of the structure. As seen in Fig. 4, required local element density may increase by 6-7 orders of magnitude between methods.

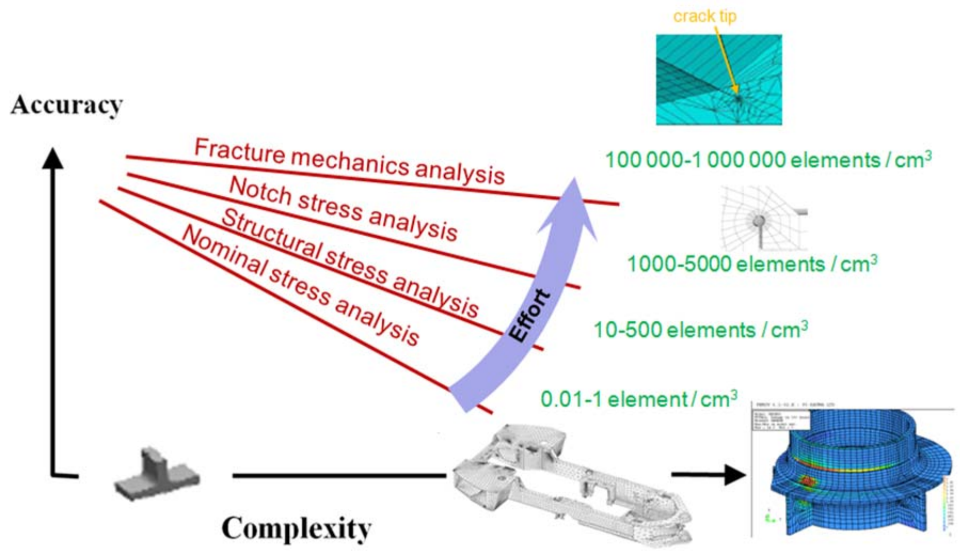


Figure 4: Qualitative view of accuracy and effort for several fatigue assessment methods for welded structures.

5.1 Effective notch method

FE analysis as a basis for fatigue design analysis of welded structures usually leads to problems related to the incompatibility of the stress results produced by FE analysis and those needed for the fatigue design procedures, i.e., nominal stresses are often difficult or impossible to define, structural stresses are determined by extrapolation techniques and stress intensity factors are found, for example, by integration with special element types. In this respect the effective notch stress approach has an advantage over the other methods in that the stress value used in analysis is unambiguous since it is the maximum computed stress at a well-defined location in the FE model. The IIW has now published guidelines for implementing the effective notch stress method in fatigue analysis of welded structures [21]. For welded structures, the stress analysis method and fatigue assessment method must be calibrated with one another. Regretfully, there is tremendous potential for misuse when one stress analysis result, even if correct, is used with a SN curves for a fatigue assessment method which is calibrated to be used with other element types or degrees of FE mesh refinement. The IIW has been very careful to harmonize stress analysis and fatigue assessment.

Baumgartner and Bruder [22] have recently studied efficient meshing strategies to be used when implementing the effective notch stress method. With respect to figure 5 and assuming a maximum allowable error in stress of 2% due to meshing, elements with quadratic shape function are recommended. Furthermore, an element edge ratio V in the first ring of V = 2 or V = 3 and a magnification factor of Z = 2 or Z = 3should be used in order to reduce the overall number of elements. For a rough calculation of notch stresses (error 4%), as few as 12 elements over 360° may be sufficient using the parameters V = Z = 2. For more accurate results 24 elements over 360°, V = Z = 2 is recommended.

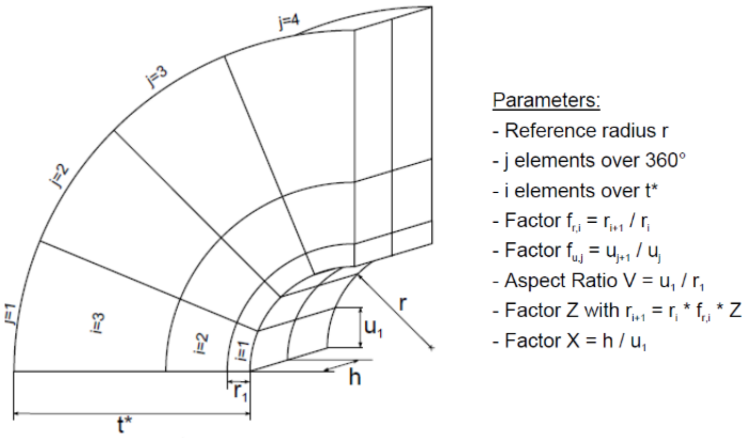


Figure 5: Parameters defining a mapped mesh of a notch

The fatigue assessment notch stress curves, $\Delta\sigma_k$ vs. N, are shown for N > $1x10^4$ [21]. The use of the effective notch method into the low cycle regime has been investigated by Saiprasertkit et al [23] and Hanji et al. [24]. They have proposed that the significant material plasticity in this region can be taken into account based on the effective von Mises strain range which is the sum of the elastic and plastic components of strain range.

$$\Delta\varepsilon_{eff} = \frac{\Delta\bar{\sigma}}{E} + \Delta\bar{\varepsilon}_p \tag{1a}$$

$$\Delta\bar{\sigma} = \sqrt{\frac{1}{2}\left[\left(\Delta\sigma_x - \Delta\sigma_y\right)^2 + \left(\Delta\sigma_y - \Delta\sigma_z\right)^2 + (\Delta\sigma_z - \Delta\sigma_x)^2 + 6\left(\Delta\tau_{xy}^2 + \Delta\tau_{yz}^2 + \Delta\tau_{zx}^2\right)\right]} \tag{1b}$$

$$\Delta\bar{\varepsilon}_p = \frac{1}{3}\sqrt{2\left[\left(\Delta\varepsilon_{p,x} - \Delta\varepsilon_{p,y}\right)^2 + \left(\Delta\varepsilon_{p,y} - \Delta\varepsilon_{p,z}\right)^2 + \left(\Delta\varepsilon_{p,z} - \Delta\varepsilon_{p,x}\right)^2 + \frac{3}{2}\left(\Delta\gamma_{p,xy}^2 + \Delta\gamma_{p,yz}^2 + \Delta\gamma_{p,zx}^2\right)\right]} \tag{1c}$$

Using 14 combinations or base material, plate thickness and filler material, load carrying cruciform joints were tested experimentally and evaluated using elastic plastic finite element analysis. Figure 6 shows the experimentally determined fatigue lives and the analytically determined range of von Mises strain. This curve also shows the effective notch stress design line for von Mises stress presented in terms of strain range. This excellent agreement is a promising new development for extending the method for low cycle fatigue assessment.

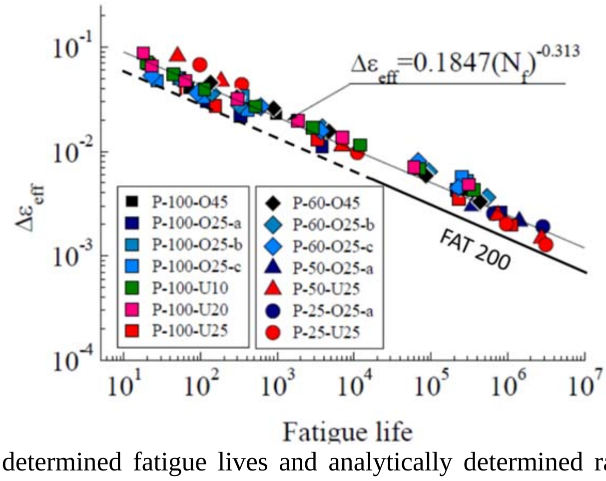


Figure 6: Experimentally determined fatigue lives and analytically determined range of von Mises strain for cruciform specimens fabricated from a variety of materials and filler materials. The effective notch stress design line for von Mises stress is also presented in terms of strain range [23].

5.2 Fracture mechanics assessment

The scientific relevance of using linear elastic fracture crack growth assessment for welded structures has been known since the early 1970s. However, the generally "unknown initial crack size" problem and the difficulty of computing stress intensity factors for welded structures of complicated geometry and subject to complex loading conditions have limited the engineering use of this fatigue assessment method. Most of the existing methods of calculating stress intensity factors require separate analysis of each load and geometry configuration. Fortunately, the weight function method considerably simplifies the determination of stress intensity factors [25, 26]. The important feature of the weight function is that it depends only on the geometry of the cracked body. If the weight function is known for a given cracked body, the stress intensity factor due to any load system applied to that body can be determined by using the same weight function. Therefore, there is no need in such cases to derive stress intensity factor expression for each load system and associated internal stress distribution. Thus, if the weight function is available, the stress intensity factor for a one dimensional crack can be obtained by multiplying the weight function, $m(x,a)$, and the internal stress distribution, $\sigma(x)$, in the prospective crack plane, and integrating the product along the crack length a.

$$K = \int_0^a \sigma(x) m(x,a) dx \tag{2}$$

The additional advantage of using the weight function method is that the stress analysis of only *un-cracked* body is necessary and its purpose is to determine the stress field, $\sigma(x)$. The weight function is dependent on the geometry only and, in principle, it should be derived individually for each geometrical configuration. However, Glinka and Shen [25,26] have found that one general weight function expression can be used to approximate weight functions for a variety of geometrical crack configurations subjected to one-dimensional stress fields of Mode I.

$$m(x,a) = \frac{2}{\sqrt{2\pi(x-a)}}\left[1 + M_1(1 - {}^{x}\!/_{a})^{\frac{1}{2}} + M_2(1 - {}^{x}\!/_{a})^{1} + M_3(1 - {}^{x}\!/_{a})^{\frac{3}{2}}\right] \tag{3}$$

In order to determine the weight function, $m(x,a)$, for a particular cracked body, it is sufficient to determine, the three parameters M_1, M_2, and M_3 in Eq. (3). Because the mathematical form of the weight function is the same for all cracks, the same integrating routine can be used for calculating stress intensity factors from Eq. (2) regardless of the geometrical configuration of a cracked body. Moreover, it has been found that only a limited number of generic weight functions are needed to enable the determination of stress intensity factors for a wide variety of load and geometry configurations. For example, cracks in welded plate structures will be finite or continuous surface cracks, finite or continuous embedded cracks, edge cracks or corner cracks.

Even though weight functions provide a powerful tool for computing stress factors, there are still numerous remaining questions that must be harmonized to ensure the consistency of LEFM as a means of assessing the fatigue strength of complex welded structures. These open questions include:

- What is the proper method for assessing the stress distribution in a welded structure that is used in the weight function?
- How does one handle the situation where the crack path is unknown or changes during crack growth?
- What numerical procedures should be defined to integrate both the weight function and the crack growth law?
- What are appropriate initial and final crack sizes?
- Do “small cracks” need to be considered?
- Can the influence of welding residual stresses reliably be considered in the crack growth assessment?
- How should threshold stress intensity factors be considered?
- When is 3D stress assessment needed and under what conditions is 2D sufficient?

Depending on how individual analysts answer the above, the expected fatigue lives many vary by one more. IIW Commission XIII is currently developing assessment procedures intended to systematically address these questions [27, 28]. The goal is that analysts with different computer tools and from different industrial backgrounds will be able apply well-defined procedures to get similar fatigue assessment results which are also consistent with existing experimental data for both simple and complex structures.

6 SUMMARY AND CONCLUSIONS

Materials and fabrication technologies for welded structures are continually evolving. The drives to reduce weight and cost, increase energy efficiency, improve performance and reduce the environmental footprint continue to provide challenges in the fatigue design and production of welded structures. This presentation attempts to provide a brief overview of current research topics and recent technological developments related to fatigue assessment for welded structures within the scope of the IIW Commission XIII. The experts that contribute to this Commission come from world-leading companies of all sizes and from major international universities and research institutes. The common objective is to provide science-based guidelines that can be applied to challenging design and life extension cases. Industries that benefit from Commission XIII publications include ship building, transportation, bridge and infrastructure, offshore, automotive, mechanical engineering and process equipment. Developments especially with regard to the definition of weld quality for fatigue performance, advanced high strength steel for welded structures, high frequency weld improvement methods and developments in fatigue assessment procedures have been summarized.

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