PRINCIPLES OF LOCAL STRESS CONCEPTS FOR THE ASSESSMENT OF WELDED JOINTS

C.M. Sonsino
Fraunhofer Institute for Structural Durability LBF,
Bartningstr. 47, 64289 Darmstadt, Germany

Introduction. For the fatigue assessment of welded structures, different concepts are applied: Nominal stress, structural stress, local stress and fracture mechanics concepts [1, 2, 3]. Among these concepts, the notch stress concepts [1,2] are gaining increasing importance in industrial applications and finding access also to fatigue design recommendations [3,4]. The basic idea of these linear-elastic notch stress concepts is the modelling of the weld toe or root, Fig. 1, with a reference radius, to calculate the local principal or von Mises stress and to evaluate it by allowable values [5]. In the following, the theoretical background of the reference radius methods will be explained. Application examples are indicated in the reference.

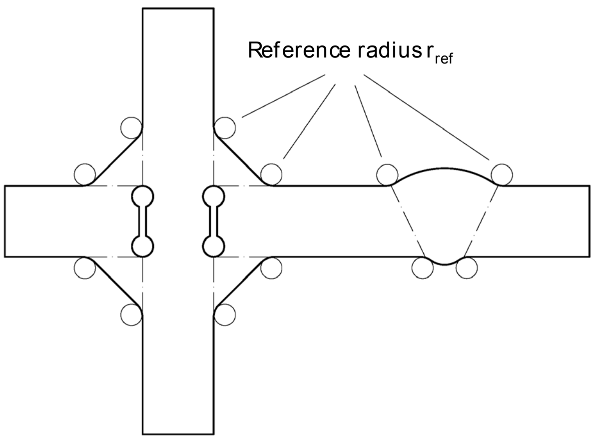


Fig. 1 - Calculation of the notch stress with reference radius

Background

The two major reference radii used are r_{ref} = 1.00 and 0.05 mm. They are based on very different hypotheses. The reference radius r_{ref} = 1.00 mm is the fictitious radius ρ_f = 1.00 mm derived from the hypothesis of micro-support. The fictitious radius is determined for the worst case of a notch with the real radius $\rho = \rho_{real} = 0$, i.e. a crack, introducing the multiaxiality factor s and the micro-support length φ^* [6, 7]. With s = 2.5 and φ^* = 0.4 mm for steels, the fictitious radius φ_f = 1.00 mm is obtained, see equation in Fig. 2b. The fictitious radius results the average notch stress gained by the integration of the stress distribution in the real notch, Fig. 2a.

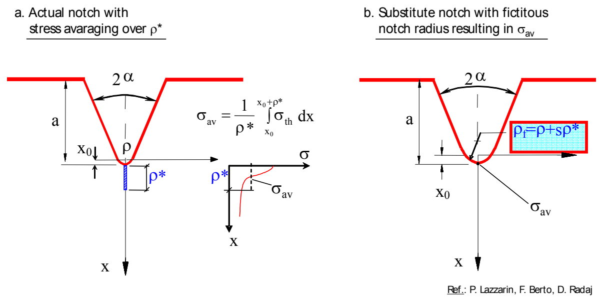
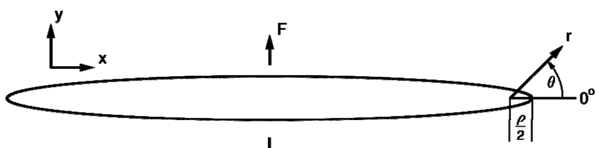


Fig. 2 - Neuber's microstructural concept

The background of the smaller reference radius r_{ref} = 0.05 mm is the relationship between the stress- intensity factor and the notch stress according to Creager and Paris [8,9] as well as the crack tip blunting [10]. The introduced reference radius r_{ref} = 0.05 mm is a compromise with regard to FE modelling and calculation of reasonable local stress components, Fig. 3, at a given stress intensity.



$$\sigma_x = \frac{K_I}{(2\pi r)^{1/2}} \cdot \cos\frac{\theta}{2}\left[1 - \sin\frac{\theta}{2} \cdot \sin\frac{3}{2}\theta\right] - \frac{K_I}{(2\pi r)^{1/2}} \cdot \frac{\rho}{2r} \cdot \cos\frac{3}{2}\theta$$

$$\sigma_y = \frac{K_I}{(2\pi r)^{1/2}} \cdot \cos\frac{\theta}{2}\left[1 + \sin\frac{\theta}{2} \cdot \sin\frac{3}{2}\theta\right] + \frac{K_I}{(2\pi r)^{1/2}} \cdot \frac{\rho}{2r} \cdot \cos\frac{3}{2}\theta$$

$$\tau_{xy} = \frac{K_I}{(2\pi r)^{1/2}} \cdot \sin\frac{\theta}{2} \cdot \cos\frac{\theta}{2} \cdot \cos\frac{3}{2}\theta - \frac{K_I}{(2\pi r)^{1/2}} \cdot \frac{\rho}{2r} \cdot \sin\frac{3}{2}\theta$$

Ref.: M. Creager

Fig. 3 - Notch stress and stress intensity

The micro-support hypothesis considers theoretically the influence of stress gradients on the local bearable fatigue strength. This influence of stress gradients is theoretically also considered by the description of the stresses at the crack tip and treated in [9].

The selection of the values r_{ref} = 1.00 and 0.05 mm is also based on empirical observations and assumptions: The radius of 1.00 mm is often observed at welded joints of structural steels with a thickness t ≥ 5 mm [11, 12]. The size of the smaller radius for thin plates (t < 3 mm) of low and medium strength ferritic car body steels corresponds approximately to their grain size [13] and, in many cases, to the radius of the notch root of spot welds [14] or laser welded joints [15].

The introduction of the reference radius r_{ref} = 0.05 mm has its justification also in avoiding the weakening of cross sections of plates with t < 5 mm if the radius of 1.00 mm is applied. Despite the different theoretical backgrounds, the general use of r_{ref} = 0.05 mm offers an option also for weld roots as well as for weld toes in thicker plates, if the different effects of stress gradients on fatigue strength are also properly considered.

As the nominal as well as the hot-spot stress concepts consider local effects on fatigue strength more in a global way using detail dependent design curves, the main motivation for applying reference radii is especially the evaluation of fatigue strength of hidden slit notches, i.e. notch roots, on a local material and stress concentration based way by a single design curve [1,2]. The reference radii can also be used for the evaluation of weld toes with significantly lower stress concentrations than slit notches, Fig. 1.

The reference radii were developed for steel joints originally. But investigations of past years show their applicability for aluminium and magnesium joints, too.

Prerequisites for calculation of notch stresses

Allowable stress ranges

For the fatigue life or strength assessment a design SN-curve in the appertaining notch stress system is needed. The IIW-Recommendations [3] for thick walled stiff welded structures proposes the SN-curve in Fig. 4 with the slope of k = 3.0 until the knee point at $N_k = 1 \cdot 10^7$ cycles and after it the continuation with k* = 22.0 (10% strength decrease per decade) for constant amplitude loading. In case of cumulative damage assessment according to the Palmgren-Miner Rule the slope of k' = 5.0 with the allowable damage sum D = 0.5 is recommended [16]. The position of the curve is defined by the FAT-value, which is the stress range with the probability of survival P_s = 97.7 % at $N = 2 \cdot 10^6$ cycles. The failure criterion is total rupture. The slope k = 3.0 suggests that the fatigue life consists only of crack propagation.

It is well known that for thin walled (t < 3 mm) and flexible welded structures the slope of the SN-curve is shallower (k > 3). Recommendations for such applications, mostly automotive, are in preparation.

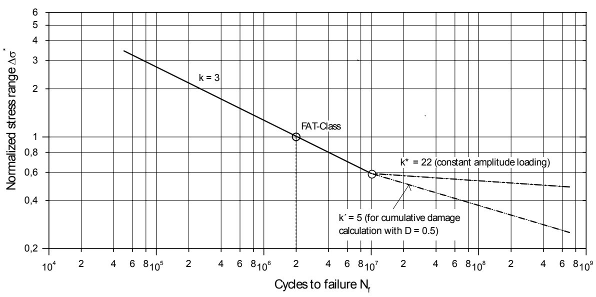


Fig. 4 - IIW-design curve for thick walled or stiff structures

In Tab. 1 FAT-values for the reference radii r_{ref} = 1.00 and 0.05 mm are compiled. These values were obtained from several investigations [5] and are part of the IIW-Recommendations. They are derived for the stress ratio R = 0.5 for considering possible high tensile residual stresses [17]. As local notch stresses can be presented either by a principal stress or by a von Mises stress, in Tab. 1 the design values according to both hypotheses are presented.

r_{ref} in mm	1.00	1.00	0.05	0.05
Hypothesis	PSH	von Mises	PSH	von Mises
Steel	225	200	630	560
Aluminium	71	63	180	160
Magnesium	28	25	71	63

All given allowable stress ranges $\Delta\sigma_{loc}$ are in MPa for
$N = 2{\cdot}10^6$, $R = 0.5$, $P_s = 97.7\%$; $k = 3.0$, $N_k = 1{\cdot}10^7$, $k^* = 22.0$, $k' = 5.0$.

Tab. 1 - FAT-values according to the notch stress concept for different reference radii and strength hypotheses (PSH: Principal stress hypothesis)

These values can be used also for thin walled structures provided that the appertaining slope is considered properly.

Calculation of notch stresses

The calculation of the notch stresses for the particular reference radii is possible only by the FE-method. For this, an accompanying guideline has been developed [4] for the IIW-Recommendations [3] for assuring a uniform procedure, e.g. the application of a key hole or U-shape notch with volume elements with quadratic displacement function, 24 to 32 elements around the hole, plane strain condition if the FE-model is two dimensional, Fig. 5.

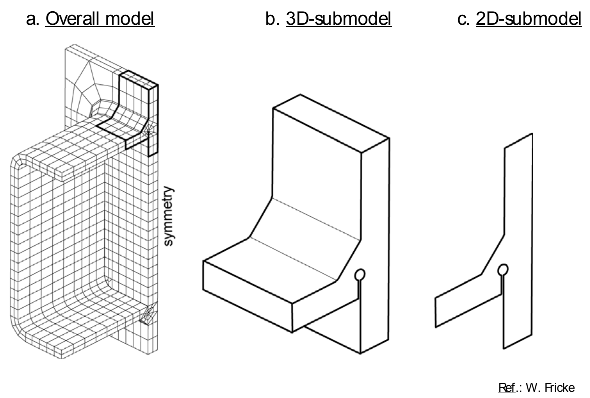


Fig. 5 – FE-modelling of a fillet-welded end joint of a rectangular hollow section

Conclusions and outlook

In this paper the most widely used two variants of the notch stress concept with the reference radius $r_{ref} = 1.00$ mm for thick walled and $r_{ref} = 0.05$ mm for thin walled welded steel, aluminium and magnesium connections were presented. Nevertheless, the presented methodology is still under development, while problems to overcome are the consideration of stress gradient dependent volume effects, which determine fatigue life significantly, as well as the slope of the SN-curve for thin walled flexible structures, the distinction between the failure criteria crack initiation and total rupture and, last but not least, the assignment of quality dependent allowable design values.

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