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Experimental study of transverse attachment joints with 40 and 60 mm thick main plates, improved by high-frequency mechanical impact treatment (HFMI)

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ABSTRACT

In recent years, high-frequency mechanical impact (HFMI) treatment has grown in popularity due to its efficiency in improving the fatigue strength of welded joints. The fatigue performance of HFMI-treated welded steel joints has, however, not been thoroughly studied for plate thicknesses above 30 mm. In this study, 40 and 60 mm thick main plates with non-load-carrying transverse attachments have been fatigue tested under constant amplitude four-point bending, both in as-welded and HFMI-treated condition to investigate the fatigue performance for large plate thicknesses, typical for weldments in bridges. Axial fatigue strengths were estimated by a modification of the experimental results with fracture mechanics calculations. The main conclusions are that HFMI treatment can result in significant fatigue strength improvement even for large main plate thicknesses and that the difference in fatigue strength between bending and axial loading is negligible for the specimen geometries used in this study.

1. Introduction

High-frequency mechanical impact (HFMI) treatment is a residual stress based post-weld fatigue improvement technique which has gained increased attention during the last decade due to its efficiency and ease of application. A number of factors contribute to the efficiency of the HFMI technique:

1) The method yields the highest fatigue strength improvement compared to other post-weld improvement techniques such as grinding, TIG-dressing or shot peening, especially in the high cycle regime [1–4].
2) The improvement becomes greater for higher material yield strengths [5] which enables the utilisation of the benefits of high-strength steels, for example in lightweight designs.
3) The treatment speed is typically similar to welding speed and faster than other improvement techniques [1,3,4].
4) Unlike hammer and needle peening, which are predecessors of the HFMI-technique, HFMI-tools produce higher quality weld toes, they emit less noise and vibrations and are, consequently, more comfortable for the user to operate [6].

The fatigue strength improvement by HFMI treatment mainly emanates from alteration of the near-surface residual stress state to compressive stresses in the order of magnitude of the material's yield strength. In addition, the following mechanisms may also lead to beneficial effects: (1) smoothening of the weld transition region from base to weld metal which reduces the stress concentration at the weld toe, (2) cold working of the weld toe through plastic deformation which increases the local yield strength due to strain hardening. See [7] for a review of the HFMI treatment and [8] for an in-depth investigation of the improvement mechanisms.

The International Institute of Welding (IIW) recently published recommendations for improvement assessment and quality assurance of HFMI-treated welded joints [6] based on the proposed guidelines in [9] and [10]. The suggested degrees of improvement are applicable for main plate thicknesses between 5 and 50 mm. However, existing experimental studies have commonly used plate thicknesses between 5 and 30 mm, e.g. [11,12], often showing no influence of thickness on the fatigue strength of HFMI-treated joints [13–18]. Iwata et al. [4] studied a wider range of thicknesses for non-load-carrying transverse attachment joints, between 10 and 50 mm, showing a clear influence of thickness on the fatigue strength of HFMI-treated joints, however, based on few experimental results. A few experiments have also been

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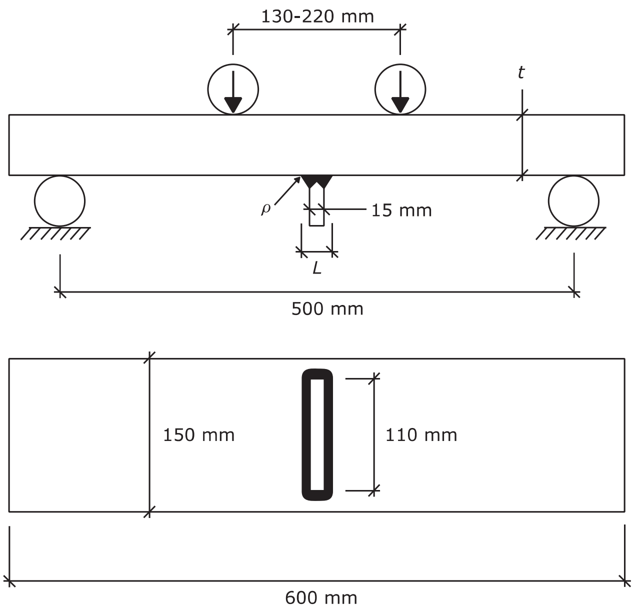

Fig. 1. Test specimen dimensions and loading arrangement.

performed on 90 mm transverse attachment joints by Schaumann et al. [19], although without comparative experiments on thinner plates. All of the results in [4] and [19] conform with the IIW recommendations. The thickness effect of HFMI-treated joints has been studied by the first author of this paper and co-workers, based on 582 existing experimental results from the literature, showing a clear thickness effect for non-load-carrying transverse attachment joints when the attachment and main plates are of the same thickness [20].

The aim of this study is to investigate the improvement gained by HFMI treatment for larger plate thicknesses than has commonly been studied experimentally. In this paper, the performance of the HFMI treatment is studied with an emphasis on bridge structures, wherein one of the most common types of welded joints prone to fatigue damage are non-load-carrying transverse attachments. The transverse attachments are often present in bridge girders in the form of relatively thin web stiffeners which are welded to flanges with large thicknesses. The steel grades are relatively low, normally S355, due to limitations by fatigue in the welded joints. Studies performed by the first author and co-workers [21–23] show that increasing the fatigue strength at the welded joints of bridges by post-weld treatment allows for the use of higher strength steels which in turn can reduce the material consumption by around 20% in the main load-carrying members. In railway bridges, which favour most from HFMI treatment due to low stress ratios, the use of high-strength steel was shown to be limited to S460 due to vertical deflection [21].

This study involves fatigue testing of non-load-carrying transverse attachment specimens with two main plate thicknesses of 40 and 60 mm and two material strengths with minimum yield stresses of 355 and 460 MPa. Prior to the fatigue testing, metallography analyses, residual stress measurements and weld geometry scanning were performed. Due to large required forces, the fatigue experiments were conducted under four-point bending, whereupon crack growth analyses with linear elastic fracture mechanics were used to modify the experimental results to represent axial loading. The experimental results show significant fatigue strength improvement even for large main plate thicknesses, exceeding the recommended FAT values given by the IIW [6]. Negligible difference in fatigue strength was calculated comparing bending to axial loading.

2. Fatigue test program

A total of 54 fatigue tests were carried out in this study of which 13 were as-welded (AW) and 41 were HFMI-treated specimens. All specimens were laser-scanned to quantify the weld toe radius, ρ, and weld toe distance, *L*, see Fig. 1. In addition, residual stress measurements by X-ray diffraction were performed, both on non-treated and HFMI-treated specimens. Optical microscopy provided microstructural images of the weld toe regions and the base metals. A description of the fatigue experiments is given in this section. The studies of weld toe scanning, residual stress distributions and microstructure are presented in the results section.

2.1. Test specimens and materials

The geometry of the specimens and the four-point bending test setup is depicted in Fig. 1 and an overview of the test series is given in Table 1. As-welded series of two different plate thicknesses were included as references for comparison with the HFMI-treated specimens. The steel plates for specimen manufacturing were delivered at separate occasions and due to different availabilities in the inventories, a plate thickness of 38 mm was delivered instead of 40 mm for series 1 and a steel grade of S500 instead of S460 for series 2. For the S500 steel grade, both the mechanical properties and chemical compositions as specified by the manufacturer certificates were similar to that of steel grade S460, see Table 1 and Table 2.

2.2. Specimen manufacturing

The main focus of the current study was on the fatigue strength of welded bridge details. Welding of the test specimens was performed in a bridge production workshop and common procedures were followed to reproduce a weld quality similar to that produced in bridges. Normally, grinding is performed on bridge welds to achieve a weld quality of class B according to ISO 5817 [24]. For this reason, the HFMI specimen welds were also ground prior to HFMI treatment, hereafter referred to as “ground + HFMI”, see Fig. 2. The grinding did not intrude into the base metal in the way burr grinding does for the purpose of fatigue improvement. The as-welded specimens in this study were not ground in order to provide a representative comparison with the treated specimens, see Fig. 3. The welding parameters, given in Table 3, were the same for all series. In order to avoid root failure during fatigue testing, the welds were made as fully penetrated K-welds. Welding was performed in an upright position as shown in Fig. 2.

The HFMI equipment used in this study was the Ultrasonic Needle Peening (UNP) device with a single indenter of 3 mm impact tip radius. The treatment was performed by considering the quality assurance

Table 1
Test series and mechanical properties according to manufacturer certificates. Number of fatigue tested specimens indicated with k.

Series	Specimens	*t* [mm]	Steel grade	f_y [MPa]	f_u [MPa]	Elongation [%]	*k*
1	460-38-AW	38	S460M	562	659	22	7
2	500-60-AW	60	S500G2M	471	596	25	6
3	355-40-HFMI	40	S355K2 + N	382	531	25	10
4	460-40-HFMI	40	S460M	566	639	23	11
5	355-60-HFMI	60	S355K2 + N	361	532	25	10
6	460-60-HFMI	60	S460G2M Z35	494	597	26	10