Fatigue life estimation of treated welded attachments via High Frequency Mechanical Impact treatment (HFMI-treatment)

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ABSTRACT: High Frequency Mechanical Impact (HFMI) is one of the newest post weld treatment methods that can be used to repair cracks in welded structures. The main effect of this method is to extend the fatigue life by putting the cracks under compression. Linear Elastic Fracture Mechanics (LEFM) is to be used as an analysis tool accompanied by Paris law. Crack growth curves are presented in this work. The effects of the induced residual stress, the initial crack size, the clamping stress, and the stress range are all incorporated in the analysis. Subsequently, the analysis results are compared to experimental results obtained from fatigue testing on transverse non load-carrying welded attachment. The scatter in fatigue test results is found to be mainly attributed to the scatter in both the induced residual stresses and the variation in the existing crack sizes before treatment. Moreover, the analysis could successfully expect at what conditions the crack would not propagate through incorporating the concept of threshold stress intensity factor.

1 INTRODUCTION

Fatigue of welds gains increasing attention in the last decades. Therefore, several post weld treatment methods have been developed to increase the fatigue strength of welded structures. High Frequency Mechanical Impact (HFMI-treatment) is one of these methods which aims at inducing compressive residual stress at the weld toe vicinity. This method can be used for treating either new manufactured or cracked structures. In the latter case, HFMI-treatment puts the existing cracks under compression and reduces the crack propagation rate. In addition to this effect, it also removes the singularity existing at the weld toe. Moreover, it causes material hardening because of the cold working effect.

Linear elastic fracture mechanics (LEFM) is used as a practical tool for fatigue life assessments of metallic structures. Branco et al. investigated the life extension of T-joints by HFMI-treatment using Paris law. The results were not satisfactory because the residual stress effect was not incorporated (Branco, Infante, & Baptista 2004). Fracture mechanics led Fueki et al. to evaluate the crack size rendered harmlessly by HFMI indenter. Herein, the stress intensity factor of the applied stress range was compared to the threshold stress intensity factor K_{th} (Fueki, Takahashi, & Houjou 2015). Besides, Leitner et al. incorporated both residual stress effect and threshold stress intensity factor concept, and satisfactory results were obtained (Leitner, Barsoum, & Schäfers 2016).

The effects of both the induced residual stress (σ_{RS}) and the existing crack sizes (a_i) on fatigue life extension of repaired welded structures is rarely studied in the literature and requires further elaboration. This paper contributes to the crack propagation calculations using fracture mechanics. Fracture mechanics calculations are used to explore the effect of various aspects induced by HFMI-treatment, including the residual stress on fatigue life

extension of welds. Moreover, the effects of existing crack size and the applied load level are also studied to figure out the “safe crack” which can be tolerated before HFMI-treatment.

2 EXPERIMENTAL INVESTIGATIONS

2.1 Fatigue testing

Axial fatigue testing is conducted on transverse welded attachments made of S355 structural steel under a stress ratio $R = 0.29$. An axial testing rig is used to generate the loading. In addition to the membrane stresses due to axial load, unintentional bending stresses are generated at the weld toe because of the specimen's straightening to get rid of the angular distortions. The specimens are divided into two groups. In group A, the specimens are tested in as-welded conditions (denoted by AW), while seven specimens are fatigue tested until a crack of specific size appeared and detected at the weld toe in group B. Afterwards, their toes are treated by single HFMI-indenter (denoted by HFMI). Finally, they are tested to failure. The dimensions of the specimens and the fatigue testing rig are shown in Figure 1, and the fatigue test results are shown in Figure 2. The treated specimens exhibited significant fatigue strength, and six of them did not fail when tested under stress range $\Delta\sigma = 150$ MPa after 10 million cycles as indicated in Figure 2.

2.2 Crack detection and repair

The specimens in group B are instrumented with five strain gauges at each side of the attachment to determine the crack size as shown in Figure 1. A previous study showed that a 25%

Figure 1. a) Specimen's geometry with attached strain gauges (dimensions in mm); b) Fatigue testing rig.

drop in strain in any of the attached gauges corresponded to 0.6-1.2 mm crack (Al-Karawi, von Bock und Polach, & Al-Emrani 2020). Afterwards, a HiFIT indenter with a 3 mm diameter is used for treatment. The treatment is performed in accordance with the International Institute of Welding IIW recommendations (Gary Marquis 2016). Moreover, beach marks are created on one the surface by reducing the stress range to its half without changing the maximum stress for 5000cycles.

2.3 Stress concentration evaluation

Stress concentration factor gives the ratio between the local stress to the nominal stress. In order to find out the local stresses at the weld toe, the toe radii of the specimens in as-welded state and after HFMI-treatment are investigated using a 3D laser scanner. The geometry scanning shows a remarkable increase in the weld toe radii after HFMI-treatment (The average value increases from 0.67 mm to 2.1 mm). Therefore, the obtained average radii are used as inputs for 2D elastic finite element analysis conducted using ABAQUS/CAE to evaluate the stress concentration factors due to membrane loading. Local mesh size is selected in accordance with the effective notch approach, which is followed to get around the singularity at the weld toe (Hobbacher et al. 2009). The model for evaluating the stress concentration factors is shown in Figure 3. More information about the model can be found in (Al-Karawi, von Bock und Polach, & Al-Emrani 2020).

2.4 Residual stress and distortions

The residual stresses at the weld toe are investigated by means of the hole drilling method. Several holes are created at the weld toes of some specimens from both groups (i.e. AW & HFMI). Compressive residual stress is found in as-welded conditions, while higher compression is induced after HFMI-treatment. The depth of compression is obtained from a previous paper based on literature reviews (Al-Karawi, von Bock und Polach, & Al-Emrani 2020). The distributions are plotted in Figure 4. Four curves are plotted for the HFMI induced residual stresses containing the maximum and the minimum surface residual stresses with two depth of compression ($z = 1.5$ or 2 mm).

In order to quantify the tensile bending stresses generated by straightening the distorted specimens, the angular distortions are measured, and the clamping stresses are investigated using elastic finite element analysis to simulate the clamping process. The mesh size and the toe radii

Figure 3. The model used for evaluating the stress concentration factors.

Figure 4. The proposed residual stress distributions according to (Al-Karawi, von Bock und Polach, & Al-Emrani 2020).

Figure 5. The clamping stress distributions.

are selected according to IIW recommendations for effective notch approach (Hobbacher et al. 2009). The clamping jaws are modelled as undeformed bodies, and hard contact is defined between them and the specimen's surfaces. The local stresses below the weld toe are extracted when the specimens get fully straightened. The results are validated against the clamping stresses obtained from the attached strain gauges. The results of the obtained maximum and minimum clamping stresses are shown in Figure 5.

3 FRACTURE MECHANICS MODEL

Linear elastic fracture mechanics analysis is carried out to estimate the specimen's fatigue lives in both as-welded state and after HFMI-treatment. Weight function approach is employed to quantify the stress intensity factors. The stress intensity factors are calculated by integrating the product of the weight function $m(x, a)$ obtained from (Al-Mukhtar 2013) times the stress profile along the prospective crack path for the un-cracked specimens $\sigma(x)$ as indicated in equation 1.

$$K = \int_0^a m(x, a) \cdot \sigma(x) \cdot dx \quad (1)$$

The local stresses (obtained from the nominal stresses multiplied by the stress concentration factors shown in Figure 3) are used to compute $\sigma(x)$. Moreover, the distributions of the residual stresses (RS) and the clamping stresses (CS) shown in Figures 4 and 5 are used to incorporate the effect of mean stresses in the analysis, as given in the definition of the effective stress ratio (R_{eff}) in equation 2. Then, Paris law is used to calculate the extension in crack size after dN load cycles, see equation 3. Paris law parameters C , m are selected to be $1.65 \cdot 10^{-13}$ and 3 respectively. The threshold stress intensity factor is incorporated to explain the obtained 6 runouts obtained in fatigue testing as shown in Figure 2. The value of C , m and K_{th} are selected in accordance with the IIW recommendations (Hobbacher et al. 2009).

$$R_{eff} = \frac{K_{min} + K_{RS} + K_{CS}}{K_{min} + K_{RS} + K_{CS}} \quad (2)$$

$$da = \begin{cases} \frac{C(K_{max} - K_{min})}{(1.5 - R_{eff})^m} dN, & K_{max} - K_{min} > K_{th} \\ 0, & \text{Otherwise} \end{cases} \quad (3)$$

The initial crack size used to commence the crack propagation in the as-welded condition is selected to be 0.5 or 0.15 mm. The former is the maximum allowable undercut height according to the British standard (BS7910 2005), while the latter is the recommended initial crack size according to the IIW recommendations. On the other hand, the existing crack sizes in the specimens in group B of 0.6-1.2 mm are used in the crack propagation analysis of the HFMI-treated specimens. The results of the fracture mechanics analysis for as-welded and HFMI-treated specimens tested under different stress ranges are shown in Figure 6. Different combinations of residual and clamping stresses are presented. Furthermore, fatigue lives, prefatigue lives and beach mark results are marked by black crosses in the figures.

Figure 6. Crack propagation curves for: a) As-welded specimens tested under nominal stress range $\Delta\sigma = 150$ MPa; a), c), d) HFMI-treated specimens tested under nominal stress of 150, 180 and 210 MPa respectively.

Figure 7. The effect of different parameters on fatigue lives of HFMI-treated specimens tested under applied stress range $\Delta\sigma = 150, 180$ and 210 MPa respectively.

Most of the experimental results are found in the band of the generated curves in as-welded conditions. Moreover, the analysis could predict the 6 run-outs when the HFMI-treated specimens are tested under a stress range $\Delta\sigma = 150$ MPa as the obtained ΔK is less than K_{th} (see Figure 6b). Remarkably, the specimens become significantly stronger after HFMI-treatment although they contain cracks of $0.6 - 1.2$ mm. Moreover, the analysis results are in line with the beach marking results, as shown in the same figure. In addition, the fatigue lives of 4 out of 5 specimens tested under stress range $\Delta\sigma = 180$ or 210 MPa are also well predicted by the analysis as shown in Figure 6c, d.

Fatigue test results are highly scattered in both as-welded and HFMI-treated conditions. The analysis gives an insight into the reason behind the scatter, which is traced back to the differences in four parameters: residual stress (RS), depth of compression (z), clamping stress (CS), and existing crack size (ai). The effect of these parameters on fatigue life extension are studied under different stress levels (see Figure 7). In the analysis, when one parameter is under study, the other parameters are fixed to the average values (RS = -380 MPa, CS = 83 MPa, ai = 0.9 mm and z = 1.75 mm). The effects of residual stress and initial crack size is found to be the most influential on fatigue life extension. On the other hand, the clamping stress effect is found to be less significant. Moreover, the analysis shows that eight out of the ten studied cases 'run-out' after 10 million cycles when the stress range is 150 MPa which is in line with the test results where six out of total seven specimens run-out.

4 SUMMARY AND CONCLUSIONS

Within the current study, linear elastic fracture mechanics analysis is conducted to predict the fatigue lives of transverse attachment specimens made of S355 structural steel. Moreover, several experimental and numerical investigations are conducted to evaluate the stress concentration factors, the residual stresses and the clamping stresses. Relatively long fatigue lives are obtained even in as-welded conditions which is caused by the presence of compressive residual stress at the weld toe. HFMI-treatment causes reduction in the angular distortion which reduces the clamping stress. The average weld toe radius is doubled after HFMI-treatment, which causes a significant reduction in the stress concentration factor. The performed fracture mechanics analysis incorporates the effects of stress range, residual stress, clamping stress, initial crack size and threshold stress intensity factor. The analysis results match the experiments in most of the cases. Moreover, the variability of residual stress and the initial crack size are found to be the most influential factors behind fatigue life scattering of the HFMI-treated specimens.

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