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Fatigue assessment of welded joints under slit-parallel loading based on strain energy density or notch rounding

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ABSTRACT

Three types of welded joints exhibiting weld roots with slit-parallel tensile stresses combined with predominant mode 2 loading are assessed with regard to their fatigue strength based on the strain energy density (SED) concept in comparison to the fictitious notch rounding (FNR) concept: the butt weld joint with permanent backing plate, the fillet-welded single-sided attachment joint and the fillet-welded double-sided lap joint. This mainly numerical analysis extends a more fundamental previous investigation of the authors. The common feature of these joints is the markedly one-sided angular distribution of the SED or notch stress at the slit tip of the weld root. The main geometrical influencing parameters, plate thickness ratio and joint face width ratio, are varied systematically for a main plate thickness of 10 mm. The effect of slit closure is considered where the effect may occur. Fatigue-effective stress concentration factors are determined. Corresponding endurable structural membrane stresses are given based on Lazzarin's uniform $\overline{W}$–N curve on the one hand (SED approach) and based on the endurable notch stress for the reference radius $\rho_r = 1$ mm in the IIW recommendations on the other hand. Finally a welded sandwich panel joint is considered, for which some fatigue test data are available. Sufficiently accurate results can already be achieved by the SED approach using an extremely coarse FE mesh.

1. Introduction

Among the local approaches of fatigue assessment of welded joints [1,2], two types deserve special attention: the fictitious notch rounding (FNR) approach, codified by the International Institute of Welding (IIW) [3] and by the German Forschungskuratorium Maschinenbau (FKM) [4] based on the reference notch radius $\rho_r = 1$ mm and the local strain energy density (SED) approach proposed by Lazzarin et al. [5–12] which is now under consideration by the IIW [13].

The codified FNR approach has considerable drawbacks in case of a high T-stress at the slit tip. The corresponding notch effect is extremely overrated. Also, there are ambiguities in positioning the centre of the fictitious circle, especially at slit tips, Fig. 1. The different positions shown in the figure have nothing to do with the actual microshape at the weld root. They are permissible options within the assessment procedure. And there is cross-sectional weakening caused by the fictitious notch, the effect of which on the notch stresses can only roughly be taken into account. Finally welded thin-sheet structures cannot be assessed in respect of fatigue by the FNR approach, at least not with the 1 mm reference radius.

The more recently developed SED approach has not the drawbacks of the FNR approach. There is no overrating of the notch effect, no ambiguity of circle positioning and no cross-sectional weakening. It is well supported by ample fatigue data in the medium and high-cycle fatigue range, at least for weld toe fractures under predominant mode 1 loading. It is applicable based on extremely coarse FE meshes without major loss in accuracy [10,11,14].

The SED approach for fatigue assessment of welded joints made of steel or aluminium alloy is recommended in the following form. The locally averaged total SED is better suited for fatigue assessments than the corresponding distortional SED, contrary to the fatigue evaluation by the global approaches based on structural or nominal stress [15]. The local region, where the SED is averaged, is conceived as a circular area (in the case of plane problems, otherwise as a circular cylinder) surrounding the weld toe (re-entrant corner, $2\alpha = 135°$) or weld root (slit tip, $2\alpha = 0°$). The radius of this 'control area' or 'control volume' is $R_0 = 0.28$ mm for structural steels and $R_0 = 0.12$ mm for aluminium alloys. Using full sectors (weld toe) or full circles (weld root) is the normal, well-established procedure. Semicircles centred by the expected crack path is considered to be better suited in cases of a markedly one-sided angular distribution of the (non-averaged) SED. The adjustment of the stated R_0 and $\overline{W}$–N values are assumed here to be unnecessary within a first approximation which remains conservative.

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Nomenclature

a	throat thickness of fillet weld
E	elastic modulus
g	root face length
h	attachment height
K_{I}, K_{II}	SIF, mode 1 and mode 2
K_{eq}, K^{*}_{eq}	equivalent SIF, without and with T-stress
K_{t}, $K_{\mathrm{t,W}}$	fatigue-effective SCF, the same SED-related
$K_{\mathrm{t,cc}}$, $K_{\mathrm{t,ec}}$	SCF of fictitiously rounded, concentric and eccentric notch
$K_{\mathrm{t,W,fc}}$	SED-related SCF, full circle variant
$K_{\mathrm{t,W,sc}}$	SED-related SCF, semicircle variant
K_{t1}, K_{t2}	SCF, at weld toe and weld root
k	inverse gradient of S–N curve
l	length of tensile-loaded model
N	number of cycles to failure
n, n_1, n_2	exponent of t/t_0, tensile and shear loading
P_{s}	probability of survival
R	stress ratio, minimum to maximum stress
R_0	radius of control area or volume
r	distance from slit tip
T_{σ}	scatter range index
t, t_0	plate thickness, its reference value
t_1, t_2	plate thickness (see Figs. 3, 5 and 7)
$t_{1,0}$	reference plate thickness
u_0	remote displacement in x-direction
W, $W_{\max}$	total SED, its maximum value
$\overline{W}$, W_{n}	averaged SED at notch, nominal SED
$\overline{W}_{\mathrm{fc}}$, $\overline{W}_{\mathrm{sc}}$	SED averaged over full circle and semicircle area
$\Delta\overline{W}_{\mathrm{E}}$	endurable averaged total SED
w, w_1, w_2	plate length (see Figs. 3, 5 and 7)
α	notch opening semi-angle
Δ	relative deviation
δ	slit width
θ	polar angle centred by slit tip
κ_1, κ_2	shape factor, mode 1 and mode 2 loading
$\kappa_{1,0}$, $\kappa_{2,0}$	reference shape factor
λ_1, λ_2	eigenvalue of singularity, mode 1 and mode 2
ν	Poisson's ratio
ρ	notch radius
ρ_1, ρ_2	notch radius at weld toe and weld root
ρ_{r}	reference notch radius
σ	reference remote membrane stress
$\bar{\sigma}_0, \bar{\sigma}_{0\mathrm{b}}$	actual remote membrane and bending stress
$\bar{\sigma}_{0\mathrm{E}}$	endurable remote membrane stress
σ_{nE}, σ_{nE0}	endurable nominal stress, the same for $t = t_0$
σ_{y}	stress component in Cartesian system
σ_{θ}, $\sigma_{\theta,\max}$	tangential notch stress, its maximum value
$\Delta\sigma_{\mathrm{E}}$	reference fatigue strength
$\Delta\bar{\sigma}_{\mathrm{nE}}$	endurable nominal stress in base plate
$\Delta\bar{\sigma}^{*}_{\mathrm{nE}}$	endurable nominal stress in weld throat
τ_{nE}, τ_{nE0}	endurable nominal shear stress, the same for $t = t_0$
τ_{xy}	shear stress component in Cartesian system
FE	finite element
FNR	fictitious notch rounding
IIW	International Institute of Welding
MFH	MacFarlane and Harrison
SCF	stress concentration factor
SED	strain energy density
SIF	stress intensity factor
cc, ec	concentric circle, eccentric circle
fc, sc	full circle, semicircle

It is the purpose of the paper at hand, to apply the SED approach in comparison to the FNR approach to three application-relevant types of welded joints exhibiting weld roots with slit parallel tensile stresses combined with predominant mode 2 loading, thus generating markedly one-sided angular distributions of the SED inclusive of a high T-stress component: the butt weld joint with permanent backing plate, the fillet-welded single-sided attachment joint and the fillet-welded double-sided lap joint. These types of welded joints or structural details are insufficiently documented in the literature in respect of their fatigue strength, but some fatigue test data are available and endurable nominal stresses are given in the IIW recommendations [3]. The fatigue assessment based on the FNR approach is problematic for the reasons stated above. This investigation is primarily related to fatigue originating from the weld root, but it is supplemented by a corresponding SED and FNR analysis at the weld toe where appropriate. By comparison of the endurable stresses with regard to root and toe fractures, the more probable mode of failure is indicated. Finally, the two assessment methods above are applied to a welded sandwich panel joint, a novel option in ship structure design, which has recently been considered by Fricke et al. [16].

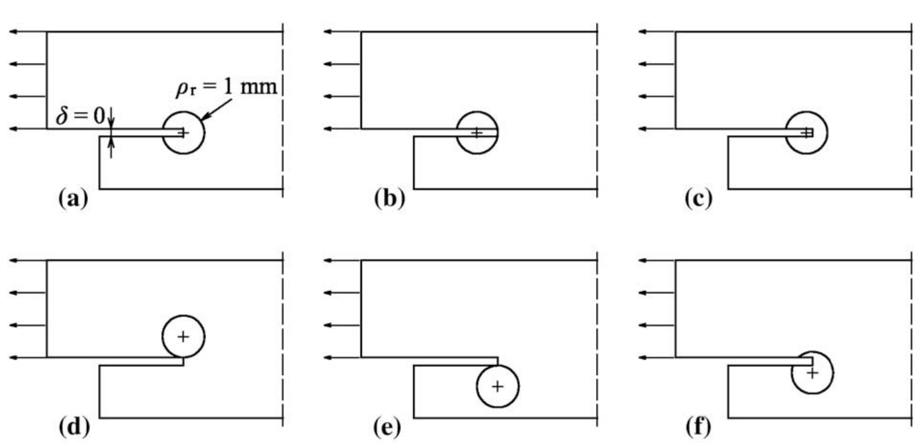

Fig. 1. Ambiguity of notch positioning in the FNR approach applied to the weld root of a butt weld joint with backing plate (symmetry half of the model): concentric circle (a), eccentric circle horizontally displaced to different extents (b and c) and eccentric circle vertically displaced to different extents (d, e and f).