Sustainable steel and composite bridges through increased lifetime by fatigue treatment

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Abstract. To achieve sustainable long-living infrastructures such as steel and composite bridges, the improvement of the fatigue behavior is crucial. By using high frequency mechanical impact (HFMI) treatment of critical welds, the fatigue service life of welded structures can significantly be extended due to the introduction of compressive residual stresses. Particularly with the use of high-strength steels in combination with HFMI-treatment has become economic in terms of fatigue design, thus, leading to reduced use of material resources. Even for welding in existing structures, positive results have already been achieved with post-weld treatment. For this innovative method, the amount of lifetime benefit and the conditions for successful application in the view of quality assurance have sometimes become object of critical questions. In various research projects, these questions could successfully be answered. By means of numerical and experimental investigations, design approaches have been developed and evaluated for the application of those treatments in constructional bridge design. The paper summarizes the results of two research projects on the subject of HFMI-treatment with the focus on the use for steel and composite bridges. An insight on the improved fatigue design, the practical use, the benefits for the constructions and possible application fields is given.

1. Motivation

Based on two projects, the aspect of sustainability in steel and composite bridge construction due to the application of high frequency mechanical impact (HFMI) treatment on critical construction details achieving lifetime extensions and efficient use of materials in terms of material savings is presented.

The advantages of using high-strength steels in combination with the application of HFMI-treatment in composite and steel bridge construction could be shown in the European research project "Optimal Use of High Strength Steels within Bridges - OptiBri"[1]. In the first step, a typical European composite bridge construction was selected for a multi-span four-lane highway application and it was designed in steel grade S355 (design A). In the second design step, the steel grade was replaced by a high-strength steel S690, so that at some details the cross sections could be reduced due to higher yield strength (design B). However, due to the current conservative design rules for S690 according to Eurocode, no complete utilization of the material is possible. The aim of this RFCS research project [1] was to work out the critical issues for stability and fatigue for the design states, and to improve and optimize the use of high-strength steel grades. In a third step, therefore, a third bridge design, was developed with an "improved" design based on the research results (Design C). Especially in the construction field of fatigue and stability, there is a need for improvement and development of the codes under certain conditions.
Even when used in a railway bridge construction with steel grade S355, lifetime extensions by HFMI-treatment are possible. As part of the FOSTA-AiF-research project P978 Holistic Assessment of steel- and composite railway bridges according to criteria of sustainability [2], specific investigations were carried out in order to optimize different railway bridge types. In the construction of modern railway bridges, innovative design solutions such as thick-plate through bridges, see figure 1, with improved life-cycle assessment and fatigue resistance are important. By improving single structural details, the critical weld detail will be strengthened due to the application of HFMI to extend the fatigue service life. The aim of construction variant types are structures with low maintenance, furthermore that surrounding traffic routes and utilization are affected only in minor extent by rehabilitation and maintenance works. To assess the benefits of these optimized constructions within the life-cycle of the bridge, the conventional and improved constructions were compared with each other by applying sustainable analyses.

![Figure 1. Thick-plate through bridge.](image)

2. Sustainability in bridge construction due to HFMI-treatment

2.1. Application of HFMI-treatment

As shown in several projects ([3, 4, 5]), the fatigue strength of new and existing structures can be increased on selected notch details by post-weld treatment. The process of repetitive hammering with a hardened pin along the weld toe, see figure 2, achieves plastic deformation of the notch. By the application of HFMI-treatment, three modes of action are covered: reducing the notch effect at the weld toe by plastic deformation, see figure 3, increasing the hardness of the surface layer with reduction of micro cracks, and introduction of residual compressive stresses in surface areas of the notch by cold deformation. However according to [3], the latter is more important.

![Figure 2. HFMI-treatment.](image)  
![Figure 3. HFMI-treated weld toe.](image)

The suitable application of HFMI are for welds where the fatigue failure originates from the weld toe, not from the weld root. In Germany, especially the Pneumatic Impact Treatment (PIT) [6] and High Frequency Impact Treatment (HiFIT) [7], the methods are distributed.
Many investigations have been conducted on the effectiveness of HFMI application related to new constructions, so the HFMI-treatment was, in most cases, performed directly after the welding process in order to show that an improved notch detail can be achieved right from the start. Also, several investigations have been conducted for high strength steels because this has proven to be the most effective due to the higher introduced residual stresses. However, also for S235 an increase of fatigue strength by HFMI has been demonstrated in [5].

With the draft of the German DASt-guideline “Development of a DASt-guideline for high frequency mechanical impact treatment” [8] a design concept for HFMI-treated welds is available. As part of the quality assurance, the first investigations were made on HFMI-treated base material specimens within the FOSTA-short study “Development of a simple quality assurance test for the application of high frequency mechanical impact treatment” [9]. Further studies on quality assurance were carried out for the component-specific application on the weld toe in the BAW research project "Investigations on the effect of varying qualities of HFMI-treatment and assessment of simple methods for checking the post-weld-treated toe" [10]. Within the project [10], different treatment intensities were investigated by fatigue tests, residual stress and mobile hardness measurements. It was confirmed that an over or under treatment of the notch detail unloaded transverse stiffener due to the selected PIT-treatment duration time has no effect on the fatigue strength, see figure 4, which compares the welded (aw) specimens with the HFMI-treated specimens with low, normal, and high intensities.

![Figure 4. Results of BAW project [10] on untreated and HFMI-treated specimens.](image)

2.2. Critical notch details related to steel bridge construction [11]

In OptiBri [1], the critical structural welded joint details in the main girders by using vehicle FLM3, the damage equivalent factors were assessed and optimized in the design of High Strength Steel (HSS) S690. By the application of post-weld treatment, the fatigue strength could be improved and possible enhancement of the present Eurocode rules was suggested.

The critical details for twin plate girder decks were identified and summarized in [11], cf, and in figure 5 for the typical FAT detail categories. It was outlined that FAT80 is the critical detail category which exists at welded joints between the bottom flange and the transverse stiffeners. A reduction of the average structural steel weight, especially at the span of the bottom flanges is achieved by increasing the FAT category due to HFMI-treatment of welded joints at the bottom flange level, and by improving the designs of transverse and longitudinal stiffeners.
2.3. Sustainability in bridge construction [13]
Since there is an enormous amount of railway bridges that have to be replaced, the demand for sustainable bridge solutions arises. Not only the builder but also the network operator is interested in sustainable bridge structures where the environmental footprint is minimized, the maintenance and following costs are low, and the line blockings can be avoided.

Considering the whole life-cycle of a bridge by covering the three aspects of economical, ecological and socio-functional effects including fabrication, erection, operation stage with its maintenance and inspection actions as well as the end-of-life with the deconstruction containing the recycling of a bridge, steel and composite bridges offer several benefits compared to concrete bridges.

This is why critical fatigue details were optimized to get an additional extension in fatigue service life and the service life of the entire bridge, which results in an enhanced sustainability. This could be reached by applying HFMI-treatment at the weld toe of the critical weld detail decisive in the design.

3. Experimental investigations on HFMI-treatment

3.1. Investigations on welded beams of high-strength structural steels [1]

3.1.1. Introduction. The yield strength independent behavior of the fatigue strength of welded joints, especially in bridge construction, means that the use of high-strength structural steels often does not pay off, since the fatigue strength is the determining factor. By the use of HFMI methods, the fatigue strength of selected welded details can be improved, due to this, even for welded joints the use of high-strength structural steels becomes more interesting and economical. As described in section 2.1, the increased fatigue strength results were achieved in the post-weld treatment of welded components made of high-strength structural steels, since the increase in fatigue strength due to HFMI-treatment is related to the magnitude of the introduced compressive residual stresses introduced, and these depend significantly on the level of the yield strength, see [4].

As part of the European research project OptiBri [1], a pilot program was carried out with numerous HFMI-treated small samples from S690 at the University of Liège.
Referencing a series of small samples at the notch detail of the “unloaded transverse stiffener”, the improved fatigue strength at $\Delta \sigma_{c, \text{HFMI} 0.1, \text{S690}} = 190 \text{ N/mm}^2$ could be determined.

With the aim of determining the effectiveness of the HFMI application for structures similar to bridge structures made of high-strength structural steels, seven S690 girder tests with welded-in unloaded transverse stiffeners were tested at the Materials Testing Institute of the University of Stuttgart by the Institute of Structural Design (University of Stuttgart). In this case the experimental setup corresponded to a conventional 4-point bending test with two hydraulic cylinders. Strain gauges were placed on the beam flanges to monitor crack initiation and allow recalculation of the nominal strain range.

3.1.2. Test results. The failure of the welded beams resulted in different failure mechanisms. Figure 6 shows the fracture is due to the failure of the HFMI-treated weld of the transverse stiffener. The crack was initiated from the top edge of the flange and represent a conventional failure from the weld toe. However, due to the improved detail of the HFMI-treated transverse stiffener, the fractures were partially initiated from the bottom flange of the base material in this beam series, see figure 7. The surface structure clearly shows that the crack was neither initiated by the longitudinal weld connecting the web and the bottom flange, nor by the transverse stiffener weld.

Figure 6. Fatigue failure on the weld toe of the transverse stiffener [14].

Figure 7. Fatigue failure of the base material [14].

Figure 8. Test results of the beam test series from S690 from OptiBri [1] compared to the IIW Recommendations [15].
The experimental results are shown in figure 8. The distinction of failure modes is documented in the diagram, the crossed squares represent failure at the weld toe of the transverse stiffener. All other test points were based on deviating failure mechanism, mainly base material failure. Based on the S-N diagram, it seems that the fatigue strength of 160 N/mm² proposed by the IIW, according to [15], can be achieved for HFMI-treated welded-in unloaded transverse stiffeners of the quality S690. Ultimately, the results of the welded beams show that the positive effect of the post-weld treatment competes with the base material failure, or the failure of the base material may be decisive over the improved fatigue strength of the transverse weld.

3.2. Investigations on the thick-plate trough bridge detail [2]

3.2.1. Introduction. The fatigue design of steel trough bridges is dominated by the three following notch details: shear in the longitudinal weld, the transverse stiffener in the bottom plate, and the mostly-neglected transversal bending due to the cross frame effects, the longitudinal fillet weld connecting the thick track plate to the inclined web plate. The latter with the detail category 36e is the most critical construction detail according to EN 1993-1-9 [16].

An extension of the service life of the construction detail and furthermore, for the bridge resulting in an improved sustainability was reached by the HFMI application by PIT for this detail. By now, there is no obvious detail category for the case of transversal bending on the fillet weld in EN 1993-1-9 [16], the fatigue strength of the untreated weld was revealed in a first test series. For the second test series, HFMI-treated fillet welds were executed to determine the improvement factors. Moreover, there was a real size test series of scaled thick-plate trough bridges to identify the real global and local stress situation where as-welded and post-weld treated specimens were tested. By now, there have been no evaluations on the influence of the HFMI application on fillet welds under transversal bending.

The specimens were tested at the Materials Testing Institute of the University of Stuttgart by a servo-hydraulic testing device with a maximum of 400 kN performed cyclically with uniform amplitude and with a frequency of around 3 to 6 Hz. Only the compressive loads were applied, the stress ratio was equal to R=0.1. With the help of five strain gauges which have been brought up on the tensioned side of the web plate, nominal stresses were detected. The failure criterion was the total failure of the weld.

3.2.2. Test results. Due to the high effects of HFMI-treatment, the failure of the specimens could only be achieved on the highest stress level. Results of specimens on lower stress levels were run-outs. Due to the small sample of HFMI-treated specimens, only tendencies for the life extension effects could be detected. Comparing the as-welded thick-plate test results to the HFMI-treated test results in figure 9, it is obvious that the HFMI-treatment has a life-extending effects onto the fillet welds. For the higher stress range, the enlargement factor kn is 2.7, in the lower stress range the enlargement of cycles is 4.3 to 4.4. This factor varies at the different stress range levels because the slope of the as-welded specimens is around 3, whereas the slope of the HFMI-treated specimens is much flatter and around 5, which is a typical value for HFMI-treated specimens.

In addition, a real size test series of four scaled thick-plate trough bridges were executed. Within this series, the stress state was measured and recorded so that the most critical fatigue weld construction detail under this load was defined.

On each of this bridge test specimen, one half of the bridge’s welds were treated with PIT. The prolonged life of these treated welds could be confirmed. Only in one case there was failure on the PIT-treated side, where later on an inner weld defect was detected. Further results can be found in P978 [2] and Breunig [17]. Improving fatigue details with the application of HFMI treatment allows for a more economical design and a longer lifetime of bridges.
4. Conclusions

Based on the OptiBri [1], investigations in section 3.1, the potential and utilization of high-strength structural steels in combination with HFMI-treatment could be demonstrated. The beam tests illustrate that the fatigue strength of the HFMI-treated detail “unloaded transverse stiffener” was significantly improved, and as a result of this type of post-weld treatment, it competes or exceeds the fatigue strength of the base material.

Secondly, in this paper, the results of NaBrüEis [2], particularly small scale tests of longitudinal fillet welds in trough bridges under transversal bending, are presented. Some of them have also been post-weld treated with the HFMI technology in order to achieve sustainable long living structures. The fatigue test results showed that the transversal bending load itself is not a critical load. The improvement by the HFMI application could be affirmed.

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