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Recent developments in local concepts of fatigue assessment of welded joints

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ABSTRACT

Several lately proposed modifications or variants of the structural stress or strain concepts, of the notch stress or strain concepts (also termed 'local stress or strain concepts') and of the fracture mechanics concepts of fatigue assessment of welded joints are reviewed, whereas the wider context is presented in a recently republished and actualised standard work. The structural stress concepts described first are based on a linearisation of the stress distribution across the plate thickness or along the anticipated crack path and, alternatively, on the structural stress 1 mm in depth below the weld toe. The structural stress is defined and set against design *S–N* curves. A further structural stress concept is presented for welded joints in thin-sheet steels and aluminium alloys. Among the elastic notch stress concepts, the variant with the reference notch radius, $\rho_r = 1$ mm, recently verified also for welded joints in aluminium alloys with plate thicknesses $t \geqslant 5$ mm and the variant with a small-size reference notch radius, $\rho_r = 0.05$ mm, applicable to welded joints in thin-sheet materials, are outlined. The elastic–plastic notch strain concept is applied to a spot-welded tensile-shear specimen starting from a small-size keyhole notch at the nugget edge. The novel notch stress intensity factor (NSIF) approach relating to crack initiation and extrapolated to final fracture of seam-welded joints in steels and in aluminium alloys is reviewed. A more recently developed crack propagation approach for spot welds is finally described.

1. Introduction

In many technical fields, the nominal stress concept is still prevailing. The application of this concept requires the definition of the nominal stress on the one hand and its permissible value with reference to a corresponding classified structural detail on the other hand. In the design code which is representative for welded joints, the IIW recommendations [1], the fatigue design categories of welded structural details are abbreviated by FAT combined with a number, Fig. 1. The meaning of FAT is 'fatigue design class'. The number following FAT designates the allowable nominal stress range $\Delta\sigma_n$ (MPa) at $N = 2 \times 10^6$ cycles with the survival probability $P_s = 97.7\%$. The fatigue design curves are valid for any R ratio.

However, in case of more complex structural details, to which neither a nominal stress nor a design category can be assigned, only local concepts are applicable [1–4]. The necessity for the application of local concepts is further justified by the fact that the fatigue process has a local character and cannot be well described by global (nominal) stresses. The local concepts may be assigned to the following three groups, Fig. 2: elastic structural strain or stress concepts (the strain version was historically earlier), notch stress or strain concepts (also termed 'local stress or strain concepts') and fracture mechanics concepts, every group further subdivided as shown in the figure and relating to seam-welded joints on the one hand and spot-welded joints on the other hand.

It is not the aim of the following contribution to give a status report on local concepts which can be derived from the authors' recently republished and actualised standard work [2] and its prior reviewing publication [3]. It is aimed to review some more recently proposed special variants of the local concepts which are under controversial discussion at the time being. The presented concept variants and related issues are arbitrary to some extent, but the authors hope that the selected concept variants will be of lasting value.

Before giving the details about the selected fatigue assessment methods, the basic physical facts behind these methods are recapitulated. The fatigue life in numbers of load cycles consists of the technical crack initiation life and the subsequent long-crack propagation life up to final fracture. The technical crack may be a surface crack, about 1 mm in depth and 2 mm in length. The technical crack initiation life comprises the microstructural crack initiation life and the short-crack propagation life up to the technical crack size. In unnotched specimens, most of the total life may be consumed in microstructural crack initiation. In sharply notched specimens, on the other hand, the crack initiation life may be very short, but initiated cracks are arrested to some extent. These basic physical facts are not mirrored in the conventional global and more

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Nomenclature

A	cross-sectional area
a	depth of surface crack
a_i	depth of initial surface crack
C	constant in integrated Paris equation
c	half width of surface crack
d	weld spot diameter
$\bar{d}$	distance from weld toe (Haibach)
F	axial force
F_a	amplitude of tensile-shear force
I	integral value (Dong)
K_1	notch stress intensity factor in mode 1
K_I	stress intensity factor in mode I
K_{II}	stress intensity factor in mode II
K_{eq}	equivalent stress intensity factor
K_f	fatigue notch factor
K_t	theoretical stress concentration factor
K_w	weld notch factor
K	inverse slope of S–N curve
M_b	bending moment
m	exponent in the Paris equation
N	number of cycles
N_f	number of cycles to failure
n	exponent of thickness ratio
$\bar{n}$	notch support factor
P_s	survival probability
p	internal pressure
R	ratio of lower to upper stress
S_s	structural stress parameter
T	torque
T_K	scatter range index (P_s = 97.7%) relating to K_1
T_N	scatter range index (P_s = 90 or 97.7%) relating to N
T_σ	scatter range index (P_s = 90 or 97.7%) relating to σ or S_s
t	plate thickness
t_0	reference plate thickness
t_1	failure crack depth
W	section module in bending
w	specimen width
δ	distance from weld toe (Dong)
δ_b	bending stress portion
θ	weld toe angle
ρ	actual notch radius
ρ^*	substitute microstructural length
ρ_r	reference notch radius
σ_{hs}	hot spot structural stress
σ_k	maximum notch stress
$\sigma_{k,a}$	notch stress amplitude
σ_n	nominal stress
σ_{per}	permissible stress
σ_s	structural stress
$\sigma_{s,a}$	structural stress amplitude
σ_{s1}	structural stress 1 mm in depth
σ_{sH}	Haibach's structural stress

recent local fatigue assessment methods for welded joints with the exception of technical crack initiation and long-crack propagation in some cases.

2. Contributions to the structural stress concepts

The term 'structural stress' designates the basic stress in a structure in areas of geometrical inhomogeneity, where fatigue cracks are initiated ('hot spots') while the notch effect is ignored. Engineering methods of structural analysis, the finite element method among them, ignore the notch effect in general so that structural stresses are determined. Another, less convincing elder name for 'structural stress' is 'geometric stress'.

The original idea of the structural stress concept has been proposed in terms of structural strains. The local strain in front of the weld toe measured by a strain gauge serves as the parameter for fatigue assessment [5]. With the introduction of the finite element method, the structural stress variant which was developed for tubular connections in steel constructions (roofs, bridges, off-shore structures) gained in importance and led to the hot spot structural stress concept as a codified procedure of fatigue assessment [1–3]. In this method, the surface stresses at prescribed evaluation points in front of the weld seam are linearly extrapolated to the weld toe, Fig. 3. Later on, the concept was transferred from tubular connections to plate and shell structures of ships and other technical equipment [6,7]. The codified procedure may be supplemented by Haibach's special procedure which is also indicated in the figure.

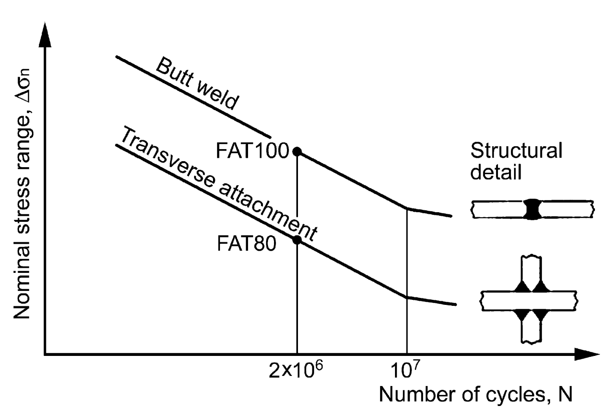

Fig. 1. Example of design S–N curves in the nominal stress concept; $\Delta\sigma_n = S = F/A$ or M_b/W; schematic diagram according to IIW recommendations [1] referring to fatigue design classes (FAT).

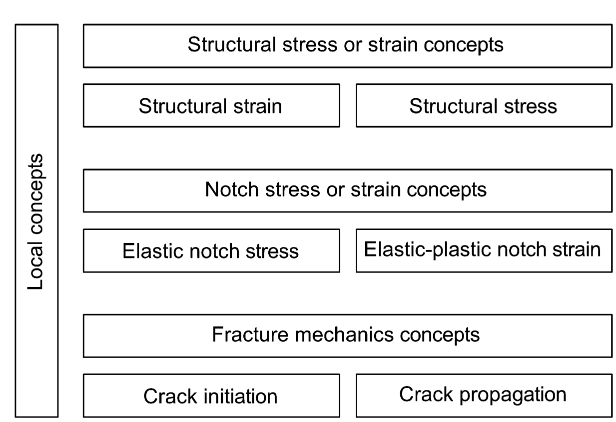

Fig. 2. Classification of local concepts of fatigue assessment of welded joints.

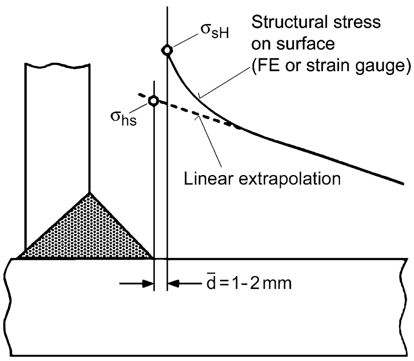

Fig. 3. Two procedures to obtain the hot spot structural stress: codified procedure of linear extrapolation (σ_{hs}) and procedure based on strain at distance $\bar{d}$ from the weld toe after Haibach (σ_{sH}).

The structural stresses depend, besides on the type and level of loading, on the shape, dimensions and arrangement of the components in the welded joint. In the method above, predominantly the normal stresses perpendicular to the weld seam affect the strength. Thus, the structural stress concept first of all serves for the evaluation of strength under loading in this direction. The following Sections 2.1–2.4 review some recent contributions to the structural stress concept.

2.1. Conventional structural stress concept

In general, welded tubular joints are distinguished from welded non-tubular joints. The latter joints are considered in the following, that is, the structural stress concept is applied to plate-type structures. The IIW recommendations [1,8] refer to this application.

The conventional method of determining the hot spot structural stress is the linear or nonlinear extrapolation of measured surface stresses to the weld toe (two or three evaluation points at locations recommended in [1]). The extrapolation of surface stresses is also applicable based on finite element models, Fig. 4a. For shell or plate structures the internal linearisation of the cross-sectional stresses gained from structural analysis offers an alternative, Fig. 4b. Systematic investigations revealed the need of detailed rules for finite element modelling and stress analysis in order to avoid too large scatter and uncertainties of the results [6–8].

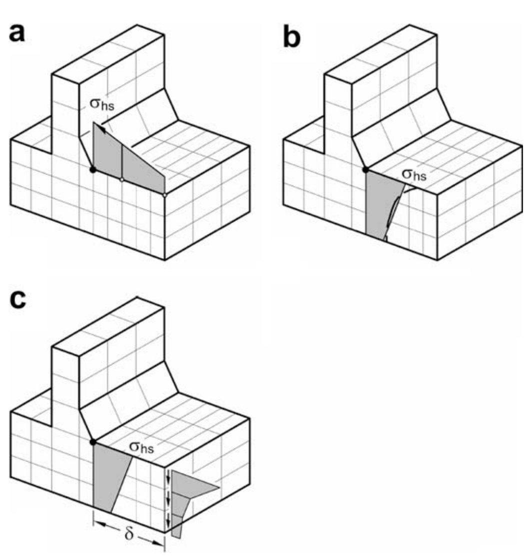

Fig. 4. Linear extrapolation of surface stresses (a) and internal linearisation of cross-sectional stresses at weld toe (b, c) in a finite element model with hexahedral elements resulting in hot spot structural stress σ_{hs}; in the variant (c) proposed by Dong et al. [12] normal and shear stresses at distance δ are the basis of σ_{hs}.

The relevant design *S–N* curves for plate-type welded structures were derived on the basis of comprehensive evaluations of available fatigue test data for fillet-welded cruciform joints and transverse attachment joints, Fig. 5. For the normal case of such welds in steels, the design guide [8] recommends the fatigue class FAT 100 (permissible stress range, $\Delta\sigma_{per}$ = 100 MPa at $N = 2 \times 10^6$ load cycles). Exceptions are load-carrying fillet welds (due to a more severe notch stress concentration at the weld toe) and longitudinal attachments at plate edges (l > 100 mm) for which FAT 90 is applicable. Correspondingly, FAT 40 or FAT 36 may be applied in the case of such welded joints in aluminium alloys.

In the case of welded joints with plate thicknesses $t \geqslant 25$ mm, the thickness effect that diminishes the fatigue strength has to be considered:

$$\Delta\sigma_{per}(t > 25\ \mathrm{mm}) = \Delta\sigma_{per}(t_0 = 25\ \mathrm{mm})(t_0/t)^n \tag{1}$$

The exponent n varies between n = 0.1 for longitudinal attachments welded to plate edges, n = 0.2 for butt-welded joints and n = 0.3 for fillet-welded joints [8].

A special problem are structural distortions caused by the fabrication process, especially axial and angular misalignments. Because the structural stress design *S–N* curves are based on measured structural stresses, they already include the effect of specimen misalignment. Therefore, their application requires explicit consideration of the influence of misalignment on the actual structural stresses whereas within the nominal stress concept, this effect is implicitly considered to a certain degree in the nominal stress design *S–N* curves.

In the normal case, the finite element models of ideal geometry, delivering the stresses, do not contain misalignment. In plate-type structures, the effect of misalignment on the structural stresses must be considered predominantly in butt-welded joints and in fillet-welded cruciform joints (because of a possible axial misalignment) as well as in fillet-welded one-sided transverse attachments (because of a possible angular misalignment). If no detailed data are available, the IIW recommendations [1] suggest multiplication of the axial stress at the weld toe with given factors which consider the effect of misalignment in the range up to 15% of the plate thickness.

Referring to the design *S–N* curves of load-carrying fillet welds mentioned above, it is alternatively possible to consider the more severe notch stress concentration at such welds by increasing the structural stress instead of reducing the FAT class. Poutiainen and Marquis [10] have proposed to superimpose a triangular stress

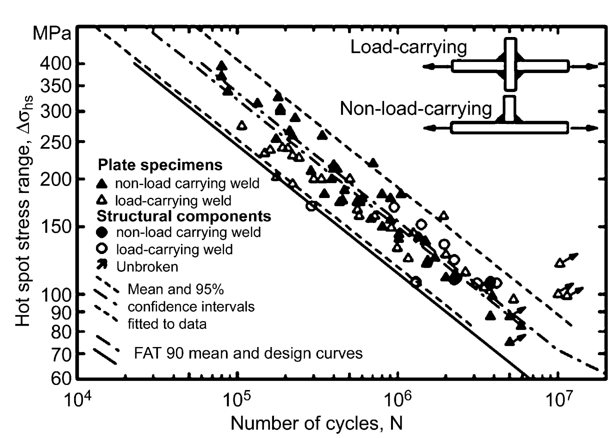

Fig. 5. Endurable hot spot structural stress ranges $\Delta\sigma_{hs}$ for load-carrying and non-load-carrying fillet-welded joints; fatigue test data and design *S–N* curves; after Maddox [9].

distribution on the linearised through-thickness stress distribution at the weld toe, the former depending on the force transmitted by the weld. This leads to a trilinear stress distribution in the case of double-sided welds which can take the size effects of the plate and the weld into account.

2.2. Modified structural stress concept

The mentioned concept variant of structural stress linearisation across the plate thickness (internal linearisation) has been modified by Dong [11,12] with the effect that the influence of the stress gradient in the direction of expected crack growth is considered based on a crack propagation approach. The internal linearisation across the plate thickness in the case of a single-sided weld is shown in Fig. 6a. In certain cases linearisation up to a depth $t_1 < t$ is recommended, Fig. 6b, for example, in the case of cracks originating from attachments at plate edges. The depth t_1 is the crack length at failure. For double-sided welded joints under symmetrical loading conditions, a linearisation across one half of the plate thickness is recommended ($t_1 = t/2$), Fig. 6c.

For the determination of the structural stresses from finite element models, Dong recommends special procedures that are claimed to be mesh-insensitive. As the grid point stresses depend on the mesh density close to the notch stress singularity at the weld toe and because these stresses are influenced by the stresses in the adjacent weld element, they should be evaluated at a distance δ from the weld toe, Fig. 4c. By means of equilibrium conditions, the membrane and bending portions may then be derived from the normal and shear stresses in the cross-section at distance δ, thus providing a linear stress distribution in the cross-section at the weld toe. The procedure ignores the shear stresses at the flank sides of the element. This may lead to inaccuracies in the case of pronounced structural stress concentrations [13]. In the case of a partial linearisation up to the depth t_1, additional stresses in the longitudinal section in this depth must be taken into account in the equilibrium conditions. As an alternative, Dong proposes to determine the structural stresses from the element nodal forces in the cross-section at the weld toe, as they better comply with the equilibrium conditions. This procedure is appropriate especially in the case of shell elements, but it excludes partial linearisation in thickness direction.

To determine the endurable number of load cycles for a given hot spot structural stress, a 'master *S–N* curve' is applied that contains a special structural stress parameter ΔS_s which is derived from the endurable hot spot structural stress range $\Delta\sigma_{hs}$ combined with the crack-growth-based modification already mentioned:

$$\Delta S_s = \Delta\sigma_{hs}(t/t_0)^{1/2-1/m} I(\delta_b)^{-1/m} \quad (2)$$

with plate thickness t, reference thickness $t_0 = 1$ mm (introduced according to [2, p. 69]), exponent m in the Paris equation describing crack growth (with $m = 3.6$ after Dong) and an integral $I(\delta_b)$ depending on the ratio $\delta_b = \sigma_b/(\sigma_m + \sigma_b)$ of bending structural stress to total structural stress and on the boundary conditions during crack growth (load-controlled or deformation-controlled). The 'master *S–N* curve' in Fig. 7 was established by evaluation of numerous test results, applying the respective hot spot structural stress according to Fig. 6 and determining the structural stress parameter ΔS_s according to Eq. (2). The scatter range index T_σ of the endurable structural stress parameter ΔS_s is $T_\sigma = 1{:}1.59$, which is an acceptable value according to code regulations for welded joints. Misalignment was not taken into account in the structural stress. This means that the effect of misalignment has been included in the master *S–N* curve to the extent misalignment was present in the test specimens.

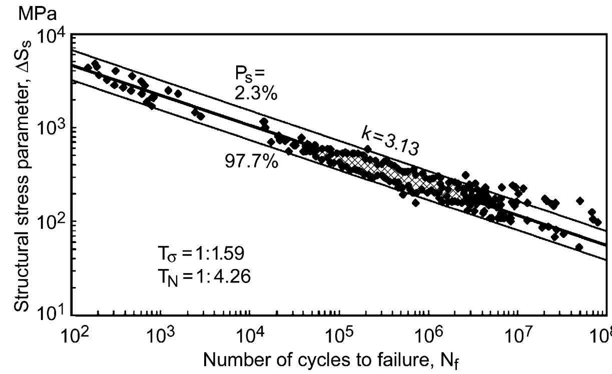

Fig. 7. Master *S–N* curve according to Dong et al. [12]; with structural stress parameter ΔS_s and survival probability P_s, inverse slope k and scatter range indices T_σ and T_N; various types and dimensions of welded joints; proprietary database and open literature.

At present, Dong's modification of the structural stress concept has some restrictions. The partial linearisation of the structural stresses presumes the definition of a fatigue-effective reference length across which linearisation is performed. This length cannot be uniformly defined but must be derived by individual adjustment to the relevant test results.

2.3. One millimetre in depth structural stress concept

An unconventional structural stress concept that considers the structural stress calculated 1 mm in depth below the weld toe (on the expected crack path) as the relevant fatigue parameter has been proposed by Xiao and Yamada [14]. The approach has been verified by these authors for non-load-carrying fillet welds executed on both sides of transverse and longitudinal attachments. Noh et al. [15] have shown that the concept is applicable also to the fatigue assessment with respect to toe failures of load-carrying fillet welds in cruciform joints considering partial and full penetration welds.

The selection of the above-mentioned evaluation point 1 mm in depth is based on analysis results for a reference structural detail, a

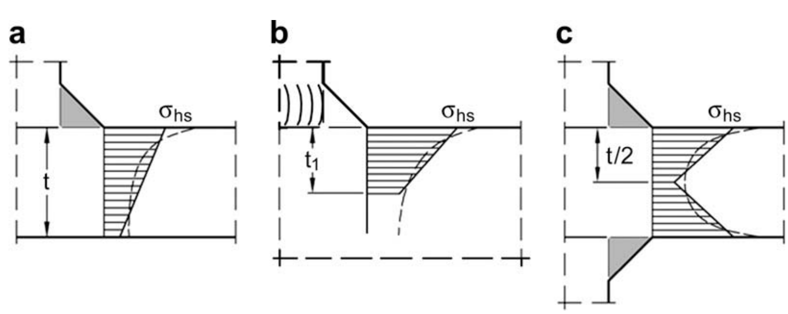

Fig. 6. Internal linearisation of the structural stresses as proposed by Dong et al. [11,12] for single-sided weld (a), edge weld (b) and double-sided weld (c) resulting in the hot spot structural stress σ_{hs}; cross-sections (a, c) and front view (b).

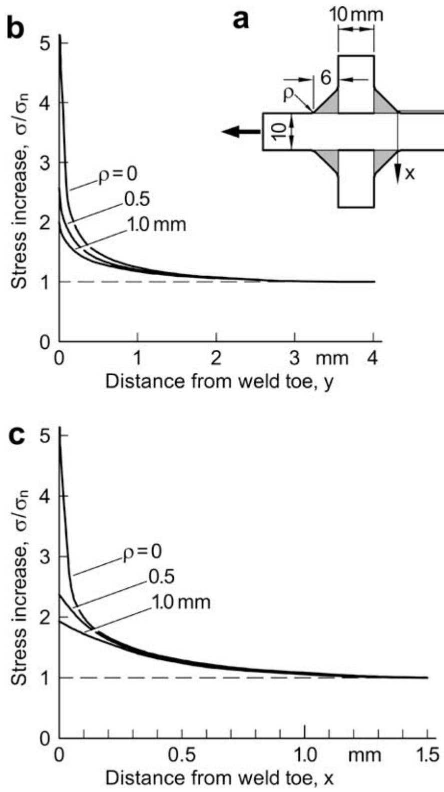

Fig. 8. Stress distributions (b, c) calculated by the finite element method for a reference structural detail (a) with non-load-carrying fillet welds (double-sided transverse attachment joint; weld toe radius ρ); after Xiao and Yamada [14] (redrawn with restriction to weld toe angle $\theta = 45°$).

plate of thickness $t = 10$ mm with double-sided transverse attachments, Fig. 8a. Finite element calculations showed that the local stress at the weld toe of the reference detail drops more rapidly in the thickness direction than on the surface. Whereas on the surface, the local stress increase extends to a distance of about 2.5 mm in thickness direction, Fig. 8b, the local stress has already dropped to nearly the nominal stress 1 mm in depth below the notch surface, Fig. 8c, independently of the weld toe radius and weld toe angle (the variation of angle is deleted from the original figure). Furthermore, it is shown that the stress 1 mm in depth is correlated with the short-crack propagation phase. The finite element analysis requires a mesh density that provides the stress 1 mm in depth with sufficient accuracy. After Xiao and Yamada [14], 1 mm is mentioned to be the maximum allowable element length in the case of hexahedral elements. On the other hand, extremely fine (plane) meshes are used by Noh et al. [15].

This concept has been applied to various types of welded joints with geometries similar to the reference structural detail, i.e. plates with transverse and longitudinal attachments or gussets. The fatigue lives determined in fatigue tests and plotted against the structural stress 1 mm in depth below the weld toe result in a sufficiently narrow scatterband whose lower bound meets the design *S–N* curve JSSC-D in the Japanese design code, Fig. 9, which corresponds to the curve FAT 100 in the IIW recommendations [1]. Furthermore, it is shown that the structural stress 1 mm in depth takes the thickness or size effect directly into account, in contrast to the stress in a depth chosen in proportion to the thickness of the plate.

The concept is applicable with plate thicknesses $t > 20$ mm, whereas in the case of a transverse attachment on a plate with $t = 10$ mm, simply the nominal stress is the result of the finite element analysis without a deterioration of the assessed fatigue

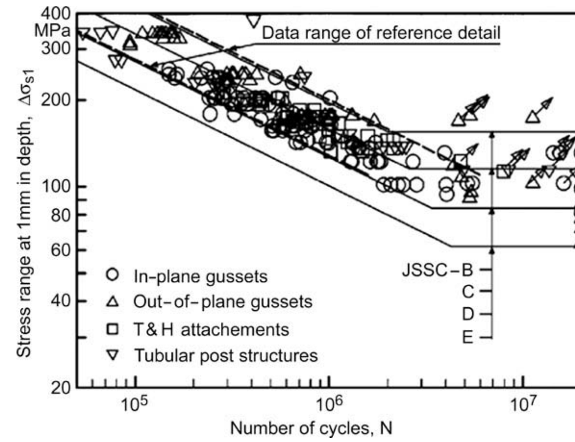

Fig. 9. Fatigue lives of different welded structural details evaluated dependent on the structural stress range $\Delta\sigma_{s1}$ 1 mm in depth below the weld toe; various types and dimensions of fillet-welded attachment joints; comparison with JSSC design curves; after Xiao and Yamada [14].

strength. Here, increased structural stresses occur only with transverse attachments of large plate thickness, with longitudinal attachments and with load-carrying fillet welds. The concept is not applicable to weld root failures.

2.4. Special structural stress concept for thin-sheet welded joints

A special structural stress concept has been proposed by Fermér and Svensson [16] for thin-sheet welded joints in automotive design with sheet thicknesses $t \leqslant 3$ mm. It is based on thin shell element models, Fig. 10a. The following modelling rules are introduced. The elements representing the weld should be twice as thick as the thinnest sheet in the joint. The elements should be sized about $5 \times 5\ \text{mm}^2$. The averaged element stresses at the nodal points adjacent to the weld provide the structural stress. Testing of various specimens with different sheet thicknesses provided two design *S–N* curves, both for steels and for aluminium

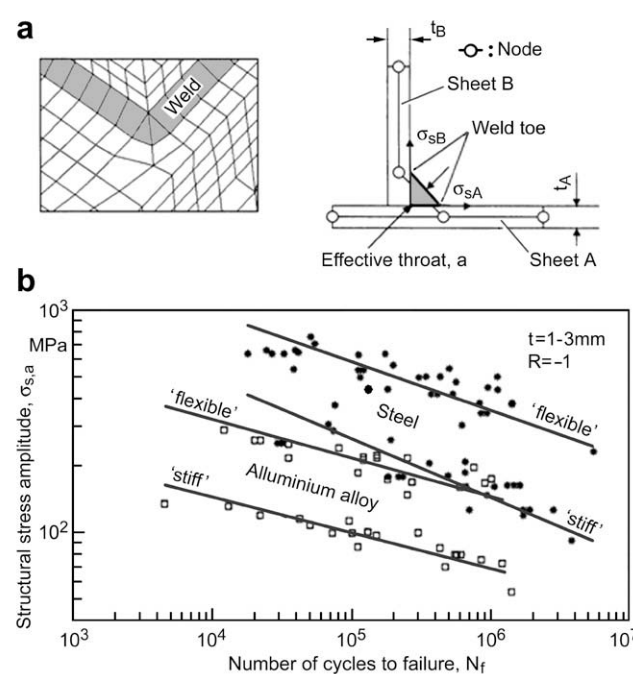

Fig. 10. Structural stress concept for GMA-welded thin-sheet joints after Fermér and Svensson [16]; finite element meshing rules (a) and design *S–N* curves (b).

alloys, Fig 10b. The *S–N* curves for 'flexible joints' apply to prevailing bending stresses in the shell elements whereas the *S–N* curves for 'stiff joints' apply to prevailing membrane stresses in the shell elements.

3. Contributions to the notch stress or strain concepts

Notch stress or strain concepts (also termed 'local stress or strain concepts') use the maximum elastic notch stresses or elastic–plastic notch strains, respectively, to assess the fatigue strength, Fig. 11 (restricted to stresses). These stresses or strains can be calculated for the sharp or mild notches at the weld toe, weld root or nugget edge where the structural stresses have already been defined. One distinguishes between elastic notch stress concepts and elastic–plastic notch strain concepts. The elastic notch stress concepts were originally restricted to the high-cycle fatigue range. The elastic–plastic notch strain concepts apply to the medium-cycle and low-cycle fatigue range [2,3].

The (elastic) notch stress concept for welded joints is based on the early work of Mattos and Lawrence [17] (notch support effect according to Peterson: critical distance approach) and of Radaj [18] (notch support effect according to Neuber [19]: fictitious notch rounding). The concept was modified by Olivier et al. [20] (statistical evaluations) and extended by Sonsino [2,3] (highly stressed material volume, multiaxial strength criteria). The elastic notch stress concept has been successfully applied to welded joints in steels and in aluminium alloys [1–3,21].

The (elastic–plastic) notch strain concept for welded joints (also early proposed by Mattos and Lawrence [17]), is based on developments for non-welded components loaded predominantly in the low-cycle fatigue range, incorporating Neuber's simple equation ('Neuber's rule') which relates the elastic–plastic notch strain to the notch stress in case of local yielding at the notch.

3.1. Modification of the notch stress concept in the IIW recommendations

The elastic notch stress concept has originally been proposed for application in the high-cycle fatigue range. It is extended for application in the medium-cycle and low-cycle fatigue range by the IIW recommendations [1]. A uniform reference notch radius $\rho_r = 1$ mm at sharp weld notches (sheet thickness $t \geqslant 5$ mm) is combined with the design *S–N* curve FAT 225 for welded joints in steel. This extension may result in non-conservative results in case of mild weld notches.

The recently approved modification of the IIW recommendations confines the applicability of the *S–N* curve FAT 225 by prescribing a minimum fatigue notch factor, $K_w = 1.6$, at the weld toe or root and by proving additionally that the parent material

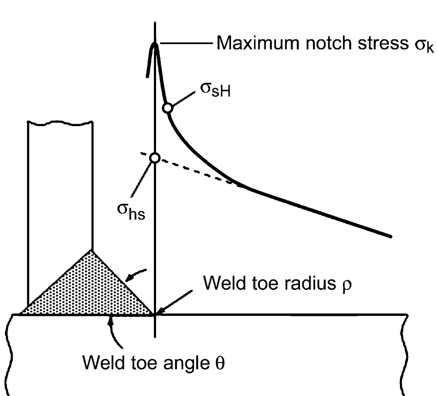

Fig. 11. Definition of the maximum notch stress σ_k in comparison to the hot spot structural stress σ_{hs} and Haibach's structural stress σ_{sH} (compare Fig. 3).

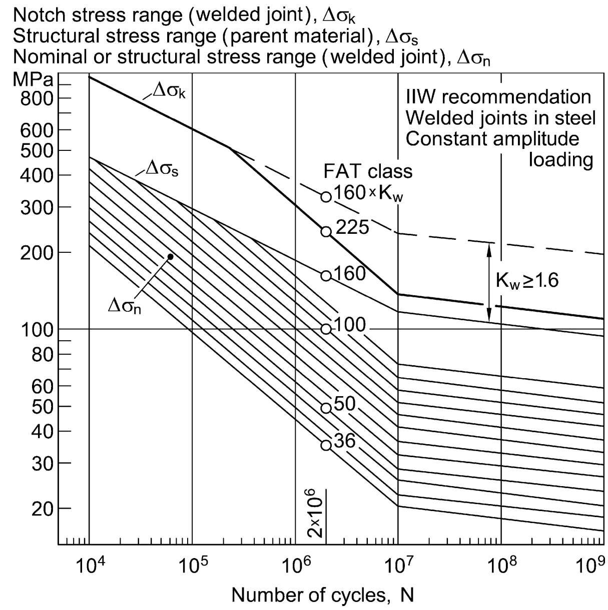

Fig. 12. Limitation to the design *S–N* curve FAT 225 (relating to reference notch radius $\rho_r = 1.0$ mm) by FAT 160 × K_w with weld notch factor $K_w \geqslant 1.6$; according to the IIW recommendations [1].

outside the weld notch provides a sufficient fatigue strength with respect to the structural stress there [1]. Considering low fatigue lives or high local stress levels, the design *S–N* curve FAT 225 must be limited by FAT 160 × K_w (with $K_w \geqslant 1.6$), Fig. 12. The limitation is given by transformation of the curve FAT 160 relating to the parent material into the local system. For this, the weld notch factor K_w of the weld under consideration has to be derived as the ratio of the maximum notch stress σ_k for $\rho_r = 1$ mm to the relevant hot spot structural stress σ_s. The described procedure corresponds to performing two assessments independently and using the less conservative result: weld notch stress (according to $K_w \geqslant 1.6$) compared with the curve FAT 225 and relevant structural stress outside the weld notch compared with the curve FAT 160.

3.2. Uniform reference radius in the codified notch stress concept

For welded joints in aluminium alloys with sheet thickness $t \geqslant 5$ mm, Morgenstern et al. [22] propose to use the same reference notch radius $\rho_r = 1.0$ mm that is uniformly applied to welded joints in steels according to the IIW recommendations [1]. Fatigue test results of various GMA-welded joints in the aluminium alloys AlMg4.5Mn and AlMgSiT6 fit well into a narrow scatterband, Fig. 13, provided the notch stresses are calculated for a reference

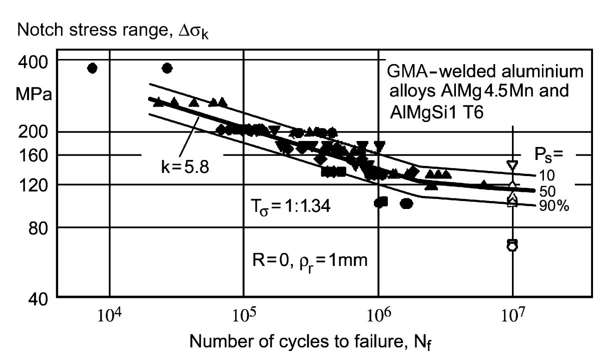

Fig. 13. Notch stress *S–N* curve for welded joints in aluminium alloys; reference notch radius $\rho_r = 1$ mm; white symbols: fatigue-tested without fracture; after Morgenstern et al. [22].

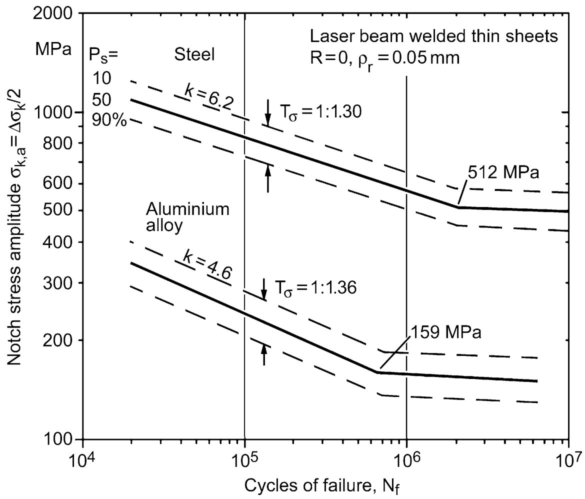

Fig. 14. Master S–N curves according to the small-size notch concept with a reference notch radius $\rho_r = 0.05$ mm for laser beam welded thin-sheet steels and thin-sheet aluminium alloys (t = 1–2 mm); after Eibl et al. [26,27].

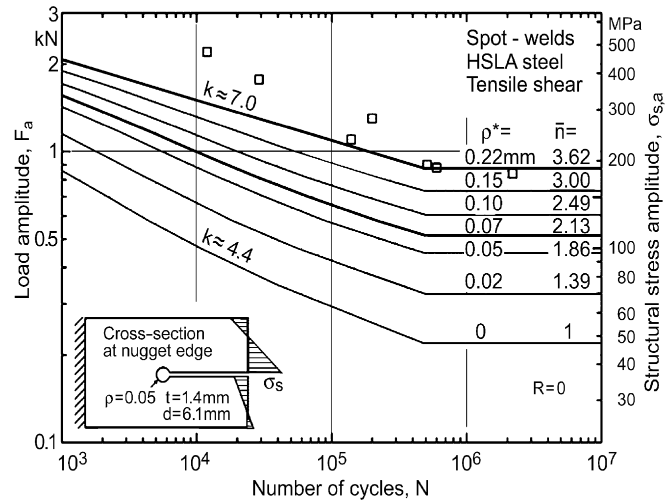

Fig. 15. Calculated S–N curves of load amplitude and of structural stress characterising crack initiation ($a_i = 0.25$ mm) in a spot-welded tensile-shear specimen; analysis based on the elastic notch stress and elastic–plastic notch strain concepts and compared with test results (square points); after Seeger et al. [31].

radius of 1 mm. At $N = 2 \times 10^6$ load cycles, this investigation results in a permissible notch stress range $\Delta\sigma_{per} = 70$ MPa (survival probability $P_s = 97.7\%$) which is now included in the IIW recommendations [1]. This value is derived for the stress ratio $R = 0.5$ (in contrast to the test condition) to cover the influence of high tensile residual stresses. The permissible stress range above is confirmed by Zenner and Grzesiuk [23]. The corresponding permissible stress range for welded joints made of magnesium alloy MgAl3 is $\Delta\sigma_{per} = 28$ MPa [24].

3.3. Small-size notch concept for thin-sheet welded joints

The notch stress concept which uses the small-size reference notch radius $\rho_r = 0.05$ mm has successfully been applied to spot-welded and laser beam welded joints, mainly in thin-sheet steels and aluminium alloys ($t \leqslant 3$ mm) [25–29]. Laser beam welded joints have been investigated by Eibl et al. [26,27]. The finite element models used are of the two-dimensional type and apply the reference notch radius just mentioned. This radius should be chosen as small as possible to minimise cross-sectional weakening, but should remain larger than the local grain size ([2, pp. 518–522]).

The maximum notch stresses from this elastic model allowed to allot the fatigue test results for specimens with different geometries (tensile-shear specimens, peel-tension specimens, hat section specimens) and with various sheet thickness combinations to narrow scatterbands of the S–N curve, Fig. 14, thus providing 'master S–N curves' with nominal fatigue strength values for the design of welded joints in steels and aluminium alloys. These curves are also applicable to the design of thin-walled laser beam welded gasoline injection elements of cylindrical shape [28]. In addition, the applicability of the concept to GMA-welded thicker sheets in aluminium alloys has been confirmed [29]. The unusually high endurable notch stresses correspond to the extremely small reference notch which causes unrealistically high elastic notch stresses. There is a close link between the small-size notch approach and the NSIF approach (see Section 4.1).

3.4. Elastic–plastic notch stress and strain concept for spot-welded joints

The first step in the elastic–plastic notch stress and strain concept is the determination of the purely elastic notch stresses. Conforming with the above statements, a small-size notch with reference radius $\rho_r = 0.05$ mm is applied to the nugget edge for the fatigue analysis of spot-welded or laser beam welded thin-sheet materials (compare the cross-sectional detail in Fig. 15). Radaj et al. [30] have presented simple and accurate notch stress equations for such keyhole notches when subjected to the basic crack tip loading conditions (modes I, II, III, and non-singular modes) which are typical for the nugget edge of spot welds. The fatigue-effective notch stresses in the high-cycle fatigue range are determined by averaging the stresses across the material-dependent substitute microstructural length ρ^* perpendicular to the notch contour [18,19].

The fatigue strength of the considered spot-welded tensile-shear specimen in the finite life region has subsequently been determined based on the elastic–plastic notch strains at the nugget edge. They have to be set equal to the endurable strains in a smooth tensile specimen, multiplied by the notch support factor $\bar{n}$ which designates the increase in endurable notch stress in the high-cycle fatigue range, $\bar{n} = K_t/K_f$. This was done by Seeger et al. [31] for the spot-welded tensile-shear specimen made of HSLA steel with nugget diameter $d = 6.1$ mm, sheet thickness $t = 1.4$ mm and specimen width $w = 38$ mm. The resulting S–N curves, with the crack depth $a_i = 0.25$ mm as the failure criterion, depend on the selected substitute microstructural length ρ^* across which the notch stresses are averaged to get the fatigue-effective notch stresses, Fig. 15. Test results reported by McMahon et al. [32] are compared with the above theoretical S–N curves. Obviously the microstructural length $\rho^* = 0.22$ mm is a realistic value (positioned between the published values [18,19] for rolled and cast steels). The slope of the appertaining S–N curve ($k \approx 7.0$), however, does not correspond to the test results. The S–N curves presented in the figure show the structural life up to a crack depth $a_i = 0.25$ mm. They do not show the total life with continued crack growth up to final fracture of the specimen, but the major portion of the total life is actually caught by the crack depth considered. The above has been a preliminary investigation aiming at a practicable elastic–plastic notch stress and strain concept for spot-welded and laser beam welded joints.

4. Contributions to the fracture mechanics concepts

The fracture mechanics concepts are subdivided into the stress intensity concepts and the crack propagation concepts. Within the stress intensity concepts, the elastic stress intensity factor of the pointed V-notch at the weld toe, or of the slit-like notch at the weld root or nugget edge, is determined and compared with endurable values represented by stress intensity *K–N* curves. The stress intensity concepts can also be assigned to the notch stress concepts. Within the crack propagation concepts, a crack propagation analysis is performed integrating the Paris equation starting with an assumed or actually initiated short-crack [1–3].

4.1. Notch stress intensity factor concept for seam-welded joints

The elastic notch stresses at pointed edge notches (V-notches) are singular at the notch tip. The stress field in close vicinity of the notch tip is controlled by the notch stress intensity factor (NSIF) [33,34]. Fillet welds have a toe notch opening angle of 135° whereas the slit end at the weld root is characterised by an opening angle of 0°. The stress state in the neighbourhood of pointed notches approximates the stress state in the neighbourhood of corresponding sharp notches with a finite notch radius. The local stress field at the weld toe can then be described by the NSIF. It depends on the level of structural stress at the transition point (weld toe), on the loading condition (tension, bending or shear load), and on the geometry of the joint inclusive of the plate thickness (size effect). One distinguishes between the basic loading modes 1, 2 and 3 which may be superimposed.

In fillet-welded transverse attachment joints under tension or bending loads, the loading mode 1 is predominant (for a notch opening angle of 135°, the stress distribution due to mode 2 is non-singular). It is anticipated, that the fatigue life of the specimens will be governed by the cyclic NSIF thus establishing K_1–N curves. The two scatterbands resulting from various published fatigue test data referring to non-load-carrying fillet-welded joints made of steel or aluminium alloy are convincingly narrow. The fact has to be noted that the thickness effect is already covered by the NSIF and that the scatter range index T_K is related to two standard deviations, Fig. 16. The plate thickness ranges considered are $t = 13$–100 mm for the steel specimens and $t = 3$–24 mm for the aluminium alloy specimens. The thickness effect which is included here with the exponent $n = 0.326$ for a notch opening angle of 135°, has to be compared with the exponents 0.1–0.3 of the thickness ratio recommended by various codes. The NSIF concept is primarily appropriate when considering crack initiation ($a_i \approx 0.3$ mm), but it is approximately applicable to the test results shown in the figure which refer to final fracture.

A handicap may arise for the application of the NSIF concept because the dimension of the NSIF depends on the notch opening angle necessitating sets of reference data for each angle of interest. For example, the endurable stress intensity factors for the weld toe (opening angle 135°, e.g. fillet welds) are not directly comparable to those of the weld root (opening angle 0°, e.g. lap joints). Evaluating the averaged strain energy density (SED) within a small circular region at the notch or slit tip removes the problem [33]. Furthermore, the SED approach may include the effect of mixed mode loading conditions, local plastic deformation and crack tip blunting on the fatigue life.

Thus, the NSIF concept has reached a state of development allowing engineering application to seam-welded specimens and structural components, but not without further verifications in individual cases.

4.2. Progress in crack propagation concepts for spot welds

The crack propagation concept by Henrysson [35,36] for spot-welded joints is based on the structural stresses determined from coarsely meshed shell element models (element size about twice the weld spot diameter) with rigid beam elements simulating the connection by the weld spot. This concept is characterised by following peculiarities:

- The shell element forces are evaluated instead of the beam element forces, thus including the eigenforces (these are forces in the shell elements not transferred by the beam element).
- The radial structural stresses at the crack initiation point of the nugget edge are calculated using simple approximation formulae (rigid core model), with the membrane stress enlarged by a factor of 2.5 in tensile-shear loading in order to collapse the endurable stresses in tensile-shear and peel-tension loading.
- The appertaining stress intensity factors (SIFs), K_I and K_{II}, determined based on the elementary formulae derived by Radaj, are combined to an equivalent SIF, K_{eq}, resulting from the Erdogan-Sih tangential stress criterion.
- The endured equivalent SIF, ΔK_{eq}, is plotted against the ratio of number of cycles to plate thickness, N/t, determined for different specimen types and loading conditions, Fig. 17 and Fig. 18. The basic relationship $t/N = C(\Delta K_{eq})^m$ is shown to be the consequence of performing a crack propagation analysis.

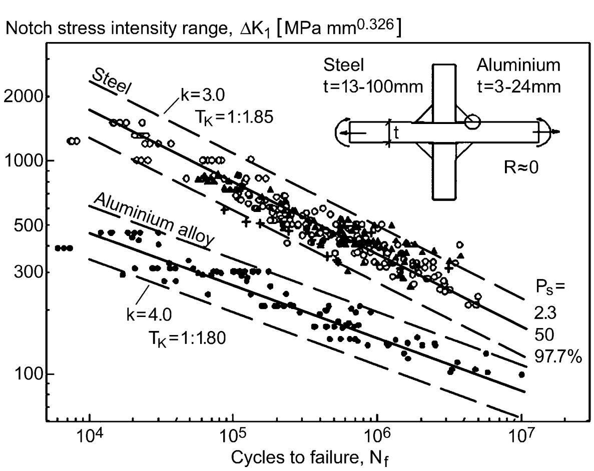

Fig. 16. Fatigue test results for fillet-welded transverse attachment joints in steel and aluminium alloy under tension and bending loads in terms of K_1–N curves; after Livieri and Lazzarin [34].

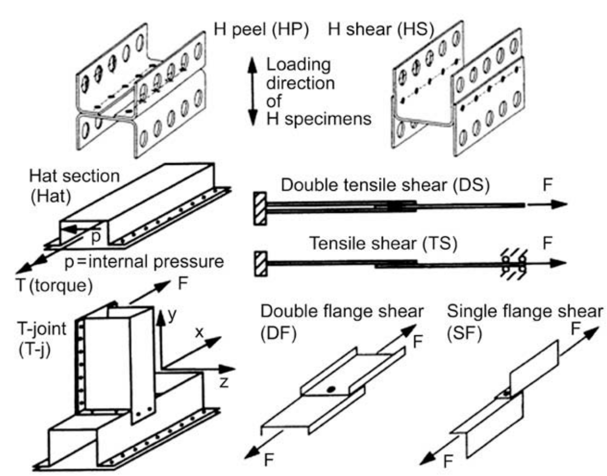

Fig. 17. Spot-welded specimen types and loading conditions underlying the fatigue test results evaluated by Henrysson [35,36].

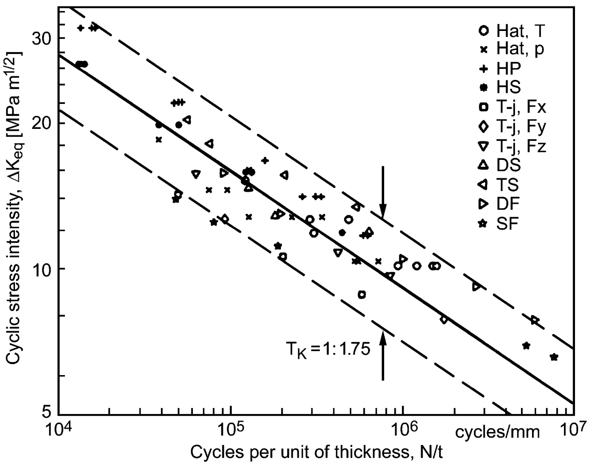

Fig. 18. Fatigue life of various spot-welded specimens (depicted in Fig. 17); test results plotted in comparison to *K–N* curves derived from crack propagation analysis; scatterband corresponding to a factor of nine in life; number of cycles *N* to failure divided by plate thickness *t*; after Henrysson [35,36].

Further investigations have been performed with regard to the mean stress effect and to the effect of variable amplitude loading [37,38]. The additional characteristic of the approach in variable amplitude applications is the consideration of crack closure with suppressed crack propagation in the SIF history. The calculated fatigue lives remain shorter by a factor of one third compared to the test data, as demanded in practice in order to remain conservative. A restriction of the procedure is the omission of the crack initiation phase with its application-relevant influencing parameters such as welding residual stresses.

5. Conclusions

The article in hand reviews some recent developments in the local concepts of fatigue assessment of welded joints, the wider context of which is presented in the recently republished and actualised standard work [2]. Specific conclusions relating to the selected concept variants are found in the relevant sections of the article. In the following, some general conclusions are stated with reference to the more comprehensive presentation in the standard work.

All local concepts have the problem that innumerable variants in modelling and procedures are possible. The spectrum is wide, beginning with the application of local load parameters to describe the component-related or specimen-related strength without further specification and ending with a detailed analysis based on material characteristics, with consideration of local material properties modified by welding and of local residual stresses caused by welding. The possible number of variants of a methodical approach is practically unlimited. Common consent on standardisations is difficult to achieve and is developing only in particular engineering sectors.

The practical application of local concepts requires consideration of defined failure criteria on which the various concept-related fatigue strength and life data are based. The *S–N* curves in the codes generally represent the total life up to final fracture. As total life comprises both the number of cycles up to technical crack initiation and also the number of cycles for further crack propagation, any concept should consider this fact in the future. The technical crack initiation phase may be further subdivided into an initiation life at the microstructure scale and a short-crack propagation life, but this is not yet under discussion in the local concepts of fatigue assessment of welded joints.

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