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Fatigue strength of welded and high frequency mechanical impact (HFMI) post-treated steel joints under constant and variable amplitude loading

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ABSTRACT

This study presents fatigue test results of longitudinal stiffener specimens in as-welded and high frequency mechanical impact (HFMI) post-treated condition under both constant amplitude loading (CAL) and variable amplitude loading (VAL). The experiments incorporate mild steel S355 and high-strength steel S700 samples at load stress ratios of R = 0.1 and R = −1 respectively. VAL tests are performed utilizing a straight-line distribution with a sequence length of $2 \cdot 10^5$ load-cycles and an omission level of 19% of the maximum stress range. The test results reveal a significant benefit of the HFMI-treatment under CAL. On the contrary, the increase in fatigue strength is majorly reduced in case of VAL. X-ray residual stress measurements for the investigated mild steel S355 specimens demonstrate that even at comparably minor load stress ranges, a certain relaxation of the HFMI-treatment induced local compressive residual stress state at the weld toe occurs. This phenomenon contributes to the decrease of the benefit by the HFMI-treatment under VAL compared to CAL. An evaluation of specified damage sums on the basis of the determination of an equivalent stress range for VAL reveals that damage sums between D = 1.0 and D = 0.5 are well applicable for a conservative fatigue assessment on the basis of the IIW-recommended fatigue design curves. However, facilitating a lightweight component design by considering experimental test results of HFMI-treated joints under CAL, a reduced specified damage sum of D = 0.3, or even of D = 0.2 in case of fluctuating mean stress states, is suggested for the fatigue assessment to avoid non-conservative results.

1. Introduction

According to the IIW recommendation [1], the fatigue strength of welded steel joints is generally independent of the base material's yield strength. In order to utilize the lightweight potential of high-strength steel materials, the application of post-treatment techniques, such as the HFMI-treatment, is well applicable [2,3]. On the basis of numerous fatigue test results under both constant amplitude loading (CAL) [4] and variable amplitude loading (VAL) [5], guidelines for the fatigue assessment [6] as well as quality assurance [7] are developed, which are recently published as IIW recommendation for the HFMI-treatment [8]. However, as in-service conditions mostly include VAL load-spectra [9,10], an in-depth knowledge about the fatigue resistance of HFMI-treated mild and high-strength steel weld joints is of utmost importance.

Palmgren [11] and Miner [12] proposed a linear damage accumulation to incorporate VAL in the course of the fatigue assessment. Thereby, the damage sum D is calculated by summarizing the ratio of the applied number of load-cycles n_i to the number of load-cycles until failure N_i at each load-level i., see Eq. (1). Herein, allowable damage sums D usually reveal values between 0.5 and 1.0, whereby a conservative value of $D = 0.5$ is recommended in [1,13].

$$D = \sum_{1}^{i} \frac{n_i}{N_i} \leqslant 0.5. .. 1.0 \tag{1}$$

An extensive study in [14] including welded medium- and high-strength steel joints under VAL shows that the real damage sum D_{real} indicates a value of $1/3 < D_{real} < 3$ for more than 90% of the analyzed data. Furthermore, investigations in [15] additionally highlight that even lower damage sums down to about $D_{real} = 0.2$ may be observable for welded steel joints, which is also mentioned in [1] in case of fluctuating mean stress states. To assess the fatigue strength under VAL and compare the results to CAL, an equivalent stress range $\Delta\sigma_{eq}$ can be calculated [1], which considers the load-spectrum and a specified damage sum, see Eq. (2).

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$$\Delta\sigma_{eq} = \sqrt[k]{\frac{1}{D}\cdot\frac{\sum(n_i\cdot\Delta\sigma_i^k) + \Delta\sigma_L^{(k-k')}\cdot\sum(n_j\cdot\Delta\sigma_j^{k'})}{\sum n_i + \sum n_j}} \quad (2)$$

Herein, D is the specified damage sum, $\Delta\sigma_i$ is the stress range and k is the slope above the knee point of the S/N-curve, $\Delta\sigma_j$ is the stress range and k' is the slope below the knee point of the S/N-curve, n_i is the number of load-cycles applied at $\Delta\sigma_i$, n_j is the number of load-cycles applied at $\Delta\sigma_j$, and $\Delta\sigma_L$ is the stress range at the knee point of the S/N-curve. For VAL it is suggested to use $k' = 2\cdot k - 1$ [16] instead of the recommended [1] value of $k' = 22$, which is only valid for CAL. Investigations considering HFMI-treated steel samples under CAL and VAL in [17–21] demonstrate that the specified damage sum D varies between values of 0.2 and 1.0. However, as a suitable definition of D is of utmost importance for the fatigue assessment of HFMI-treated steel structures under in-service VAL conditions, this paper analyses the effect of VAL on mild and high-strength steel joints and provides suggestions for D to obtain a proper equivalent stress range for design. As no further comprehensive evaluations of applicable damage sums for HFMI-treated joints are available so far, this work contributes to properly assess the fatigue strength of HFMI-treated structures under VAL. Herein, the IIW-recommended and well proven method based on the calculation of an equivalent stress range is applied utilizing commonly specified damage sums from literature. The scientific aim of this investigation is to validate the applicability of the concept for as-welded and HFMI-treated joints considering different weld geometries, base materials as well as load scenarios.

As limitation of applying a linear damage accumulation assuming a specified damage sum it can be stated that load sequence effects as well as a differentiation between crack initiation and propagation is generally not considered. Thus, an accurate fit between CAL and VAL may not be obtained; however, due to the comparably feasible practicability, this method acts as reasonable approach for engineering applications. If the crack propagation phase is dominant, a more detailed assessment, e.g. based on crack propagation concepts incorporating crack closure effects, is necessary to ensure a proper estimation of the lifetime under VAL. As subsequently presented, the crack initiation stage is prevailed especially in case of HFMI-treated joints; hence, the equivalent stress methodology is suitable to estimate the VAL fatigue strength in this work.

2. Methodology

2.1. Materials

The investigated base materials in this study are a mild steel S355 and a high-strength steel S700. In case of the latter one, the test data and material properties are taken from [21]. The nominal mechanical properties are provided in Table 1 and the chemical compositions are summarized in Table 2 for both material types.

2.2. Specimen geometries

Two different sample types are utilized within this work. For the mild steel S355, a single-sided non-load carrying longitudinal stiffener specimen and for the high-strength steel S700, a generally similar weld detail, but exhibiting a double-sided non-load carrying longitudinal stiffener, is utilized. The specimen geometries and their main dimensions, such as plate thickness and stiffener length, are presented in Fig. 1. Details in regard to the welding and HFMI-treatment process are shown in [21,22]. The main purpose of utilizing these two different sample types is not to directly compare the experimental results, but to validate the applicability of the aforementioned equivalent stress method for different applications.

Table 1
Nominal mechanical properties.

Material type	Yield strength [MPa]	Ultimate strength [MPa]	Elongation [%]
S355	355	575	22
S700	690–700	770–940	14

Table 2
Chemical compositions in weight %

Material type	C	Mn	Si	S	P
S355	0.18	1.60	0.55	0.035	0.035
S700	0.15–0.20	1.32–1.70	0.44–0.80	0.002–0.010	0.012–0.020

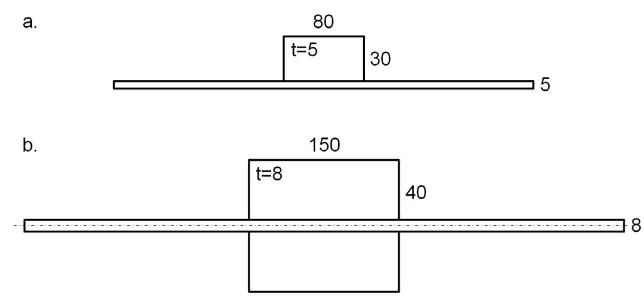

Fig. 1. Geometries of mild steel S355 (a) and high-strength steel S700 (b) specimen.

2.3. Testing conditions

The mild steel S355 specimens are tested at a load stress ratio of $R = 0.1$ under uniaxial loading in order to ensure a comparability to preliminary experimental and analysis results given in [22,23]. The high-strength steel samples are loaded with an alternating stress ratio of $R = -1$. The defined load stress ratios are kept constant during testing under CAL and VAL. As illustrated for the high-strength S700 specimens in [18], the applied load spectrum features a straight-line distribution with a sequence length of $2\cdot10^5$ load-cycles, tested randomly on a hydraulic cylinder test rig, see Fig. 2a. The omission level is set to 19% of the maximum load of the spectrum in order to reduce testing effort. Therefore, load stresses below this threshold value are not considered in the experiments as it is assumed that such small loadings do not significantly contribute to the fatigue damage, which basically fits to a proposal given in [24]. As the fatigue tests for the mild steel S355 samples are carried out on a resonant test rig, a certain adaption of the presented VAL stress history is needed. Thereby, the majority of the applied load-levels are reproduced as short load blocks each consisting of one thousand load-cycles, see detail of load-spectrum in Fig. 2b. However, the basic distributions of the load-spectra are quite similar for both material types. To ensure a proper evaluation of the specified damage sum within the subsequent work, each finally applied load-spectrum is used as basis for the analysis.

3. Experimental investigations

3.1. Fatigue test results

All fatigue tests are performed until final failure, which is defined as the complete separation of the test specimen, or without failure until a run-out limit of fifty million load-cycles. Statistical analysis is conducted utilizing the standardized procedure given in [25] and the arcsine√P-transformation presented by [26]. In case of CAL a second slope of $k' = 22$ according to [1] and for VAL a value of $k' = 2\cdot k - 1$ suggested by [16] is considered. The statistically evaluated S/N-curves are represented at a survival probability of $P_S = 97.7\%$ in accordance to [1]. Fig. 3 depicts the nominal S/N-curves of the mild steel S355 specimens tested under CAL and VAL utilizing the maximum nominal