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Evaluation of nominal and local stress based approaches for the fatigue assessment of seam welds

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ABSTRACT

In the context of the German joint research project "Applicability of fatigue analysis methods for seam welded components", fatigue tests were performed by five universities and institutes on welded components, welded parts of larger structures as well as component-like samples of weld details. The sheet thickness t was in the range 1 mm $\leqslant t \leqslant$ 20 mm. The welding parameters for all test coupons and structures tested were chosen according to the industrial production process. Based on the data acquired, nominal, structural and notch stress approaches were analysed with regard to applicability and quality of assessment. The actual weld geometry except the real notch radii was taken into account within the notch stress approach. For the notch radii various values, the reference radii 0.05, 0.3 and 1 mm, were applied.

Experimental and numerical results for welded steel components are presented. Approximately equivalent scatter ranges were obtained when applying the various approaches based on the current state of the art. It should be noted that both the nominal and the structural stress approaches are limited in their application compared to the notch stress approach. A comparison of the scatter bands obtained for the various approaches is subject to limitations because it was necessary, in each case, to use different test series as the basis for determining the scatter bands.

1. Introduction

Various fatigue strength assessment methods [1] – nominal stress approach, structural stress approach and notch stress approach – are investigated based on the database obtained for steel and aluminium structures [2] in the joint research project "Applicability of fatigue analysis methods for seam welded components". Apart from the nominal stress approach, the concepts are based on local stresses of the welded joints that are defined in different ways. Their applicability is outlined.

Compared to the nominal stress approach, both the structural stress approach and notch stress approach enable a significantly more detailed analysis of the fatigue strength of welded structural components. The structural stress approach largely takes account of the component geometry present in the joint region. The notch stress approach goes further and also takes into account the local shape of the welded joint. Local approaches conform to the possibilities of numerical calculation methods, typically the finite element method or alternatively the boundary element method, which, compared to the nominal stress approach, can be used to determine the stresses at a significantly smaller distance from the weld detail or within the weld detail itself.

The fatigue strength data, necessary for application and evaluation of the various approaches, were determined in a number of research projects on selected components or welded parts of larger structures. In the following they are referred to as "sample components", Fig. 1. Test coupons represented fatigue-critical parts of welded joints typical of the sample components considered, Fig. 2. Detailed information on the various research projects is provided in [3–8].

This paper focuses on the results obtained for welded joints in steel. An evaluation of the results for welded aluminium alloy joints is carried out in [8,9].

Overall, approximately 500 fatigue tests on steel specimens were carried out in 32 test series, Table 1.

2. Applicability of calculation approaches

The IIW Recommendations [10] provide design S–N curves for the fatigue assessment of welded joints. The S–N curves are described by straight lines in a double logarithmic plot given by the equation

$$N = 2 \times 10^6 \cdot (\Delta\sigma/FAT)^{-k},\ N \leq N_k,$$

with number of cycles to failure N, nominal or local stress range $\Delta\sigma$, slope k and stress range FAT in MPa at $N = 2 \times 10^6$ cycles,

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Nomenclature

C	confidence level
CM	cross member
LM	longitudinal member
FATx	classification reference to a *S–N* curve, in which *x* is the stress range in MPa at 2×10^6 cycles
f(*R*)	factor for mean stress correction according to IIW Recommendations
HT	post weld stress relief heat treated
k	exponent (negative inverse of Basquin's exponent) characterising the slope of a *S–N* curve in a double logarithmic plot
k_m	stress magnification factor due to misalignment
K_f	fatigue notch factor
K_t	stress concentration factor
M	mean stress sensitivity
N_u	ultimate number of cycles number of cycles after which a tested specimen is regarded as run-out
N	number of cycles to failure
N_k	number of cycles at knee point of *S–N* curve
N_i	number of cycles to initiation of technical size crack
N_r	number of cycles to rupture
P_s	probability of survival
$P_{\text{s-ref}}$	probability of survival of a reference *S–N* curve
r	real notch radius
r_f	fictitious radius suggested by Neuber–Radaj
r_{ref}	reference radius
R	stress ratio related to external loading
R_σ	local stress ratio
s	correction factor for equivalent stress hypothesis applied to ρ^*
t	sheet thickness
t^*	extent of isometric FE-mesh around a notch
T_σ	scatter index in load direction for nominal, structural hot spot or notch stresses; $T_\sigma = 1{:}(\sigma_{\text{a,Ps=10\%}}/\sigma_{\text{a,Ps=90\%}})$
V	fatigue strength ratio
WE	weld start or stop position referred to as weld end
WT	weld toe
WR	weld root
z	number of test series within a subgroup
Δ	range
ρ^*	material's structural length according to Neuber
σ_e	"elastic" notch stress calculated using Theory of Elasticity
σ_{hs}	structural hot spot stress
σ_n	nominal stress
σ_p	largest principal stress, either max σ_1 or max $\lvert\sigma_3\rvert$ whichever greatest
σ_{vM}	von Mises stress
σ_1	maximum principal stress
σ_3	minimum principal stress
Θ	weld opening angle or notch opening angle

Subscripts

a	amplitude
i	index
IIW	International Institute of Welding

Fig. 3. The FAT class depends on the assessment concept used and the structural weld detail, as well as on the base material (aluminium/steel) and relevant acting stresses (normal/shear stress). The design *S–N* curves are applicable for a probability of survival $P_s = 95\%$ with a two sided confidence level of the mean of $C = 75\%$. The slope of the *S–N* curves for details assessed on the basis of normal stresses is $k = 3$ if not stated explicitly otherwise. The "knee point" of a *S–N* curve, which describes the point where the slope of a *S–N* curve in a double logarithmic plot changes (e.g. from $k = 3$ to 22) is assumed to correspond to $N_k = 1 \times 10^7$ cycles.

The basic requirements for the applicability of the approaches as described in IIW Recommendations are briefly summarised below. The enumeration marks indicate advantages (+), disadvantages (−) and neutral items (○), respectively.

- Nominal stress approach
  - ○ Requires a meaningful definition of nominal stresses
  - − The detail catalogue provides FAT classes only for a limited number of weld details.
  - + The *S–N* curve characterised by the FAT class typically takes into account the failure location (e.g. weld toe or weld root) for the weld detail of interest.
  - + Easy to apply, if the weld detail is included in the catalogue and a nominal stress can be determined.
  - − Imperfections such as centre-line mismatch (linear misalignment) and angular misalignment are covered to a certain degree in the fatigue resistance given by the FAT class. IIW Recommendations, as well as the German FKM Guideline [11], do not provide information on "upgrading" in the case of improved weld quality.
- Structural hot spot stress approach
  - ○ Requires meaningful extrapolation of structural stresses for the detail of interest in order to derive the hot spot stress.
  - ○ Anticipated joint misalignment has to be considered in the finite element model or is taken into account using a magnification factor k_m.
  - − It is necessary to choose paths for the extrapolation to structural stresses. Various paths may exist for a given application. Various extrapolation methods have been described (location of reference points and linear or quadratic extrapolation), which, when determined by FEA, also depend on the mesh size chosen. Selection of the method is not always unambiguous.
  - − In the IIW Recommendations, consideration is only given to failure starting from the weld toe. Currently, there are no recommendations for using the structural stress to assess joints with respect to failure from the weld root. Furthermore, FAT-values are only given for stresses acting normal to the weld. Data for welds under torsion are missing.
  - ○ Due to the extrapolation procedure, this approach requires a somewhat greater effort compared to the nominal stress approach.
- Notch stress approach
  - ○ When applying the concept, it is essential to be able to reproduce the stress state at the weld detail using the reference radius chosen.
  - + Applicable to most weld details for failure from a weld toe or root. Modelling guidelines must be considered with regard to stress analysis.