

Cyclic Material Behavior of High-Strength Steels Used in the Fatigue Assessment of Welded Crane Structures with a Special Focus on Transient Material Effects

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ABSTRACT

The cyclic material behavior is investigated, by strain-controlled testing, of 8 mm thick sheet metal specimens and butt joints, manufactured by manual gas metal arc welding (GMAW). The materials used in this investigation are the high-strength structural steels S960QL, S960M and S1100QL. Trilinear strain-life curves and cyclic stress-strain curves have been derived for the base material and the as-welded state of each steel grade. Due to the cyclic softening in combination with a high load level at the initial load cycle, the cyclic stress-strain curve cannot be applied directly for a fatigue assessment of welded structures. Therefore, the transient effects have been analyzed in order to describe the time-variant material behavior in a more detailed manner. This should be the basis for the enhancement of the fatigue life estimation.

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INTRODUCTION

The development of high-strength steels is a crucial issue for the encouragement of lightweight design of modern steel structures. Within the production process of such structures, major aims arise from demands on technological features, e.g. material efficiency and reduction of weight. The service life of crane structures is characterized by high service loads, e.g. those occurring at the telescopic boom of truck cranes [1], Figure 1. With regard to fatigue, critical sections are often linked to welded joints. In the case of seam welds, the transition from the weld seam to the base material, which is additionally affected by the heat input due to welding, is a well recognized source of crack initiation.



Figure 1. Truck crane on test site [1].

Fatigue recommendations for the design and analysis of welded structures [2,3] are based on stress analysis and fatigue resistance $S-N$ curves (Wöhler curves), irrespective of the steel grade. These recommendations are limited to a yield strength of 960 MPa and describe the low cycle fatigue (LCF) behavior improperly. In the case of highly loaded welded structures, the fatigue strength of critical sections is dominated by plastic strains in the LCF regime. Therefore, a fatigue life assessment by the notch strain concept is based on the evaluation of the local strain at the weld toe or weld root and, rather, includes the cyclic material behavior. The choice of the stress-strain relationship is connected to the cyclic stress-strain curve and a hardening model.

In addition to strain-life curves, cyclic stress-strain curves are part of the results arising from strain-controlled testing. Three main purposes substantiate strain-controlled fatigue testing:

- Characteristic data in terms of the cyclic material behavior (strain-life curve and cyclic stress-strain curve) are obtained
- Damage mechanisms at notches are strain-dominated so that local effects of the stresses and strains in the material become apparent
- Input data for strain-life approaches are obtained

Current research concerns the investigation of modern steels under welded conditions and is directed at the assessment and improvement of their fatigue behavior with respect to the steel grade and welding

process. The present paper focuses on the experimental determination of the cyclic material behavior of base material and butt welded specimens of high-strength structural steels.

In comparison to stress-based fatigue life concepts, the life assessment by the notch strain approach, including an elastic-plastic numerical model of welded sections, shows a comparable assessment quality when notch support effects are considered [4]. Neither monotonic (tensile) stress-strain relationships nor stress-strain relationships from data from the literature and which, furthermore, are evaluated for the cyclically stabilized state, can be directly applied for life assessment. In fact, the cyclic material behavior should be supplemented with an analysis of transient effects.

In previous research, it has been found that, for the base material of high-strength steel sheets and butt joints, a cyclic softening occurs in the elastic-plastic range for a total strain amplitude above $\varepsilon_{a,t} = 0.4\%$ [4,5]. In the case of butt welded specimens, the reduction of the stress amplitude due to the cyclic loading is also influenced by a combination of the geometrical and metallurgical notch effects.

For the consideration in the fatigue assessment using damage parameters and energy criteria, the amount of cyclic softening and the amount of mean stress relaxation has been estimated empirically [6]. A good assessment quality for sheet metal and flange specimens, using both estimations, has been found. In the context of the further development of notch strain approaches, the analysis of transient effects is extended to high-strength steels and butt welds.

STATE OF THE ART

Fatigue Assessment of Butt Joints Considering Nominal Stress Amplitudes

A standardized fatigue assessment of numerous types of welded joints is given by fatigue classes (FAT) using the nominal stress approach and a survival probability of $P_s = 97.7\%$ according to fatigue recommendations [2, 3]. Fatigue test data from the literature are shown in Figure 2. The literature data contain uniaxial test results up to the LCF regime of butt joints with V-, X- and Y-shape manufactured from steels with yield strengths between 355 MPa and 1100 MPa. The stress ratios vary between $R = -1$ to $R = 0.5$ and the sheet thickness of the base material is 5 mm to 38 mm [4]. According to the different recommendations, FAT classes differ from each other. Relevant FAT classes for a fatigue assessment of butt joints in the HCF regime of FAT 70, FAT 80 and FAT 90 have been added to Figure 2. These are valid for a maximum yield strength of 960 MPa and a minimum of 10^4 cycles to failure. For stresses above the material's yield strength, fatigue life is strain-dominated and a transition of the S - N curve towards the tensile strength is the consequence. An improvement of the fatigue life assessment by a more realistic implementation of the cyclic (transient) material behavior and local stress-strain hysteresis may therefore be expected.

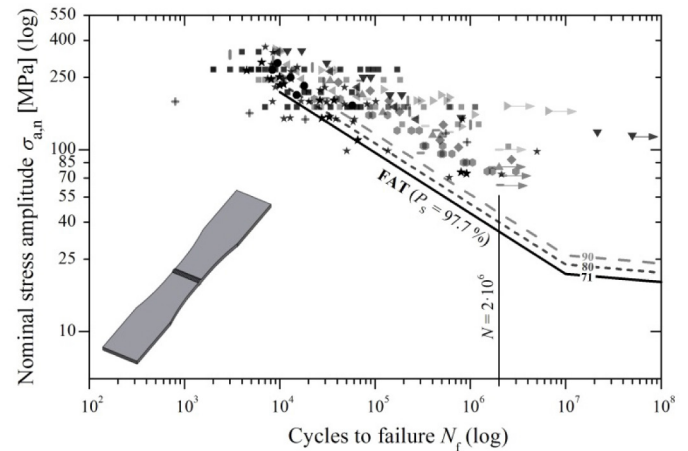


Figure 2. Overview of fatigue test data of butt joints in the nominal stress system including test results in the LCF regime from the literature.

Conventional Description of the Cyclic Material Behavior

The cyclic material behavior is a set of characteristic fatigue data resulting from strain-controlled tests. A stabilized state is defined at the half number of cycles to crack initiation N_i , whereas N_i is commonly evaluated for a reduction of the stress amplitude of 10 % compared to the stabilized state. Essentially, it comprises the cyclic stress-strain curves and strain-life curves. The strain-life curve, according to Basquin [7], Coffin-Manson [8, 9] and Morrow [10], is a summation of the elastic strain $\varepsilon_{a,e}$ and the plastic strain $\varepsilon_{a,p}$, so that the total strain amplitude $\varepsilon_{a,t}$ equates to

$$\varepsilon_{a,t} = \varepsilon_{a,e} + \varepsilon_{a,p} = \frac{\sigma'_f}{E} \cdot (2N_i)^b + \varepsilon'_f \cdot (2N_i)^c \quad (1)$$

where σ'_f is the cyclic strength coefficient, E the Young's modulus, b the cyclic strength exponent, ε'_f the cyclic ductility coefficient and c the cyclic ductility exponent.

The cyclic stress-strain curve of Equation (2) was introduced by Ramberg and Osgood [11] in the form

$$\varepsilon_{a,t} = \varepsilon_{a,e} + \varepsilon_{a,p} = \left(\frac{\sigma_a}{E}\right) + \left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}} \quad (2)$$

where σ_a is the stress amplitude, K' the cyclic hardening coefficient and n' the cyclic strain-hardening exponent.

The characteristic parameters of cyclically stabilized stress-strain curves can be derived from strain-life curves using the compatibility conditions of Equations (3) and (4):

$$n' = \frac{b}{c} \quad (3)$$

$$K' = \frac{\sigma'_f}{\varepsilon'_f \cdot \frac{b}{c}}$$

Trilinear Approach of the Strain-Life Curve

The strain-life curve according to Equation (1) might not be the best choice for any material to represent the cyclic material behavior from low cycle fatigue to high cycle fatigue and long life fatigue. For the case of aluminum wrought alloys, a trilinear strain-life curve was introduced, which divides the elastic part of the strain-life curve into three sections [12, 13]. A separate strain-life curve is assigned to each section and transition conditions are allocated. In the first section (σ_{f1}' , b_1), an elastic-plastic material behavior is assumed so that relations according to Ramberg-Osgood and Coffin-Manson $\epsilon_f' \cdot (2N_f)^c$ are valid. Section two (σ_{f2}' , b_2) is characterized by an elastic-plastic first hysteresis loop. With respect to cyclic hardening, the formation of dislocations results in a hysteresis, which is dominated by elastic strains. For the third section (σ_{f3}' , b_3), the hysteresis shows macroscopic elastic strains. The trilinear strain-life curve is therefore given by a system of equations. The presentation according to Equation (5) requires the determination of eight parameters.

$$\epsilon_{a,t} = \epsilon_{a,e} + \epsilon_{a,p} = \frac{\sigma_{fi}'}{E} \cdot (2N)^{b_i} + \epsilon_f' \cdot (2N)^c \quad \text{with } i = 1, 2, 3 \quad (5)$$

Under consideration of the compatibility conditions for the first section of the trilinear strain-life curve, the cyclic stress-strain curve analogous to Equations (3) and (4) is derived from σ_{f1}' , b_1 , ϵ_f' and c . A more precise description of the cyclic material behavior has been found using this procedure.

A New Methodology for the Consideration of Transient Effects

Transient effects of the stress-strain relationship under cyclic loading, such as cyclic hardening/softening, mean-stress relaxation or ratcheting, may have an influence on the fatigue life. In [6], a strain-based fatigue assessment using two damage parameters and one energy parameter for the consideration of cyclic softening and mean-stress relaxation, has been evaluated. The cyclic softening of the stress amplitude σ_a and relaxation of the mean stress σ_m have been simulated based on experimental data of the cyclic stress evolution. The basic idea is that both parameters can be described by considering their dependence on the strain amplitude and the number of cycles separately (linear independence). The amount of cyclic softening is dependent on the strain amplitude and the number of cycles was observed to reach stabilization. For this reason, the description using exponentially decreasing functions has been chosen.

The amount of cyclic softening $\Delta\sigma_a$, defined as the difference between the maximum amount of softening $\Delta\sigma_{\infty, \max}$ (occurring at the maximum strain amplitude) and the stress amplitude of the stabilized state, as a function of the strain amplitude ϵ_a for sheet metal specimens, is shown in Figure 3. This value represents the difference between the initial (quasi-static) and cyclically stabilized stress-strain curves. An exponential equation with optimization parameters k_0 and ϵ_0 is used to estimate the amount of cyclic softening. Furthermore, the dependence on the logarithmic number of cycles $\log(N)$ has been

expressed by another exponential function and optimization parameters b_0 and b_1 , so that the cyclic softening of the stress amplitude is estimated using Equation (6).

$$\sigma_a = f(\epsilon_a, N) = \sigma_{a, \text{cyc}}(\epsilon_a) + \Delta\sigma_{\infty, \max} \cdot (1 - e^{k_0(\epsilon_a - \epsilon_0)}) \cdot e^{b_0 \log(N)^{b_1}} \quad (6)$$

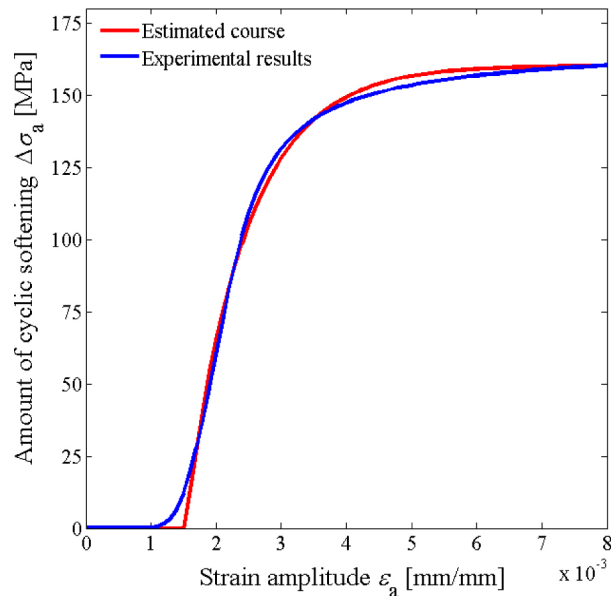


Figure 3. Estimation and experimental results of the amount of cyclic softening including optimization of parameters k_0 and ϵ_0 [6].

Two independent regressions are applied to perform the estimation according to Equation (6). Experimental results and the estimation for sheet metal specimens are shown in Figure 4. The difference in the stress amplitudes between estimation and experimental results is mainly due to the fact that the estimated curves are based on a regression, while experimental data vary due to scatter of a single test. For higher strain amplitudes, the estimations are in good agreement with the experimental results. Comparable results have been found for specimens extracted from flow split flanges.

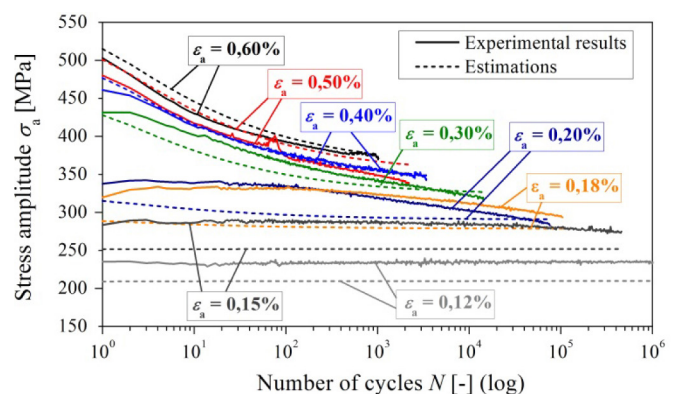


Figure 4. Estimation and experimental results of the stress amplitudes including for HC340LA sheet metal in the as-received state [6].