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Fatigue strength and life determination of weldments based on fracture mechanics

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Abstract

The paper provides an overview on the results of a German cluster project on the use of fracture mechanics to the determination of the fatigue strength of weldments with fatigue cracks originating at the weld toes. The approach includes (a) a concept for short crack propagation for which the common ΔK concept is not applicable and the crack closure effects are still being gradually build-up, (b) a method for determining fatigue life relevant initial crack sizes as they are needed in any fracture mechanics analysis and (c) multiple cracking and crack coalescence at load levels higher than the endurance limit. The analyses are stochastically performed. Both, the endurance limit and the finite life branch of the S-N curve are determined.

Besides a brief introduction into the approach, validation examples are presented. These comprise different weldment types (butt welds, cross joints and longitudinal stiffened plates), two steels (S355NL and S960QL) of quite different strengths, different weld geometries due to different welding techniques (WIG, MAG), as-welded and stress relieved welds and different stress ratios varying from $R = -1$ to $R = 0.5$.

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Introduction

The idea to apply fracture mechanics to the fatigue strength and life of weldments is anything but new. Almost half a century ago Maddox (1970) was one of the first to mention it. In 1974 he wrote: "It is now widely recognized that flaws will inevitably exist in welded structures and the old idea of removing all detectable defects must be replaced by the 'fitness for purpose' design philosophy. This makes it necessary to define reliable methods of assessing the significance of flaws, particularly in the context of fatigue,

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The most promising approach to this problem lies in the use of the fracture mechanics based description of fatigue crack propagation.” (Maddox, 1974). Since then, many studies have been performed on the issue. There is not enough space here for a detailed discussion of the existing material. What, however, should be pointed out is that even the IIW Recommendations for fatigue assessment of weldments (Hobbacher, 2016) includes fracture mechanics as an option, see also the textbook of Radaj et al. (2006).

With view exceptions, which will be mentioned below, the schemes of the existing approaches for fracture mechanics-based determination of the fatigue strength of weldments are characterized by the following features: (i) the crack driving force is described by the linear elastic ΔK factor, (ii) the initial crack size is assumed as a fixed value originally fitted to or based on back-calculations from S-N data also using the ΔK concept, (iii) the crack closure phenomenon is neglected, (iv) only one crack is considered for which the residual lifetime is obtained, (v) variations in the local geometry of the highly stressed regions in the weldments, e.g. the weld toes, are not taken into account, and (vi) welding residual stresses are not or in a very simplified way taken into account. Any of these assumptions are oversimplifications or at least disputable.

In the German project cluster IBESS (which stands for the German abbreviations for “Integral method for fracture mechanics based determination of the fatigue strength of weldments”) eight partners were involved. The aim was to develop a concept taking into account all the points mentioned above and to avoid the shortcomings as far as possible. The cluster was funded by DFG and AiF. For reasons of space, no exhaustive discussion of all aspects is possible here. Instead the reader is referred to a special issue of the journal Engineering Fracture Mechanics which is in progress.

Short and long crack propagation

With respect to fatigue crack propagation three stages can be distinguished: (i) the growth of microstructurally short cracks, (ii) the growth of mechanically/physically short cracks and (iii) the growth of long cracks. In the presence of material defects the second stage usually plays the major role with respect to the overall lifetime (Polak, 2003). Although comparable with respect to their size which is in the order of the dimension of the plastic zone surrounding the crack tip, mechanically and physically short cracks shall be separately discussed in the following.

Mechanically short crack

The crack driving force of mechanically short cracks cannot be described by the linear elastic ΔK concept but requires an elastic-plastic parameter. Within the IBESS project the cyclic J integral ΔJ is used, for the determination of which the authors used an analytical solution of Zerbst et al. (2011). The parameter ΔJ is determined by

$$\Delta J = \frac{\Delta K^2}{E'} \cdot [f(\Delta L_r)]^{-2} \quad (1)$$

with the function $f(\Delta L_r)$ being a plasticity correction function determined in conformity with the R6 solution (2009) but modified for cyclic loading such that

$$\Delta L_r = \frac{\Delta \sigma_{\text{app}}}{2 \cdot \sigma_0} \quad (2)$$

and

$$f(\Delta L_r) = \left[\frac{E \cdot \Delta \varepsilon_{\text{ref}}}{\Delta \sigma_{\text{ref}}} + \frac{1}{2} \frac{\Delta L_r^2}{E \cdot \Delta \varepsilon_{\text{ref}} / \Delta \sigma_{\text{ref}}} \right]^{-1/2} \quad (3)$$

The stresses and strains refer to the stabilized cyclic stress-strain curve. The parameter $\Delta \sigma_{\text{app}}$ is the applied cyclic stress range (referring to the gross cross-section) and σ_0 is a reference yield stress for which Madia et al. (2014) provided parametric equations. ΔK is obtained by weight function solutions based on the through thickness profiles of the elastic stresses. For the latter, the authors have generated parametric solutions applicable to Single-V and Double-V joints as well as to T- and cruciform joints subjected to tensile and bending loading which cover a wide range of weld toe radii (from 0.1 to 4 mm) and flank angles (from 10° to 60°) (Kiyak et al., 2016). For more details with respect to the determination of ΔJ see Madia et al. (2017). The analytical approach has been validated against numerical ΔJ solutions. An example for a cruciform joint shows Fig. 1. Details can be found in Tchoffo Ngoula et al. (2017).

Physically short crack

An important issue in fatigue crack propagation is the crack closure phenomenon. Crack propagation is only assumed at stresses at which the crack is open, i.e., the compression part of ΔK or ΔJ will not contribute to it.

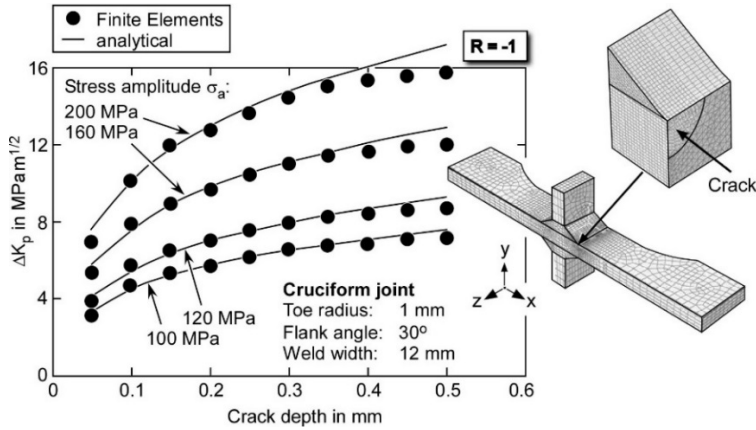


Fig 1:
 Comparison of finite element and analytical ΔJ values using Eqs. (1) to (3), according to Tchoffo Ngoula et al. (2017)

The effect is usually modelled by a crack closure parameter $U (= \Delta K_{eff}/\Delta K)$ such as illustrated in Fig. 2. The crack closure phenomenon, in that context, means that crack closure even occurs at applied stress levels above zero because of geometrical misfit between the crack faces due to (i) the plastic zone ahead of the crack tip which remains at the crack wake when the crack propagates, due to (ii) corrosion products on the crack faces and due to (iii) local mixed mode effects, see, e.g., Suresh (2003). Near the fatigue propagation threshold ΔK_{th} , particularly the effects (ii) and (iii) play an important role. The crack closure phenomenon is the more pronounced the lower the stress ratio of loading $R (\sigma_{min}/\sigma_{max})$ and it disappears at high stress ratios.

Different to long cracks, where the crack closure phenomenon has reached a stable state independent of the crack size, it is not existent at all at the beginning of the fatigue process and it gradually develops at the physically short crack stage. This refers to a U value of 1 at an initial crack size a_i in Fig. 2 which then decreases until it reaches a horizontal plateau U_{LC} when the long crack stage (LC) is reached. The transient behaviour of U can be obtained from the so-called cyclic R curve at the right side of Fig. 2 by

$$\frac{U_{sc}(a) - 1}{U_{LC} - 1} = \frac{\Delta K_{th}(a) - \Delta K_{th,eff}}{\Delta K_{th,LC} - \Delta K_{th,eff}} \tag{4}$$

The cyclic R curve describes the crack size dependency of the fatigue crack propagation threshold at the physically short crack stage. Note that the threshold consists of an intrinsic part $\Delta K_{th,eff}$, which depends on the crystal lattice and the elastic properties of the material and is identical to ΔK_{th} at high R ratio, and a crack-opening part, $\Delta K_{th,op}$, such that $\Delta K_{th} = \Delta K_{th,eff} + \Delta K_{th,op}(a)$. For a discussion of the parameters influencing $\Delta K_{th,op}$ see Zerbst et al. (2016), for its determination Maierhofer et al. (2017).

Initial crack size and multiple crack propagation of weld toe cracks

When Maddox is cited above, stating that “flaws will inevitably exist in welded structures” this calls for a more thorough consideration. Zhang and Maddox (2009), referring to metallurgical investigations, state that the average depth of such flaws is 150 μm with a maximum at 0.4 mm and that even high quality welds contain flaws up to 100 μm depths. But, does this necessarily mean that flaws of that size must be treated as initial cracks in fracture mechanics analyses?

What is important in that context is that the fatigue limit is not associated with crack initiation but with crack propagation (Miller, 1993; Murakami, 2002). In other words: The fatigue limit is that stress level below which all cracks that previously have been capable of growth are arrested. Crack arrest will occur (i) when a (microstructurally) short crack is hindered to proceed from one into a neighbouring grain, (ii) when the crack driving force ΔK_{eff} of a (physically) short crack decreases due to the gradual build-up of the crack closure phenomenon, and (iii) when a long crack is loaded at stress levels below the long crack fatigue crack propagation threshold $\Delta K_{th}(LC)$. In the case of cracks at notches the decreasing stress from the notch root will have a similar effect.

It is self-evident that an arrested crack will not be relevant with respect to fatigue life. This suggests the following conclusion: The size of the largest crack at the transition from crack arrest to crack growth defines a lower bound to the initial crack size used in fracture mechanics analysis. The principle is illustrated in Fig. 3 and shall be further explained in the following.

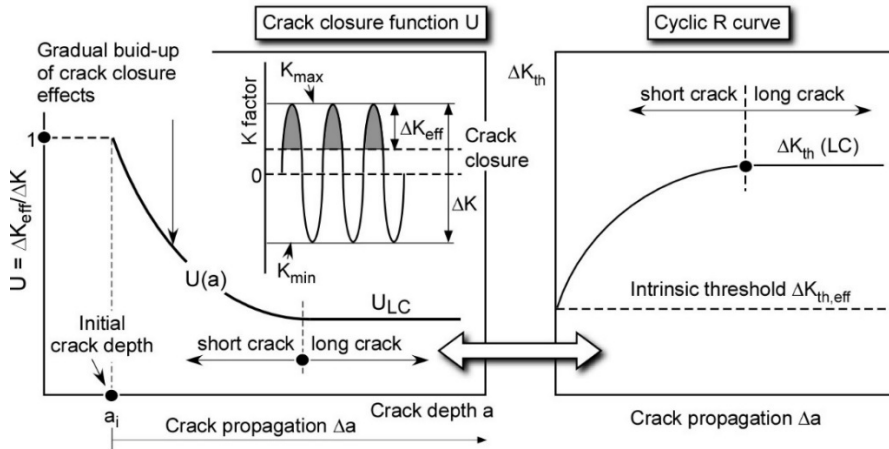


Fig. 2: Development of the crack closure function U with (physically) short crack propagation which is mirrored by the cyclic R curve $\Delta K_{th}(\Delta a)$

At the left-hand side of Fig. 3 a cyclic R curve analysis (the general principle is also illustrated in Fig. 4a) is shown. This is comparable to a monotonic R curve analysis where the crack driving force (of a component) as a function of the crack size is plotted together with the monotonic crack resistance curve, e.g., a J - Δa curve, (of the material). The third parameter of the “fracture mechanics triangle” is the initial crack size (here designated by a_i). In the monotonic case, the applied load, the crack driving force curve of which touches the R curve defines the transition from stable to unstable crack extension. This is similar in the case of a cyclic R curve analysis with the difference that the transition is between crack arrest and fatigue crack propagation. Within the frame of the present approach, R curve analyses are used for both, (i) the specification of the lower bound of the initial crack depth a_i of the material and (ii) the determination of the fatigue limit of welded components including their weld toe notches.

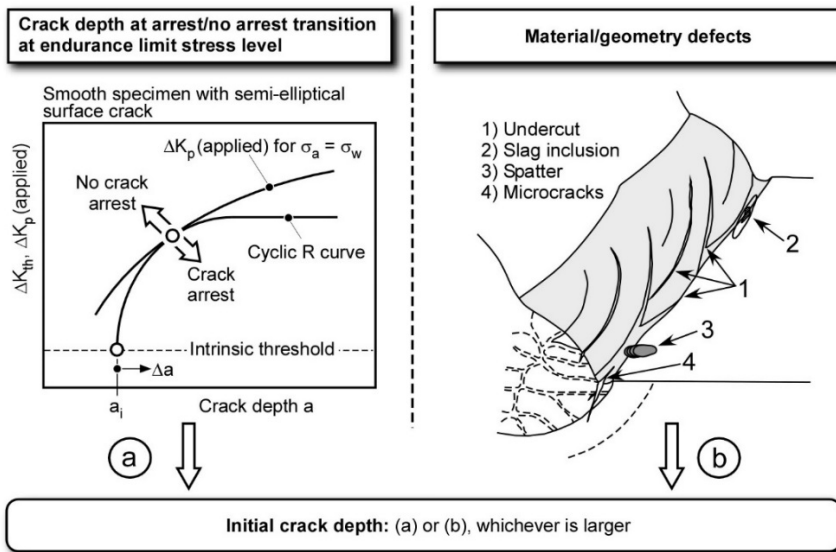


Fig. 3: Definition of the initial crack size a_i for the fracture mechanics-based determination of the fatigue strength of weldments within the frame of the IBESS method.

Initial crack depth

For specifying a_i , a crack driving force curve is theoretically determined for a smooth plate containing a semi-circular surface defect of varying depth a . The applied load refers to the fatigue limit of the material at a stress ratio of $R = -1$. It might be known from compendia or experiments or estimated from parameters such as the ultimate tensile strength or the hardness of the material. Note, however, that this might be more complicated than thought at the first moment, because what matters is the material in which the

(short) crack spends most of its lifetime, and this is the heat affected zone when the crack initiates from the weld toe. That the mechanical properties of this area might be significantly different from the base metal properties is illustrated by the hardness distributions of the joints shown in Fig. 5. Within the IBESS cluster project all material properties including the cyclic stress-strain curves, the fatigue crack propagation thresholds, the cyclic R curves and the monotonic fracture resistance and have been obtained on thermo-mechanically simulated material specimens, for more detailed information see Kucharzyk et al. (2017). It is self-evident and also experimentally demonstrated in Fig. 4 (c) that immediately above the fatigue limit (the amplitude of which was about 100 MPa in the present case) just one crack is capable of growth.

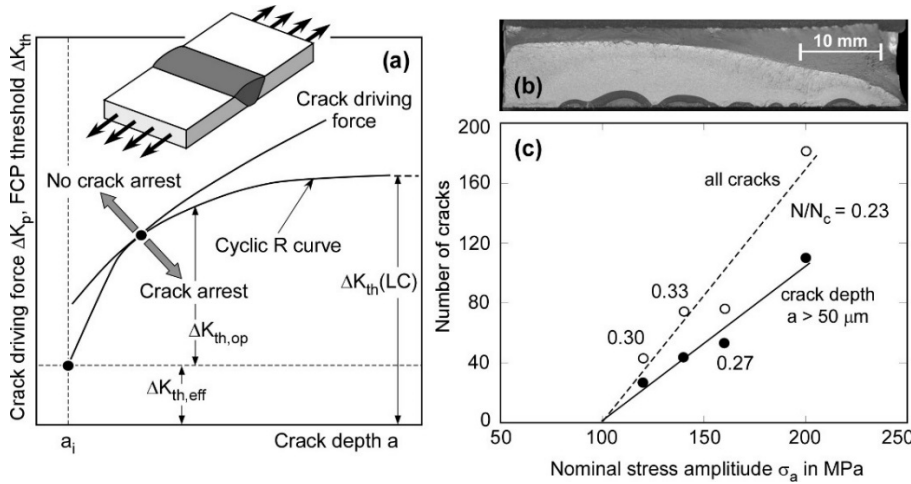


Fig. 4: (a) Basic principle of a cyclic R curve analysis; (b) Multiple crack propagation visualized by heat tinting; (c) Number of cracks along the weld toe of a S355NL butt weld as a function of the stress level; according to Schork et al (2017).

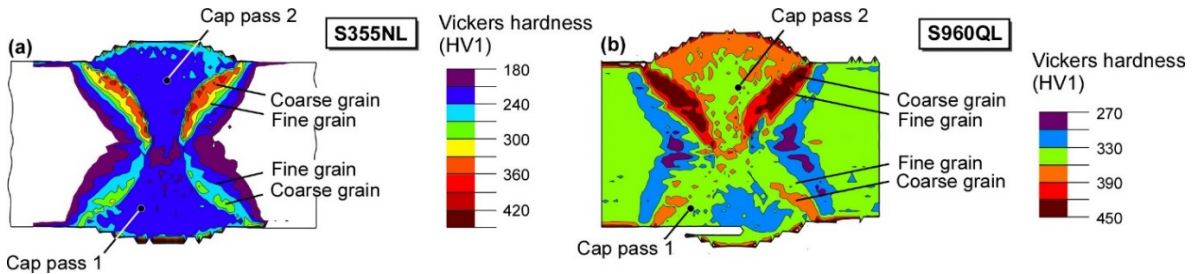


Fig. 5: Hardness distributions across the welds of S355NL and S960QL butt welds; according to Kucharzyk et al. (2017).

After the crack driving force has been specified such as described above, the cyclic R curve is added, however fixed only at the ordinate with its origin being at the intrinsic $\Delta K_{th,eff}$. Shifting it along the abscissa, the initial crack at the transition from crack arrest to growth is obtained by the curve position fulfilling the tangency criterion between crack driving force and R curve. As mentioned above, the initial crack size determined this way is a lower bound value. If crack-like defects larger than this are present, such as illustrated at the right-hand side of Fig. 3, these will take over the part of the initial crack.

Multiple cracks

That fatigue crack initiation at weld toes is a multiple crack problem is known for a long time (e.g., Otegui et al., 1989), and also that this is affected by the variation of the local geometry along the weld toe. As noted above, this is usually neglected in the literature approaches on fracture mechanics application to the fatigue strength of weldments. An exception is Lecsek et al. (1995) where the authors propose a procedure comparable to the present one. As can be seen in Fig. 4 (c) the number of cracks along the toe (with an overall length of 50 mm in the present case) increases with the load level.

To cover the problem of multiple cracking, the weld toe is theoretically spit into equidistant sections, each of these containing a crack and being characterised by a separate local geometry in terms of the weld toe radius, the flank angle, weld reinforcement and a secondary notch depth. The latter might refer to an undercut, but other features such as the roughness of the base plate or notches at the edges of the weld ripples may be treated as secondary notches as well. The varying geometry results in different stress states,

i.e. stress concentration factors and stress-depth profiles along the weld toe with the consequence that the initial cracks in the sections will find quite different growth conditions. In some of the sections they will extend rapidly, in others slowly and in some even not at all. When the surface points of two cracks touch, coalescence is assumed such that the length of the new crack at surface equals the sum of the lengths of the former individual cracks and the depth refers to those of the former deeper crack.

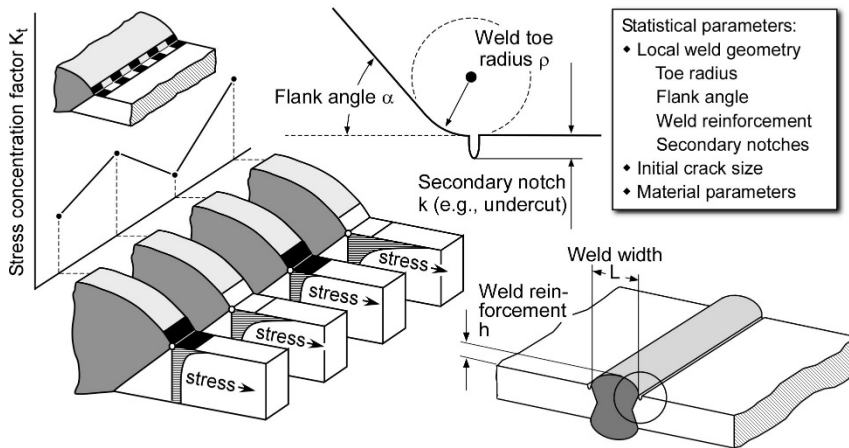


Fig. 6:

Subdivision of the weld toe into equidistant sections each of which is assigned to a random set of the geometry parameters toe radius, flank angle, weld reinforcement and secondary notch depth as the basis for the stochastic determination of both, the finite life fatigue strength and the endurance limit by the IBESS methodology.

Stochastic determination of the finite life fatigue and the endurance limit of weldments

Synthetic weldments are generated by fitting together the sections along the weld toe of Fig. 6 with each section being characterised by a separate local geometry. The random geometry is based on available statistical distributions of the parameters weld toe radius, flank angle, weld reinforcement and secondary notch. Fatigue crack propagation analyses are carried out for both, the finite life fatigue strength and the endurance limit. The finite life failure criterion might be monotonic fracture or another criterion such as a certain crack depth to wall thickness ratio. A number of synthetic weldment specimens is generated for each stress level such that the result of the analysis is a scatter band. With respect to the endurance limit (defined for 10^7 loading cycles in the present case) the number of specimens is counted which fail before reaching the 10^7 cycles. This number increases with the stress level and vice versa. Based on that information and the total number of specimens “tested” at each stress level a statistical distribution of the endurance limit is established. An example is shown in Fig. 7.

Further validation examples

The method was applied to a large number of welds comprising different weldment types (butt, cruciform, longitudinal stiffened), different materials and plate thicknesses (S355NL and S960QL - $T = 10$ mm; S355J2+N - $T = 3$ mm) with two weld geometries respectively manufacturing techniques (MAG and TIG) for each, and in the as-welded and stress relieved state. Only few of the results can be shown here because of the limited available space, see, however Madia et al. (2017).

As can be seen in Figs. 7 and 8, for butt welds of S355NL and S960QL tested at a stress ratio of $R = -1$ the experimental data are predicted well when heat affected zone (HAZ) data are used for the analyses. No validation of the endurance limits was performed, however, comparison with literature data (Ritter, 1994) yielded quite satisfying results. Conservative predictions have been obtained for $R = 0$ and 0.5 in Figs. 9 (a) and 10(a). As the reason the authors suspect a local R ratio lower than the nominal one in the tests due to compression residual stresses generated by residual stress re-distribution under cyclic loading (Hensel et al., 2017). No HAZ material data were available for the 3 mm thick butt welded plates of S 355J2+N (Fig. 9b). Instead data from the 10 mm plates have been applied. Finally, Fig. 10 (b) shows an application of an extended weld quality scheme (DIN EN ISO 5817, 2014). Based on this, the weldments were classified by C63 which is in good agreement with the IBESS predictions.

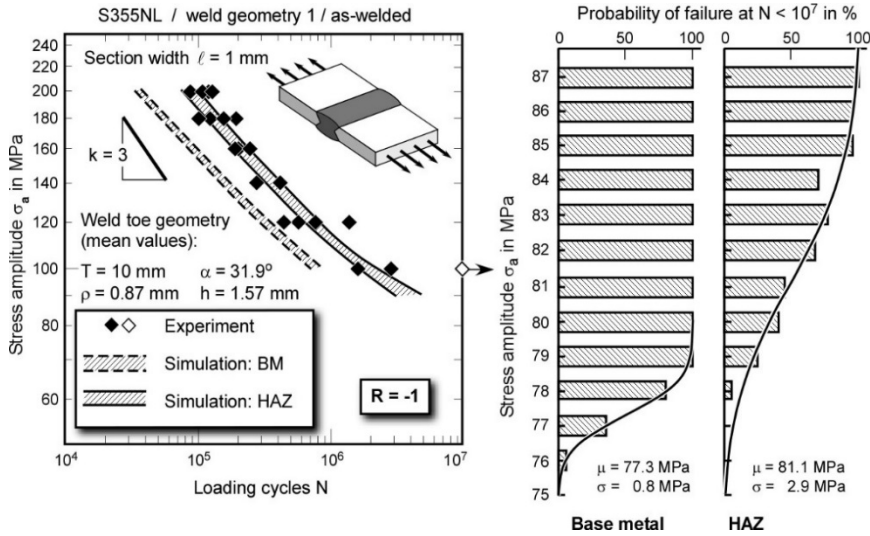


Fig. 7:

Validation example of the IBESS method. S355NL, butt weld, T = 10 mm, as-welded, loaded at R = -1.

The analysis is performed for base metal and HAZ properties with the latter revealing better results such as expected.

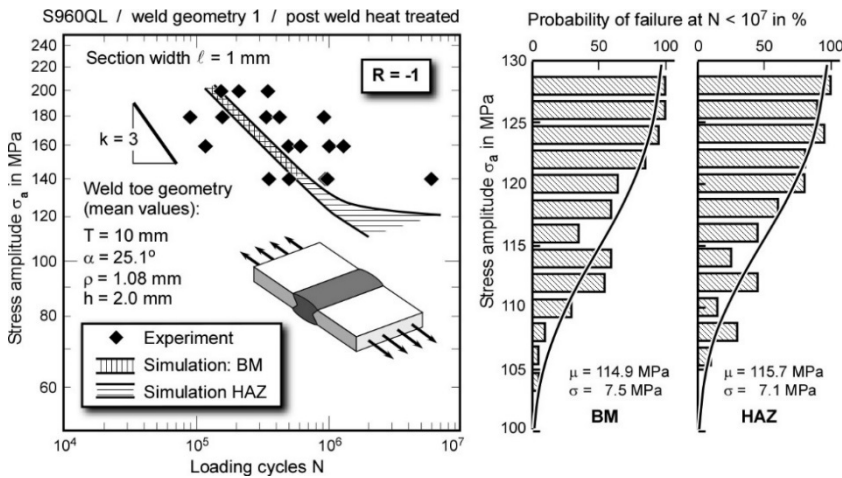


Fig. 8:

Validation example of the IBESS method. S960QL, butt weld, T = 10 mm, post weld heat treated, loaded at R = -1.

The analysis is performed for base metal and HAZ properties. That the results coincide is presumably due to the fact that the deformation at the toe of the higher strength material is still elastic up to higher net section stresses.

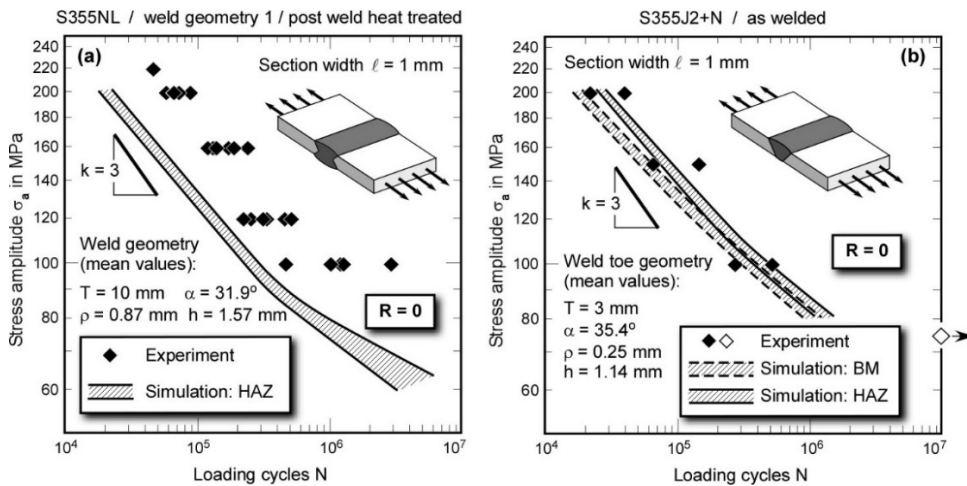


Fig. 9: Validation examples of the IBESS method.

(a) S355NL, butt weld, T = 10 mm, post weld heat treated, loaded at R = 0.

(b) S355J2+N, butt weld, T = 3 mm, as-welded, loaded at R = 0.

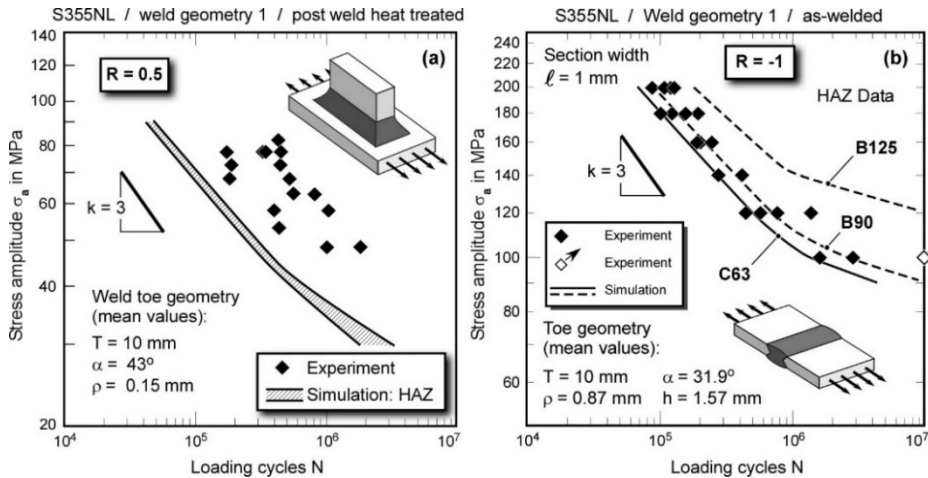


Fig. 10: Validation
 (a) S355NL, longitudinal stiffened, $T = 10$ mm, stress relieved, $R = 0.5$.
 (b) S355NL, butt weld, $T = 10$ mm, as-welded, $R = -1$; analysis based on (extended) weld quality (ISO 5817), Schork et al (2017).

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