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The strain-life approach applied to welded joints: Considering the real weld geometry

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ABSTRACT

Fatigue assessment of welded joints is a challenging task. Various codes and guidelines provide assessment procedures with specific ranges of application. If an approach is applied, which requires numeric calculations, the modelling of the weld profile is critical. In the contribution at hand, the combination of the real weld geometry obtained by 3D laser scanning and the strain-life approach is investigated. By doing so, the effect of additional stress concentration from the weld profile itself can be studied, leading to predictions of fatigue lifetime, which take into account the individual features of the weld. By taking into consideration the strain-life concept, different methods for mean stress and plasticity correction are available. Therefore, fatigue lifetimes resulting from different combinations of the aforementioned procedures are compared to the ones obtained experimentally. Depending on the combination of mean stress, as well as plasticity correction and material data, the predicted fatigue lifetimes vary from being unrealistic to pretty accurate. The results are very sensitive to material input data, for which base material properties are assumed in this contribution. Further investigations are necessary to verify the potential of this procedure, preferably with the application of experimentally determined material properties for the heat affected zone and the weld material. The location of crack initiation has been predicted with high accuracy.

1. Introduction

Welded joints are fatigue critical areas resulting from occurring stress concentrations. As different assessment codes and guidelines exist for the purpose of design, they provide different approaches for a prediction of fatigue lifetime. The most popular assessment procedures, applicable in the high cycle fatigue (HCF) regime, are the nominal stress, the structural hot-spot and the effective notch stress approach. All these concepts differ in their basic assumptions, modelling strategies, meshing requirements if needed and acceptable values for fatigue strength. They all have in common at least two aspects: the lack of a model for the description of the material behaviour under fatigue loading and, if finite elements (FE) are applied for stress or strain calculation, the use of a simplified representation of the weld profile. The first issue leads to more or less phenomenological relations between stress evaluation and a value for fatigue resistance [1], mostly determined through experiments. The latter shortcoming leads to a simplified or, in the worst case, to a non-realistic consideration of stiffness and stress concentration as it completely disregards the supplementary notch effect resulting from individual weld geometry. Due to the realistic consideration of the weld geometry, promising approaches have been recently reported where 3D laser scanning of the weld profile was applied in order to obtain a realistic representation of the weld [2,3]. The consideration of the real weld geometry in an assessment approach seems to be a step towards a component's individual and hopefully more precise prediction of fatigue lifetime. As far as the modelling of the material behaviour is concerned, the strain-life (ε-N) approach is encouraging, as some of the already mentioned drawbacks are at least to some degree addressed in this procedure. No additional strategy in dealing with high stresses is necessary because plastic material behaviour is considered through elastic-plastic corrections and the material behaviour is presumed to be described by the cyclic stress-strain curve and the Masing effect. Therefore, the aim of the contribution at hand is to investigate if a combination of the ε-N approach in different combinations of mean stress corrections, material data, plastic correction and the application of the real weld geometry obtained by 3D laser scanning, represents a promising approach for the prediction of the fatigue lifetime of welded butt joints. This contribution is structured as follows. After the Introduction, the basics of the strain-life approach will be reviewed briefly. In the third section, the results from an extensive numerical study will be presented. In the final step, these results will be discussed until drawing to a conclusion.

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2. The strain-life approach to fatigue

In the strain-life approach, it is assumed that the material at an arbitrary point in a component shows the same fatigue behaviour than a test specimen under the same cyclic deformation [4]. This presumption is shown in Fig. 1 as for the application in base material and for welded joints.

Whereas for the base material (BM) only one material data set is sufficient, three different cases have to be distinguished for the assessment of welded joints. The area around the weld can be divided into the weld material (WM) and the heat affected zone (HAZ). Added to those areas, at an adequate distance away from the HAZ, the material properties can be assumed to be again the same as for the base material. This classification will be discussed later. A further presumption of the strain-life approach is that hysteresis loops become stabilised after a number of cycles and the strain range can be evaluated from the cyclic stress-strain curve as shown in Fig. 2.

The evolution of the hysteresis tips due to cyclic loading can be modelled by using the Ramberg-Osgood relation (Eq. (1)):

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \tag{1}$$

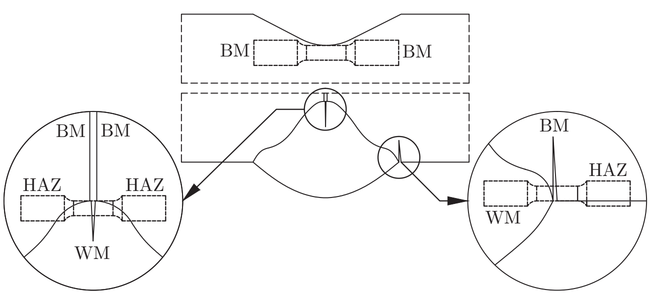

Fig. 1. Strain-life approach applied to base material and welded joints [5,6].

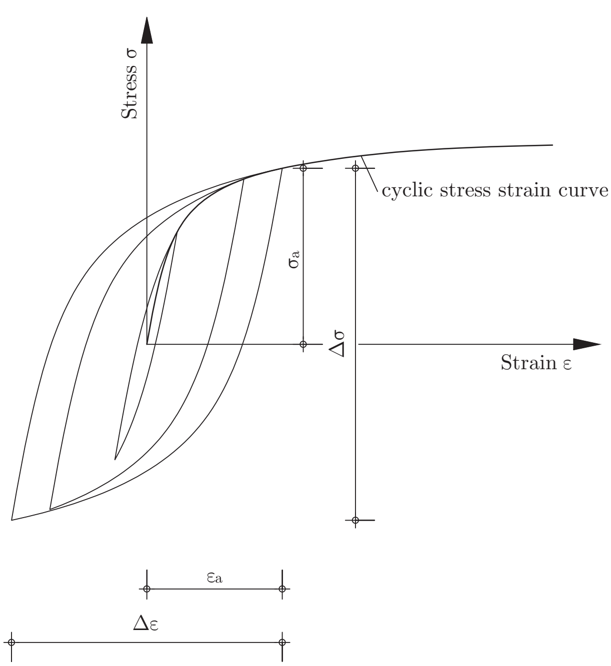

Fig. 2. Cyclic stress-strain curve [4].

where $\Delta\varepsilon$ and $\Delta\sigma$ notate the true strain and stress range. E is the Young's modulus, K' and n' are the cyclic strain hardening coefficient and exponent.

The idea of relating the fatigue lifetime to plastic strains is expressed by the well-known Coffin-Manson equation, which links the plastic strain amplitude ($\Delta\varepsilon_p/2$) to the load reversals up to crack initiation ($2N_f$) as shown in Eq. (2) [7].

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f'(2N_f)^c \tag{2}$$

The parameters ε_f' and c are the fatigue ductility coefficient and the fatigue ductility exponent. In the case of HCF, plastic effects are often assumed to be negligible and the fatigue lifetime is expressed by applying the Basquin relation [7].

$$\frac{\Delta\varepsilon_e}{2} = \frac{\sigma_f'}{E}(2N_f)^b \tag{3}$$

In this equation σ_f' is the fatigue strength coefficient and b the fatigue strength exponent. The total life can be expressed through an equation assembled by the before mentioned relations, whereas the plastic strains dominate in the low cycle (LCF) regime and the elastic strains in the high cycle fatigue (HCF) domain, where the load is low and plastic effects are often assumed to be insignificant. The relation between elastic and plastic strains, expressed in Eq. (4), is shown in Fig. 3.

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c \tag{4}$$

2.1. Plasticity correction

The strain-life approach offers the possibility of considering plastic effects, either by applying correction procedures or by performing elastic-plastic FE calculations and using the results as input for the strain-life equation. Popular approaches for the correction are the Neuber hyperbola [5] or the approach proposed by Hoffmann and Seeger [9]. The Neuber approach is a simplified method for the approximation of the plastic effects at exceedance of the yield limit used by many fatigue solvers. By assuming a proportional relation between nominal σ_n as well as true stress and strain (σ_t and ε_t) in the notched area, the intersection point with the cyclic stress strain curve can be determined by applying Eq. (5) using the elastic stress concentration factor K_t.

$$\sigma_t\varepsilon_t = \frac{K_t^2\sigma_n^2}{E} \tag{5}$$

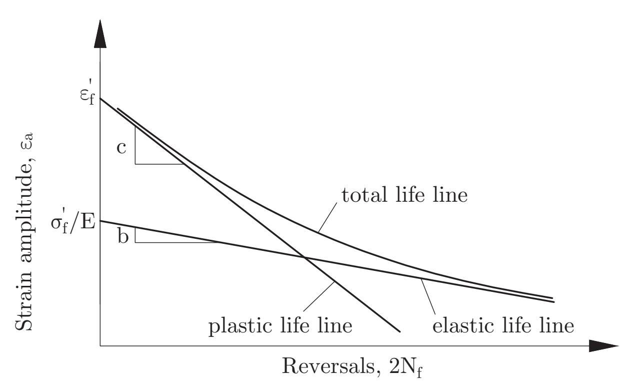

Fig. 3. Strain-life curve on a log-log scale [8].