

Experimental evaluation of HFMI effectiveness for weld repairs

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Abstract

One of the methods to increase the fatigue life of welds is the HFMI (High Frequency Mechanical Impact) treatment, which involves creating compressive stress in the weld surface and improving the notch geometry around the weld toe. In this study, fatigue tests were conducted on specimens loaded by four-point bending. The benefits of the HFMI method were compared to specimens without post-welding treatment (as welded). The loading was applied at several levels with constant stress range amplitude and stress ratio (parameter R). The impact of the HFMI method was also investigated for steels of different strengths, ranging from S355 to S960. After completing the fatigue tests and the initiation of fatigue cracks, the welds were repaired and the HFMI treatment was applied again. These repaired specimens were loaded with the same parameters as in the case of the previous specimens. Finally, the benefits of the HFMI method for both new and repaired welds were compared and evaluated, depending on the specific loading conditions and material strength. The results show an increase in cycles to failure when using the HFMI method for both new and repaired welds. This has significant potential for future repair and reconstruction of bridge structures damaged by fatigue.

Keywords

Fatigue; HFMI treatment; Weld repair; Steel bridge; S-N curve.

1. Introduction

Welded steel structures subjected to cyclic variable loading are prone to fatigue damage. Fatigue damage represents the initiation and subsequent propagation of fatigue cracks through the structural material, typically in the weld zone and the heat-affected zone (HAZ). The primary causes are material and geometric imperfections introduced during welding, which act as stress concentrators and accelerate the initiation and growth of these cracks (Hobbacher, 2008). As the strength of a material increases, its ductility typically decreases. When using and welding high-strength steels (HSS), it is essential to select appropriate welding materials and procedures to prevent a significant reduction in ductility in the weld joint area, which would adversely affect the overall fatigue performance of the welded joint. To maintain suitable fatigue properties, it is crucial to choose an appropriate combination of welding parameters, heat input, preheating or annealing (Hobbacher & Baumgartner, 2024).

The methods collectively referred to post-welding treatments for improving fatigue properties include several options for weld toe modification depending on the selected technology. The basic technologies are commonly used

surface burr grinding (BG) (Pedersen et al., 2010) or TIG dressing (Huo, 2004). Other methods involve mechanical surface strengthening, collectively referred to High-Frequency Mechanical Impact (HFMI). The most frequently applied modifications are ultrasonic impact treatment (UIT) (Marquis & Barsoum, 2013; Gunther et al., 2005; Cheng, 2003), ultrasonic peening (UP) (Kudryavtsev et al., 2007), high-frequency impact treatment (HiFIT) (Marquis & Barsoum, 2013; Krasnowski, 2018; Telljohann & Dannemeyer, 2009) or pneumatic impact treatment (PIT) (Gerster et al., 2013).

HFMI treatment is based on mechanical surface hardening of the weld toe region, achieved through localized plastic deformation and the introduction of compressive residual stresses. The plastic deformation is induced by impacting the surface with a steel pin at a frequency of approximately 100 Hz. This process creates a smooth radius at the weld toe, improving the notch geometry. As a result of the deformation, compressive stresses are introduced into the surface layer of the weld, which help to reduce undesirable tensile stresses (e.g. residual stresses from welding or other thermal manufacturing processes), thereby enhancing the fatigue life of the treated welded joints. The steel pin is mounted in a tool holder, which is guided along the weld toe either manually or semi-automatically. The compressive stresses introduced by the HFMI treatment typically penetrate to a depth of 1–2 mm below the surface, depending on the selected material thickness. The distribution of the induced compressive stress is nonlinear and the effect diminishes with increasing distance from the surface (Marquis & Barsoum, 2013; Al-Karawi et al., 2021; Marquis & Barsoum, 2016; Krasnowski, 2018; Telljohann & Dannemeyer, 2009).

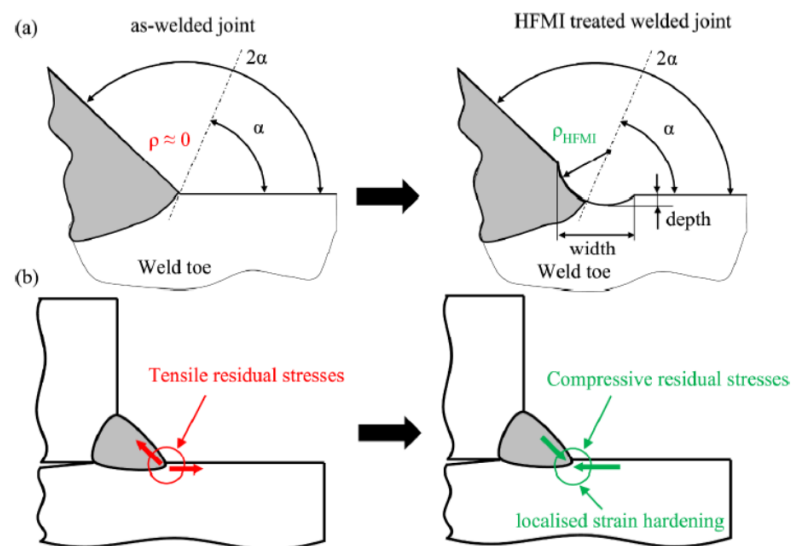


Figure 1: Principle of the HFMI treatment method (Campagnolo et al., 2021)

However, when applying the HFMI method, certain differences in fatigue behavior arise compared to conventional welded joints and assessments based on Eurocode. These differences are primarily due to the principle of mechanical surface hardening. The decisive factor is no longer solely the absolute stress range, but also the mean stress (i.e., the difference between maximum and minimum stress), expressed by the load ratio parameter R . As the R ratio increases, the effectiveness of the HFMI treatment (and consequently the fatigue life) decreases (Marquis & Barsoum, 2016; Leitner & Barsoum, 2020). This is because higher mean tensile stresses lead to a faster relaxation of the compressive stresses introduced into the surface layer, resulting in a more rapid loss of the HFMI effect. Material strength also plays a significant role. According to current experimental results, the fatigue life of welded joints treated with HFMI increases proportionally with the yield strength of the base material. This may be explained by the differing microstructures of high-strength steels, where a higher proportion of martensite and bainite is typically present structures, which may causes capable of absorbing greater compressive residual stresses induced by the HFMI treatment. The resulting improvement in fatigue life is generally reflected by an increased detail category, depending on the steel strength class and the level of mean stress (Yildirim et al., 2015; Marquis et al., 2025).

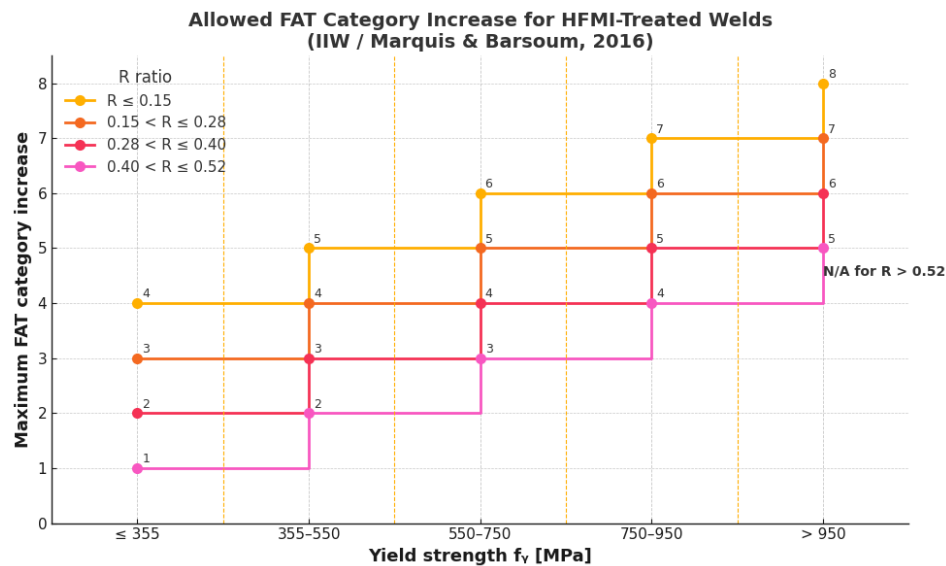


Figure 2: Allowed FAT category increase for HFMI treated Welds (Marquis & Barsoum, 2016)

This study therefore focused on various steel grades (ranging from S355 to S960) and different loading parameters. The subject of the investigation was the fabrication of welded structural details (V and X butt welds) representing realistic bridge components containing fatigue cracks. The objective of the study was to simulate the repair of such structures and to evaluate the potential benefits of the HFMI method under subsequent identical cyclic loading. This process represents a realistic simulation of the repair of a fatigue-damaged structure and explores the possible application of the HFMI method for these scenarios.

2. Experimental programme

2.1. Materials and test specimens

In this study, basic specimens with V and X full penetration butt welds were designed to represent typical transverse weld details found, for example in bridge structures. Test specimens with dimensions of 300x80x20 mm were manufactured and subjected to four-point bending in the laboratory. Four steel grades were selected: S355J2+N, S460NL, S690QL and S960QL. This selection made it possible to obtain results across different strength classes and to compare them with the recommendations provided by the IIW.

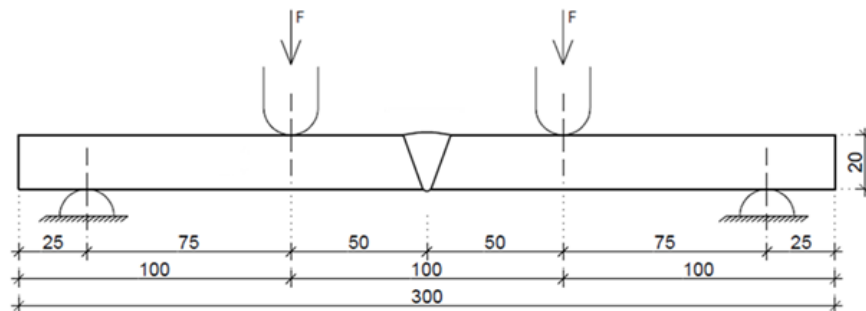


Figure 3: Geometry of the specimen with butt V-weld (identical for the specimen with X-weld)

A total of 52 test specimens were manufactured for fatigue testing (26x butt V-weld and 26x butt X-weld). The following table shows their distribution by weld treatment.

Table 1: Number of specimens for fatigue testing

Weld type	V and X		
Stress ratio R	0.1		
Treatment	As Welded	HFMI	HFMI repair
S355J2+N	4	4	4
S460NL	6	5	4
S690QL	5	4	4
S960QL	4	4	4

2.2. Manufacturing of specimens and technical parameters

The manufacturing of the specimens was made in the university's welding workshop. First, individual Welding Procedure Specifications (WPS) were developed to ensure uniformity and repeatability of the welding process. The specimens were then welded under identical conditions. The following table lists the specific technical parameters used during the welding of the specimens.

Table 2: Technical manufacturing parameters

S355 specimens: Technical manufacturing parameters	
Welding method	135 (MAG) according to EN ISO 4063
Filler material	EN ISO 14341-A: G46 3 C1 4Si1/G50 5 M21 4Si1
Shielding gas	M21 (82% Ar + 18% CO ₂) – STARGON 18
Preheat temperature	-
S460 specimens: Technical manufacturing parameters	
Welding method	135 (MAG) according to EN ISO 4063
Filler material	EN ISO 14341-A: G46 3 C1 4Si1/G50 5 M21 4Si1
Shielding gas	M21 (82% Ar + 18% CO ₂) – STARGON 18
Preheat temperature	-
S690 specimens: Technical manufacturing parameters	
Welding method	135 (MAG) according to EN ISO 4063
Filler material	EN ISO 16834-A: G 69 4 M21 Mn3Ni1CrMo
Shielding gas	M21 (82% Ar + 18% CO ₂) – STARGON 18
Preheat temperature	100 °C
S960 specimens: Technical manufacturing parameters	
Welding method	135 (MAG) according to EN ISO 4063
Filler material	EN ISO 16834-A: G 89 4 M20 Mn4Ni2CrMo
Shielding gas	M21 (82% Ar + 18% CO ₂) – STARGON 18
Preheat temperature	150 °C

After the manufacturing was completed, non-destructive testing (NDT) of the welds was made. First, a visual inspection (VT) was performed, followed by magnetic particle testing (MT) and ultrasonic testing (UT). The visual inspection was evaluated according to EN ISO 5817 (quality level B), which corresponds to the standard typically applied in bridge construction and is suitable for welded details subjected to fatigue loading.

The specimens were divided into two main groups after the completion of NDT inspections. The first group consisted of as-welded samples, which were left in their original welded condition without any further treatment. The second group comprised samples treated with the HFMI treatment. It was applicated manually with using the Hifit device at a frequency of approximately 100 Hz with a pin diameter of 3 mm. Subsequently, the samples were transported to the testing laboratory for the commencement of fatigue tests.

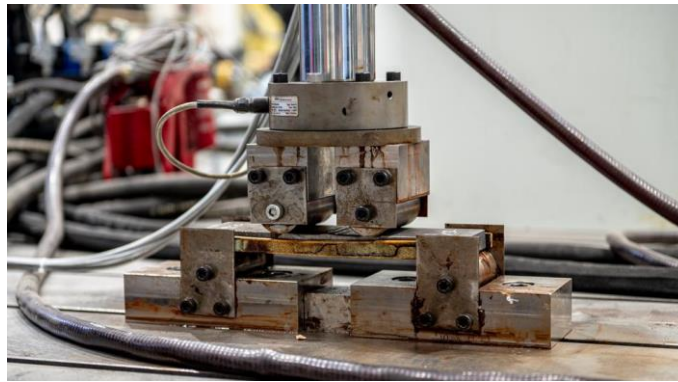


Figure 4: Testing equipment with specimen during the fatigue experiment

2.3. Experimental procedure

Fatigue testing of the as-welded samples was initiated first. The theoretical stress range was calculated according to Eurocode 3 (EN 1993-1-9), and a basic stress ratio of $R = 0.1$ was established. The samples were tested at several variable stress amplitude levels in order to determine the resulting S-N curves. The specimens were equipped with strain gauges to monitor and record the normal stress over time. The criterion for terminating the fatigue test was reaching the limit number of cycles without failure (runout) or the initiation of a fatigue crack, which was typically indicated by a drop in the strain gauge readings and subsequently confirmed by NDT penetrant testing (PT). The criterion for reaching the limit number of cycles without failure (runout) was set at 5 million cycles (in some first cases 10 million cycles). After finishing the fatigue tests of the as-welded specimens, the specimens treated with the HFMI method were tested. They were loaded with the same stress range parameters and stress ratio as the as-welded samples. In cases where no failure occurred during the fatigue test (runout), the normal stress values were increased according to calculations to obtain conclusive fatigue results.



Figure 5: Localization of the fatigue crack using NDT penetrant testing (PT) after completion of loading

Finally, selected as-welded samples containing fatigue cracks were subjected to a repair procedure. This involved grinding out the entire area of the fatigue crack, followed by re-welding using the same parameters as during the original sample fabrication. This process simulates a realistic repair procedure applicable to actual welded structures. After the repair welding, the HFMI treatment was applied to all repaired specimens using the same parameters as those used for HFMI treatment on new welded joints.



Figure 6: Repair of a specimen affected by a fatigue crack

3. Results

The results of the fatigue tests are categorized according to the steel grades. Recommended S-N curves are evaluated for the as-welded samples, along with the potential theoretical upgrade of the detail category when applying HFMI, in accordance with IIW Recommendations (Marquis & Barsoum, 2016).

The evaluation begins with S355 specimens tested under a stress ratio of $R = 0.1$. Based on the obtained results, the samples treated with HFMI clearly demonstrate an improvement in fatigue life by four detail categories (or more), in accordance with the IIW Recommendations (Marquis & Barsoum, 2016). Even the specimens without any post-weld treatment (as welded) exhibit higher fatigue life than predicted, which can be attributed to the conservative nature of the EN 1993-1-9 standard. Particularly promising are the results of the repaired welds treated with HFMI, which show fatigue performance comparable to newly welded joints with HFMI treatment. This finding indicates significant potential for the future application of HFMI technology to repair welded structures made usually of S355 grade steels (e.g. bridges).

The following table presents the results of the number of cycles to failure, along with their graphical representation using the corresponding S-N curves. For the evaluation of the results, standard S-N curves according to the currently valid EN 1993-1-9 (for as-welded specimens) and the IIW Recommendations (for HFMI specimens) are used (Marquis & Barsoum, 2016).

Table 3: Number of cycles to failure for S355 steel grade specimens

Material	S355		
Stress ratio R	0.1		
Spec. number	Treatment	Stress range [MPa]	Number of cycles to failure
1	As Welded	100	10 000 000*
2	As Welded	100	10 000 000*
3	As Welded	200	1 531 011
4	As Welded	200	1 486 900
5	HFMI	200	10 000 000*
6	HFMI	200	5 000 000*
7	HFMI	250	5 000 000*
8	HFMI	300	1 900 389
9	HFMI repair	300	2 728 703
10	HFMI repair	300	1 741 976
11	HFMI repair	320	474 210
12	HFMI repair	320	974 818
* No failure occurred in the specimen. The limit number of cycles was reached without the formation of a fatigue crack (runout).			

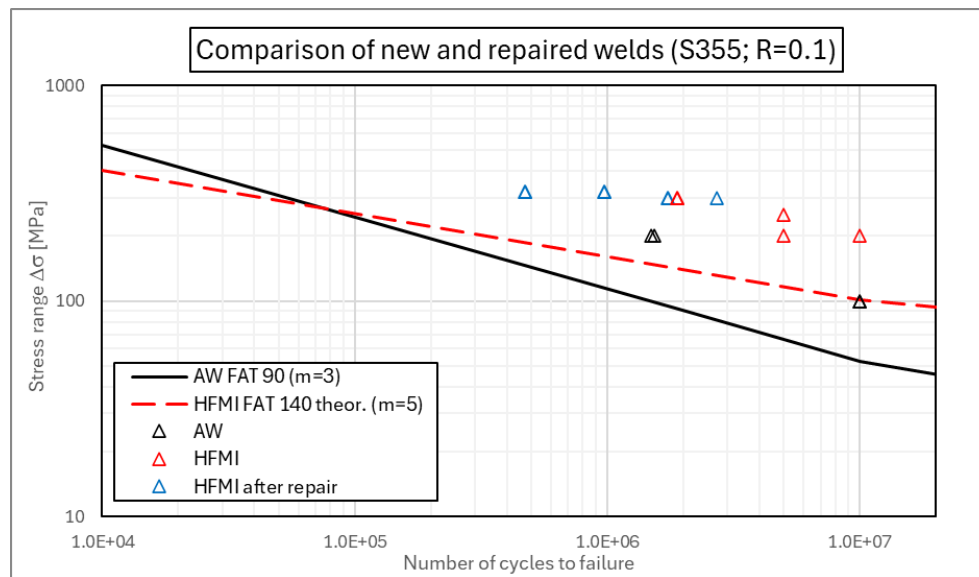


Figure 7: Comparison of results S355 steel grade specimens

Subsequently, the evaluation was made for S460 specimens tested under a stress ratio of $R = 0.1$. According to the obtained results, the HFMI-treated specimens again clearly demonstrate an increase in fatigue life by five detail categories (or more), which is in line with the IIW Recommendations (Marquis & Barsoum, 2016). Once again, the as-welded specimens also show improved fatigue life, which can be attributed to the conservative nature of the EN 1993-1-9 standard and the high quality of the welding process combined with thorough NDT inspections. The results of the repaired welds treated with HFMI once again show significant potential, achieving fatigue performance comparable to newly welded joints with HFMI treatment.

Table 4: Number of cycles to failure for S460 steel grade specimens

Material	S460		
Stress ratio R	0.1		
Spec. number	Treatment	Stress range [MPa]	Number of cycles to failure
13	As Welded	200	474 157
14	As Welded	200	3 018 047
15	As Welded	300	210 929
16	As Welded	300	331 088
17	As Welded	350	129 096
18	As Welded	350	309 218
19	HFMI	200	4 393 464
20	HFMI	200	5 000 000*
21	HFMI	300	984 402
22	HFMI	350	847 345
23	HFMI	350	947 066
24	HFMI repair	300	589 985
25	HFMI repair	300	1 175 960
26	HFMI repair	350	254 244
27	HFMI repair	350	688 634

* No failure occurred in the specimen. The limit number of cycles was reached without the formation of a fatigue crack (runout).

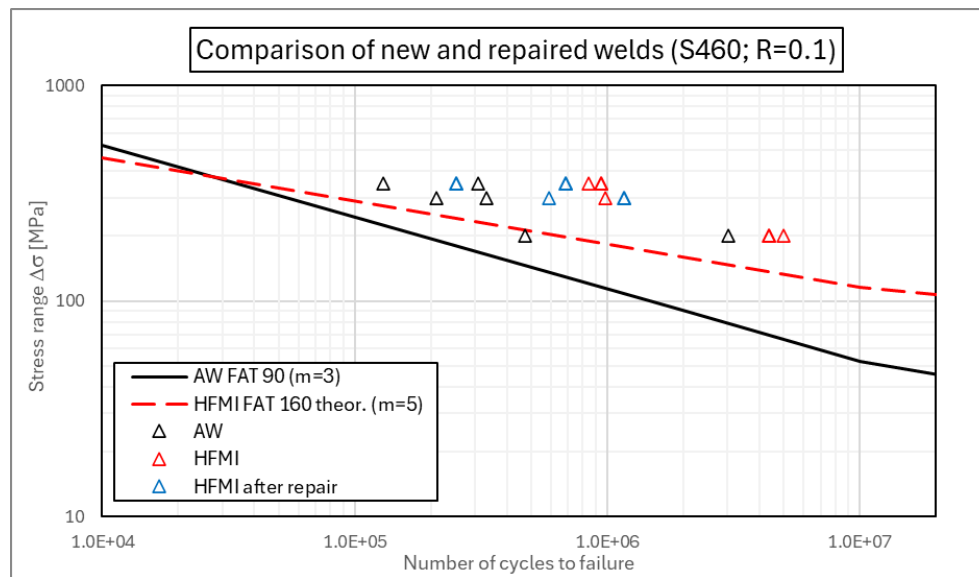


Figure 8: Comparison of results S460 steel grade specimens

Furthermore, an evaluation was performed for S690 specimens tested under a stress ratio of $R = 0.1$. According to the obtained results, the HFMI-treated specimens once again clearly exhibit an increase in fatigue life by six detail categories (or more), which is consistent with the IIW Recommendations (Marquis & Barsoum, 2016). The as-welded specimens also demonstrate improved fatigue life. As in the previous cases, the repaired welds treated with HFMI achieved fatigue performance comparable to newly welded joints with HFMI treatment.

Table 5: Number of cycles to failure for S690 steel grade specimens

Material	S690		
Stress ratio R	0.1		
Spec. number	Treatment	Stress range [MPa]	Number of cycles to failure
28	As Welded	200	2 674 867
29	As Welded	300	501 424
30	As Welded	300	372 388
31	As Welded	500	55 796
32	As Welded	500	79 230
33	HFMI	300	5 000 000*
34	HFMI	350	5 000 000*
35	HFMI	500	167 150
36	HFMI	500	289 026
37	HFMI repair	400	426 198
38	HFMI repair	400	116 523
39	HFMI repair	450	309 494
40	HFMI repair	450	160 857
* No failure occurred in the specimen. The limit number of cycles was reached without the formation of a fatigue crack (runout).			

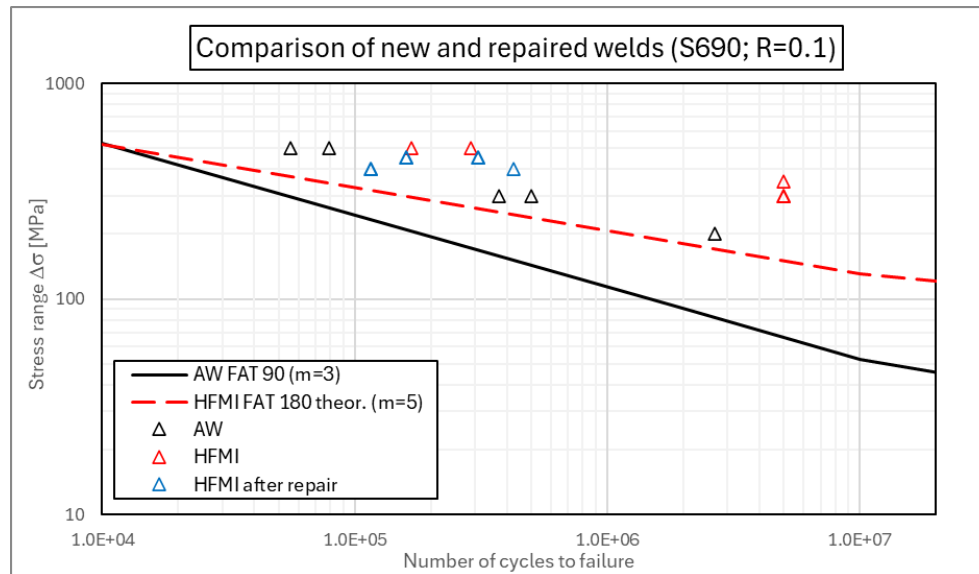


Figure 9: Comparison of results S690 steel grade specimens

Finally, the evaluation was carried out for S960 steel specimens. According to the obtained results, the HFMI treatment generally extended the fatigue life of the welded joints; however, the S-N curves are very similar to those of the as-welded specimens. This can be attributed to the specific fatigue behavior of high-strength steels (HSS) and the influence of welding on this type of material. Another contributing factor may be the testing under high stress levels, which led to early failure of the specimens. In this case, a more detailed evaluation would require conducting additional series of long-duration fatigue tests with lower stress ranges, better representing long-term fatigue behavior.

Table 6: Number of cycles to failure for S960 steel grade specimens

Material	S960		
Stress ratio R	0.1		
Spec. number	Treatment	Stress range [MPa]	Number of cycles to failure
41	As Welded	300	492 569
42	As Welded	500	55 205
43	As Welded	500	60 774
44	As Welded	800	16 832
45	HFMI	300	5 000 000*
46	HFMI	500	70 656
47	HFMI	500	293 794
48	HFMI	800	15 584
49	HFMI repair	450	110 727
50	HFMI repair	450	172 590
51	HFMI repair	500	32 423
52	HFMI repair	500	110 359
* No failure occurred in the specimen. The limit number of cycles was reached without the formation of a fatigue crack (runout).			

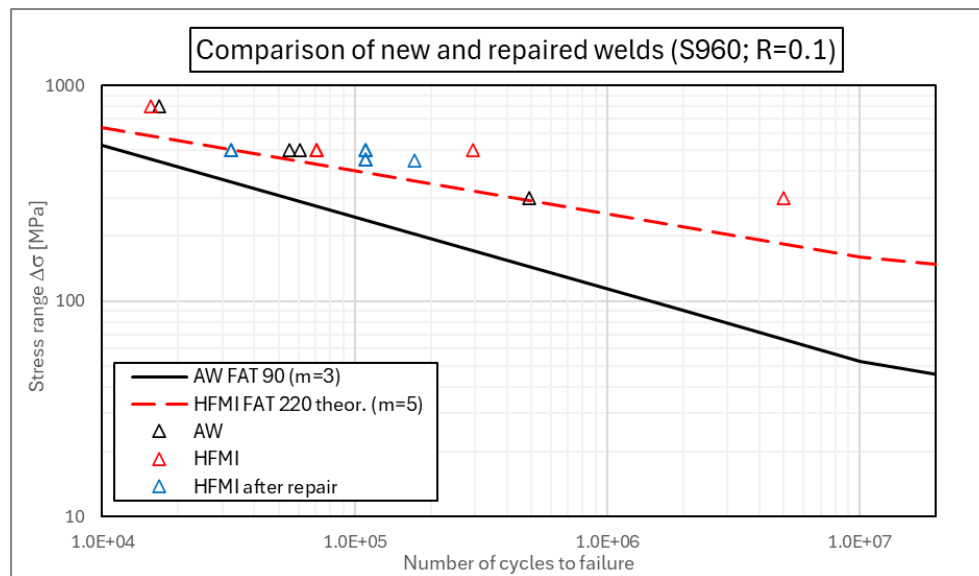


Figure 10: Comparison of results S960 steel grade specimens

4. Conclusion

This study comprehensively evaluated the effectiveness of the High Frequency Mechanical Impact (HFMI) treatment in improving the fatigue life of welded steel joints across a range of steel grades, from standard structural steel (S355) to high-strength steels (S960). The experimental results demonstrate an increase in fatigue strength with increasing yield strength of the base material, which is consistent with the findings reported in studies (Leitner & Barsoum, 2020; Yildirim & Marquis, 2012; Pijpers et al., 2009).

Through a series of controlled four-point bending fatigue tests, the performance of HFMI-treated specimens was compared to untreated (as welded) specimens and subsequently to repaired welds subjected again to HFMI treatment. The four-point bending test results confirmed the assumptions in accordance with the IIW recommendations (Marquis & Barsoum, 2016), despite the fact that the majority of experiments reported in the literature have been evaluated under axial loading. Nevertheless, a comparison of results indicates good agreement between axial and bending loading in many cases, as demonstrated, for instance, by study (Shams-Hakimi et al., 2017).

The experimental results consistently demonstrated a significant increase in fatigue life for specimens treated with HFMI. For S355 steel an improvement of at least four detail categories was observed, for S460 five categories and for S690 up to six categories, all in alignment with the IIW Recommendations (Marquis & Barsoum, 2016). The increase in fatigue life across different steel strength grades is likewise reported by studies focusing on yield strength and the effect of HFMI (Leitner & Barsoum, 2020; Yildirim & Marquis, 2012; Pijpers et al., 2009). Even the as welded specimens showed longer fatigue life than the default classifications provided in EN 1993-1-9, which can be attributed to the standard's conservative assumptions and the high-quality execution of welding and NDT procedures in this study.

Repaired specimens – those in which fatigue cracks were removed and the welds re-executed using identical parameters, followed by HFMI treatment – proved particularly promising. Their fatigue performance closely matched that of new HFMI treated welds. This finding suggests a high potential for the application of HFMI not only as a preventive post-weld treatment but also as an effective method for the rehabilitation of fatigue-damaged steel structures. This could prove especially beneficial in the maintenance and life extension of steel bridges made of standard structural steels such as S355. This observation, as well as the appropriateness of HFMI application, is also discussed in other studies (Ummerhofer et al., 2013; Yildirim, 2016).

In the case of ultra-high-strength steel S960, the HFMI treatment did result in a moderate increase in fatigue life, however the S-N curves of the treated and untreated specimens were very similar. This may be explained by the distinct fatigue behavior of HSS, where the welding process and the associated thermal effects can reduce the benefit gained from mechanical surface treatments like HFMI. Additionally, the testing at high stress levels may have caused early failure, masking the potential benefits of the treatment. For a more complete evaluation of HFMI effect on S960, further testing under lower stress amplitudes and longer fatigue durations is recommended.

In summary, the HFMI method has been shown to significantly enhance fatigue resistance in welded steel joints, particularly in steels up to S690. Its effectiveness for both new and repaired welds makes it a strong candidate for broader application in fatigue-critical steel structures. Future research can focus on optimizing its use for ultra-high-strength steels and on integrating HFMI more broadly into fatigue design and maintenance strategies for critical infrastructure.

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