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Full paper

A Numerical and Experimental Study on Fatigue Life of HFMI-treated Cover Plates in Steel Bridges

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Abstract

There are a lot of bridges in Sweden that need to be upgraded and strengthened due to heavier traffic. One common method to strengthen existing steel bridges is the addition of cover plates to various bridge elements. Welded cover plates are avoided due to their poor fatigue performance. To mitigate this issue, high frequency mechanical impact (HFMI) treatment is suggested. 3-point bending fatigue tests were done to investigate the effect of weld size and stress range on fatigue life of HFMI-treated welded cover plates. The effective notch stress method was employed to analyze the stress concentration factors at the weld toe and root. Two case studies (5-mm and 7-mm weld throat size) were numerically analyzed and compared with experimental tests. The numerical results are in good agreement with experimental tests. It was found that the weld throat size plays a significant role in the stress distribution at the weld and thus on the failure mode (toe or root cracking) of welded details. Two different failure modes, toe and root cracking, were observed.

Keywords

Cover Plate, HFMI Treatment, Notch Stress, Fatigue Life, Root Cracking

1 Introduction

Many existing bridges need to be strengthened to meet the growing demands of heavier vehicles and increased traffic volumes, both now and in the future. A variety of techniques are available to enhance the load-bearing capacity of these structures, ensuring they remain safe and functional under modern transportation demands [1]. The addition of cover plates in highly loaded areas of existing steel beams represents a commonly employed technique for the structural reinforcement and upgrading of steel bridges [2],[3]. Fixing cover plates to the beams can be performed using bolted or welded connection. Each method has its own advantages and challenges [4].

Extensive experimental evidence confirms that HFMI treatment provides a notable increase in the fatigue resistance of welded details [5], [6]. Moreover, various techniques have been developed to evaluate the fatigue performance of welded components improved by HFMI treatment [7], [8]. Distinct S-N fatigue curves for HFMI-treated welds corresponding to different steel grades are proposed by Marquis and Barsoum [9]. Shams Hakimi et al. [10] reported the use of HFMI treatment for improving fatigue strength of welded bridge details in some existing

bridges and also some new bridges. While most fatigue tests on HFMI-treated details have focused on transverse butt welds, transverse attachments, and longitudinal attachments, experimental data on HFMI-treated welded cover plates remain scarce.

Roy and Fisher [11] conducted experimental investigations on the fatigue performance of HFMI-treated welded cover plates. Their results showed that HFMI treatment significantly improves the fatigue resistance of cover plate connections. Moreover, the enhancement in fatigue strength was found to be more pronounced for details fabricated with larger transverse fillet welds. Hui et al. [12] investigated the fatigue life improvement of welded cover plates treated using ultrasonic impact treatment. Among the twenty HFMI-treated cover plate ends examined in their study, twelve failed due to crack initiation at the weld root, whereas only three exhibited crack initiation at the weld toe. These results indicate that the potential for root cracking should be carefully considered in the design of HFMI-treated welded cover plate details. Al-Emrani et al. [3] performed experimental and numerical investigations on the fatigue life improvement of beams strengthened with cover plates welded at midspan and treated using HFMI. Their experimental results demonstrated that HFMI

treatment increases the fatigue strength of welded cover plate details by more than four detail categories. In their study, they only had toe cracking. But in the literature, some root cracking are reported [12]. Noghabi et al. [13] investigated the effect of geometric parameters on fatigue life of HFMI-treated cover plates. They developed some expressions for estimation of stress concentration factors at the weld toe and root. They found that the failure mode (toe or root cracking) is dependent on both stress concentration factors and stress range.

Experimental evidence has shown that fatigue failures can initiate at the weld root, potentially limiting the maximum fatigue strength enhancement achievable through HFMI treatment. This observation exposes an important gap in current research and emphasizes the need for comprehensive studies on the factors governing the fatigue behaviour of HFMI-treated connections, particularly concerning whether toe cracking or root cracking governs the failure mode.

2 Methodology

2.1 Experiments

Two different weld throat sizes, a_w , were used in experimental tests, 5 mm and 7 mm. The length of the beams was 3 meters and the distance between supports was 2.5 meters. The length of cover plates was 1 meter. The flange thickness, t_f , was 10 mm and the cover plate thickness, t_c , was 15 mm. A configuration of test setting is illustrated in Figure 1. All specimens were HFMI treated manually by HiFit machine using a 3-mm pin diameter. The HFMI treatment speed was 20-30 mm/sec. The average groove depth is about 0.15 mm, and the average diameter is about 3.2 mm. Figure 2 shows the specimen end after HFMI treatment. The fatigue test specifications and results are summarized in Table 1. It should be mentioned that if there was no crack after 5 million cycles, we considered it as run-out.

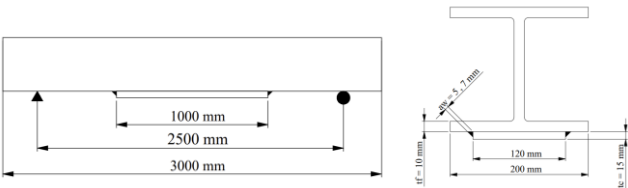


Figure 1 The dimensions of the beams and cover plates.



Figure 2 HFMI treatment of cover plate ends.

Table 1 The geometry dimensions and results of experimental tests.

variant	a_w (mm)	Stress Range (MPa)	Fatigue Life $\times 10^3$
C05	7	96.4	3054
C06-1	7	96.4	Run out
C06-2	7	115.4	1685
C07	7	115.4	759
C08	7	115.4	541
C09	7	105.8	950
C10	7	105.8	1850
C11	7	105.8	1480
C12	7	105.8	1001
B01-1	5	80	Run out
B01-2	5	96.4	3400
B02-1	5	80	Run out
B02-2	5	96.4	Run out
B02-3	5	115.4	1760

The fatigue tests were carried out using a dedicated testing machine designed for evaluating beams under bending, capable of loading two specimens simultaneously. The hydraulic jack applied force to the lower beam, and through the roller supports and prestressed fixture, the same loading was transferred to the upper beam.

All tests were conducted under constant amplitude loading with a R-ratio of 0.1 and a frequency of 7 Hz. To enable early crack detection, all specimens were instrumented with strain gauges. Fatigue loading was terminated once the crack had propagated through the flange thickness, which was taken as the failure criterion. The experimental setup used to apply the cyclic loads to the specimens is shown in Figure 3.

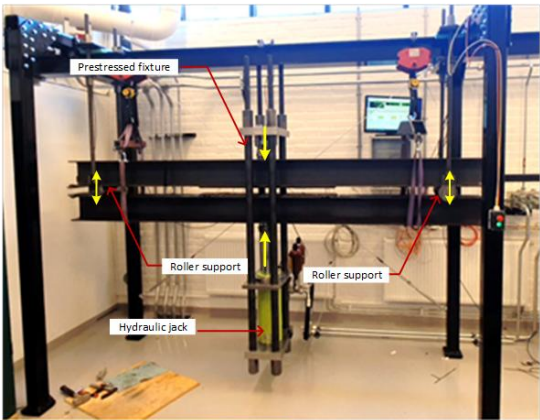


Figure 3 The set-up for fatigue testing of two beams simultaneously.

2.2 Finite Element Modelling

Finite element (FE) analyses were performed using Abaqus/CAE. The Effective Notch Stress (ENS) method is used to evaluate the local stresses at the weld toe and root of the cover plate. Particular attention was paid to mesh refinement at critical locations, such as the weld toe and root, where stress concentrations are highest. A mesh sensitivity analysis was carried out to verify the adequacy of the selected mesh size. Linear elements were used in all analyses. The mesh configuration adopted in the finite element model is shown in Figure 4. The effective notch stress is calculated in accordance with the specifications of the IIW recommendations [14], using a reference radius of $r_{ref} = 1$ mm. Wendler et al. [15] calculated notch stress considering the real world geometry. They found that using IIW recommendation is conservative.

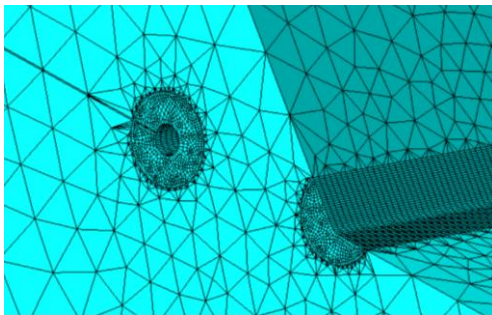


Figure 4 The applied mesh in FEM.

The applied load on the beam was selected such that the nominal stress at the weld toe was 1 MPa. Consequently, stress at the toe and root notches are equal to the corresponding stress concentration factors, i.e., $\sigma_{toe} = K_{toe}$ and $\sigma_{root} = K_{root}$. The stress concentration factors at the toe and root are summarized in Table 2. Figure 5 illustrates the effective notch stresses (maximum principal stress) at the weld toe and root. Fatigue cracks are expected to propagate perpendicularly to the direction of the maximum principal stress. It is obvious that decreasing the weld size would result in increasing the stress concentration factors. Moreover, the ratio of toe to root stress concentration factor, K_{toe}/K_{root} , decreases and the possibility of root cracking increases.

Table 2 Stress concentration factors obtained in analyses.

t_f mm	t_c mm	a_w mm	K_{toe}	K_{root}	K_{toe}/K_{root}
10	15	7	5.035	4.621	1.089
10	15	5	5.648	5.889	0.960

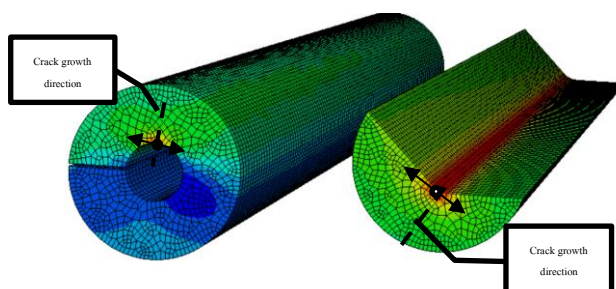


Figure 5 The effective notch stress in the weld toe and root and the possible path of crack growth.

2.3 Analytical Model

In accordance with the IIW recommendations, the fatigue life of welded cover plate details can be estimated [9]. The stress range at which the cracking mode changes from toe to root cracking is defined, based on our previous study [13], as follows:

$$\Delta\sigma_{toe}^* = \sqrt{\frac{\alpha^3 \Delta\sigma_{c,root}^3 \Delta\sigma_{c,toe}^5}{\alpha^3 \Delta\sigma_{c,root}^3}} \quad (1)$$

where $\alpha = \Delta\sigma_{toe}/\Delta\sigma_{root}$ represents the stress ratio, $\Delta\sigma_{c,root}$ is the detail category associated with root cracking (225 MPa), and $\Delta\sigma_{c,toe}$ denotes the detail category for HFMI-treated joints (e.g., 320, 360 MPa), depending on the yield stress.

It is evident that $\Delta\sigma_{toe}^*$ is governed by the detail categories for toe and root cracking and by the ratio of the corresponding stress concentration factors, $\alpha = \Delta\sigma_{toe}/\Delta\sigma_{root}$.

3 Results and Discussion

The failure mode of the HFMI-treated specimens was found to depend strongly on the weld size. As depicted in Figure 6, HFMI-treated specimens with a 7-mm weld size primarily failed by toe cracking, whereas those with a 5-mm weld size failed by root cracking (There is also a small crack originated from toe). This distinction highlights the influence of weld geometry on the dominant cracking mechanism and suggests that the structural response under cyclic loading differs markedly between the two configurations.

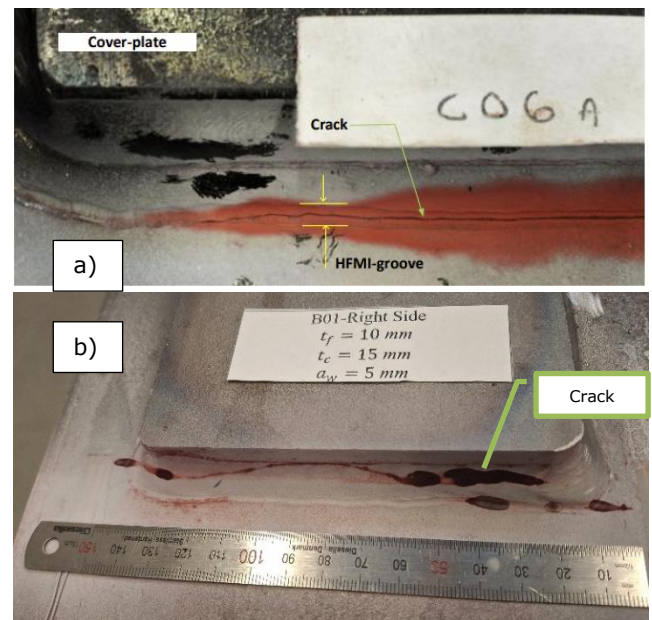


Figure 6 Fatigue cracks in the HFMI-treated specimens a) toe cracking (7-mm weld size) b) root cracking (5-mm weld size).

Using Equation (1), a toe-to-root failure chart can be constructed for a given value of $\Delta\sigma_{c,toe}$, while $\Delta\sigma_{c,root}$ is kept constant at 225 MPa (Due to the fact that HFMI treatment can only be performed at the weld toe). Figure 7 presents such a chart for $\Delta\sigma_{c,toe} = 360$ MPa, which corresponds to

HFMI-treated welds in steel S355 according to the IIW recommendations. The curve illustrates the relationship between $\Delta\sigma_{\text{toe}}$ and $\Delta\sigma_{\text{root}}$ in a log-log scale, indicating the stress range at which the fatigue failure mode transitions from toe cracking to root cracking. Specifically, regions above the curve correspond to root cracking failures, whereas regions below the curve correspond to toe cracking failures.

Experimental data from the literature (Hui et al. [12], Vilhauer [16], and Al-Emrani [3]) as well as from the present study are superimposed on the chart. As shown, most points below the line correspond to toe cracking; however, one data point located above the line also exhibits toe cracking. This deviation may be attributed to inadequate HFMI treatment. Hui et al. [12] reported a similar observation, noting that in one instance the HFMI treatment was not performed correctly. Another possible explanation is that residual stress at the weld root may be compressive, or that weld penetration, an aspect not represented in the ENS model, reduces the stress concentration at the root.

In our analysis, the observed failure mode progressed from the root toward the weld surface for 5-mm weld size and from toe for 7-mm weld size. In the region near the transition line, both toe and root cracking failures may appear (as shown in Figure 6).

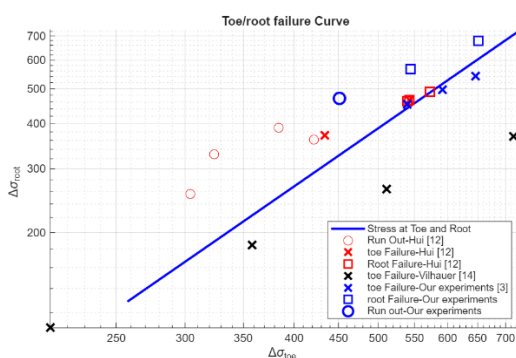


Figure 7 The failure mode curve.

4 Conclusion

In this study, the effect of weld size on fatigue life and failure mode of welded cover plates, when the ends of these plates are treated with High Frequency Mechanical Impact (HFMI) treatment is investigated numerically and experimentally. It is found that the weld throat size is the factor that most significantly affects the stress concentration factors both at weld toe and root. When the weld size decreases, the toe to root stress ratio decreases and the possibility of root cracking increases. The designers should consider the possibility of root cracking in designing welded details. When the weld size to cover plate thickness ratio (a_w/t_c) is greater than 0.5, the risk of root cracking failure decreases.

Acknowledgments

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