LifeExt 2 Implementation – Prolonged life for steel bridges

LifeExt 2 Implementation – Livslängdsförlängning av stålbroar

Open report / Publik rapport

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Content

1 Summary

Many bridges in the world have reached, or exceeded, their design fatigue life. It is a challenge for society to wisely manage this huge asset of old bridges. Replacing bridges only because their theoretical life span has been reached is not a sustainable solution, neither from societal nor economical point of view. Therefore, methods for accurate damage assessment and repair, techniques for extending the service life of existing bridges, should be top priority in all countries. The projects LifeExt-1 [1] and LifeExt-2, the latter reported here, was created to address these issues - to enable substantial life extension for existing bridges by applying weld improvement techniques on the most critical positions of a bridge. These areas receive faster damage accumulation due to their high stress concentration and by improving these areas, the whole bridge life can be prolonged. Based on the hypothesis that fatigue damage in a fatigue loaded structure that has been in service for a certain time is accumulated mainly in these very local areas and therefore can be successfully treated locally, the projects LifeExt-1 and -2 had the following objectives and outcome for life extension studies:

- The possibility to remelt (remove) a fatigue crack was studied, and cracks of up to 2mm depth can be removed by a TIG-remelting directed more into the base material, i.e. along the crack depth direction instead of the classic TIG-treatment directed more towards the weld toe and lower part of the weld reinforcement. (LE1)
- Suitable NDT methods for identification and quantification of fatigue damage have been evaluated, and UT-TOFD was adapted to be used with a manipulator in situ in fatigue testing in LifeExt-1 and in the field (on a bridge) with a new manipulator in LifeExt-2. Small defects can be detected with UT-TOFD, a typical size of a detectable indication is 1-2 mm, and the vertical depth accuracy is around ±0.5 mm, depending on conditions. In the LifeExt projects, cracks below 1mm depth could also be identified and the size accuracy reached ±0.1 mm.
- The possibility for HFMI-techniques to restore the fatigue life of a fatigue damaged welded detail has been investigated for different levels of “pre-fatigue” before HFMI-treatment. Both in terms of % of calculated fatigue life as a selected pre-fatigue level, and with aid of the adapted UT-TOFD, a certain fatigue crack depth could be targeted in the pre-fatigue before HFMI treatment and a continued fatigue testing. It was shown that HFMI can restore fatigue life even if there is a fatigue crack of 1-1.5mm depth present. This is however not allowed (a surface crack should always be repaired first) but if such a crack is missed in NDT evaluations prior to HFMI-treatment, the HFMI will still give the wished life enhancement. (LE1 & LE2)
  In LifeExt-2, further investigations have shown that HFMI should be applied on an existing structure preferably before 50% of its calculated fatigue life is reached. Not least since a significantly larger amount of NDT evaluations will be required otherwise to quantify the status of the bridge before treatment.
- A (fatigue) damage model was developed that incorporates repair techniques. (LE1)
- A method was developed for judgement of suitability for LifeExt treatments, and selection of suitable techniques. (LE1)
- Different modelling methods have been developed to simulate the post weld treatments and predict the fatigue life. (LE1 & LE2)
- An important part in LifeExt-2 was to study how quality assurance (QA) for these life-prolonging techniques should be performed, and to apply the techniques on a bridge, evaluate and document methodology and results. The bridge in Stöde was selected by TRV for these investigations and the work and results are described in this report. A document on the important factors for QA of life-prolonging methods HFMI and TIG has been compiled in Swedish for TRV, to be utilised in future procurements and TRV regulations. (LE2)
- A HFMI process education of operators had been identified as urgently needed to be developed and was enabled by an expansion of the LifeExt-2 project. Here, a pilot course for HFMI operators was developed and test-run with 5 participants at Fredrika Bremer Industrigymnasium in Haninge in south Stockholm. The course evaluation showed that the theoretical part could be reduced for the education of operators, but it is a suitable course

as-is to “train the trainers” (i.e. the welding teachers) and a future possibility to continue to spread these HFMI-courses for operators should be identified.
- Also included in the expansion of the LifeExt-2 project was the development of (lacking) important HFMI data to the revision of Eurocode3. Here, 3m long HEA beams supplied with a reinforcing cover plate welded to the lower flange, was HFMI-treated and fatigue tested. The results were as expected and in line with theory in the guideline for HFMI. (LE2)
- The regulations in TRV should be updated to incorporate the possibility to utilize HFMI (TIG is mainly present). This work has started during LifeExt-2 and is on-going -also the revision of Eurocode3 and the HFMI-Guideline where data for many HFMI-treated welded details will be included (with data contributions from LifeExt -1 and -2).
- There are more challenging tasks that will be encountered when the LifeExt techniques are applied to other bridges during a coming scale-up of the LifeExt techniques. – A “LifeExt3 scale-up” project that acts similar to LifeExt2 (docking on to and supporting bridge renovation projects with research and examinations) could better enable and increase the speed of this scale-up. It could also incorporate activities to continue to enable education of HFMI operators, QA-staff and designers.

2 Sammanfattning på svenska

Många broar i världen har nått eller överskridit sin beräknade livslängd. Det är en utmaning för samhället att förvalta denna mängd av gamla broar. Att byta ut broar för att den teoretiska livslängden är uppnådd är ingen hållbar lösning, varken ur samhällelig eller ekonomisk synvinkel. Därför är metoder för korrekt bedömning och tekniker för att förlänga livslängden för befintliga broar högsta prioritet i alla industriländer. Projekten LifeExt-1 [1] och LifeExt-2, det sist nämnda rapporterat här, skapades för att ta itu med dessa problem - att möjliggöra att en betydande livslängdsökning kan nås för befintliga broar genom att applicera efterbehandlingsmetoder för svetsförband på de mest kritiska positionerna på en bro. Dessa områden får en snabbare skadeackumulering eftersom de har stora spänningskoncentrationer och genom att förbättra svetsförbanden i dessa områden med nya tekniker kan hela brons utmattningslivslängd förlängas. Baserat på hypotesen att utmattningsskador i en utmattningsbelastad struktur som har varit i drift under en viss tid ackumuleras mycket lokalt i dessa kritiska områden och därför framgångsrikt även kan behandlas lokalt, hade projekten LifeExt-1 och -2 följande mål och resultat för sina livslängdsförlängningsutredningar:

- Möjligheten att återuppsmälta (ta bort) en utmattningsspricka studerades, och sprickor på upp till 2 mm djup kan avlägsnas genom en TIG-uppsmältning riktad nedåt i materialet, dvs längs sprickdjupsriktningen istället för den klassiska TIG-behandlingsriktningen som kan riktas mer mot svetsens fattningskant och svetsrågens nedre del. (LE1)
- Lämpliga OFP-metoder för identifiering och kvantifiering av utmattningsskador har utvärderats och UT-TOFD har anpassats för att användas med en manipulator in situ vid utmattningsprovning i LifeExt-1 och i fält (på en bro) i LifeExt-2 med en nyutvecklad manipulator. Små defekter kan upptäckas med UT-TOFD, en typisk storlek på en detekterbar indikation är 1-2 mm, och den vertikala noggrannheten är runt ±0,5 mm, beroende på förhållanden. I LifeExt-projekten kunde även sprickor under 1 mm djup identifieras och storleksnoggrannheten för sprickorna nådde ±0,1 mm.
- Möjligheten för HFMI-tekniker att återställa utmattningslivslängden för en utmattningsskadad svetsad detalj har undersökts för olika nivåer av "förutmattning". Både vad gäller % av beräknad utmattningslivslängd som vald förutmattningsnivå, samt med hjälp av den anpassade UT-TOFD som mäter sprickstorlek. Med UT-TOFD kunde ett önskat utmattningssprickdjup mätas och provas in i förutmattningen inför HFMI-behandling och efterföljande fortsatt utmattningsprovning. Det visades att HFMI kan återställa utmattningslivslängden även om det finns en utmattningsspricka på 1-1,5 mm djup. Detta är förvisso inte tillåtet (en ytspricka ska alltid repareras) men om en sådan spricka missas i OFP-

utvärdering före HFMI-behandling kommer HFMI fortfarande kunna ge önskad livslängd. (LE1 & LE2)

- I LifeExt-2 har ytterligare undersökningar visat att HFMI bör appliceras på en befintlig struktur helst innan 50 % nåtts av dess beräknade utmattningslivslängd. Inte minst eftersom det annars kommer att krävas en betydligt större mängd OFP för att fastställa brons skick före LifeExt-behandling.
- En (utmattnings)skademodell utvecklades som innehåller reparationstekniker. (LE1)
- En metod utvecklades för bedömning av lämplighet för LifeExt-behandlingar och val av lämpliga tekniker. (LE1)
- Olika modelleringsmetoder har utvecklats för att simulera behandlingar och prediktera utmattningslivslängd (LE1 & LE2)
- En viktig del i LifeExt-2 var att studera hur kvalitetssäkring (QA) av dessa livslängdsökande tekniker bäst ska utföras, samt att tillämpa teknikerna på en bro, utvärdera och dokumentera metodiker och resultat. Bron i Stöde valdes ut av TRV för dessa undersökningar och arbetet och resultaten beskrivs i denna rapport. Ett dokument om de viktiga faktorerna för QA av livsförlängande metoder HFMI och TIG har sammanställts på svenska för TRV. (LE2)
- HFMI utbildning av operatörer hade identifierats som brådskande behov och möjliggjordes av en utökning av LifeExt-2-projektet. Här utvecklades och testkördes en pilotkurs för HFMI-operatörer med 5 deltagare (2 var svetslärare) på Fredrika Bremer Industrigymnasium i Haninge i södra Stockholm. Kursutvärderingen visade att den teoretiska delen skulle kunna reduceras för utbildning av operatörer, men i sig är det en lämplig kurs för att ”utbilda utbildarna” dvs svetslärarna och en framtida möjlighet att fortsätta att kunna sprida denna HFMI-kurs för operatörer till fler svetsskolor behöver identifieras.
- I utbyggnaden av LifeExt-2-projektet ingick också framtagandet av (saknade) viktiga HFMI-data till kommande revision av Eurocode3. Här svetsades och HFMI-behandlades 3 m långa HEA-balkar försedda med en förstärkande täckplåt svetsad på den nedre flänsen - och utmattningstestades. Resultaten var som förväntat och i linje med riktlinjen för HFMI. (LE2)
- Regelverk i TRV ska uppdateras för att införliva möjligheten att använda HFMI (TIG finns med i huvudsak, omsmältningsmetodik ska förtydligas). Detta arbete har startat under LifeExt-2 och pågår, liksom revideringen av Eurocode3 och HFMI Guideline där data för många HFMI-behandlade svetsade detaljer inkluderas (med databidrag från LifeExt -1 och -2).
- Fler utmaningar kommer att mötas när LifeExt-teknikerna tillämpas på andra broar under den kommande uppskalningen. – Ett "LifeExt3-uppskalningsprojekt" som liknar LifeExt2 (ansluter till och stödjer ett eller flera brorenoveringsprojekt med forskning och undersökningar) skulle bättre kunna möjliggöra och öka hastigheten på denna uppskalning. Projektet skulle också kunna inkludera aktiviteter för att fortsätta att möjliggöra utbildning av HFMI-operatörer, QA-personal och konstruktörer.

3 Background

Many bridges in the world have reached, or exceeded, the calculated fatigue life for the structure. It is a challenge for society to manage a wise management and replacement of these old bridges. All cannot of economic reasons be replaced with the wished pace. Therefore, new methods for status judgements and life extension techniques are of high importance to develop and implement. The LifeExt-1 project studied the potential for steel bridges with life enhancement methods such as HFMI and TIG-treatment. The LifeExt-2 project reported here was created to be able to test-implement the methods and findings from LifeExt-1, i.e. to enable substantial life extension for existing bridges by applying weld and life improvement techniques locally on some selected (most critical) positions on a bridge. These areas receive faster damage accumulation due to their high stress concentration and by improving these areas, the whole bridge life will be prolonged. This topic, the background, and the treatment techniques are well described in the open report from LifeExt-1 [1] and only a short overview is given in this chapter of the report.

3.1 Life extension methods

HFMI- High Frequency Mechanical Impact

In 2016, the International Institute of Welding (IIW) published a guideline for HFMI treatment of welded structures [1] including proper treatment procedures, quality control and amount fatigue strength improvement that can be claimed for steel grades 235 – 960 MPa in yield strength. The gain in fatigue life from HFMI treatment is dependent on the yield strength of the material. A welded joint of a low strength steel (yield stress < 355 MPa) which is in as-welded condition classified as FAT 90 (fatigue stress range of 90 MPa at N= 2 x 106 cycles) can be classified after HFMI treatment as FAT 140. If the material would be a high strength steel, the FAT class could increase even more from FAT 90 in as-welded state to FAT 180 for HFMI treated. This shows the extreme efficiency of HFMI treatment as fatigue strength improvement technique for welded structures [2], given that the treatment is correctly executed and the technique robust. Due to this improvement, the structures can be built lighter resulting in material, resource and cost savings; or the lifetime can be significantly extended which increases the life cycle efficiency of the product. One typical application of post-weld treatment HFMI, a MAG fillet weld in as-welded condition and after HFMI treatment, is presented in Figure 1.

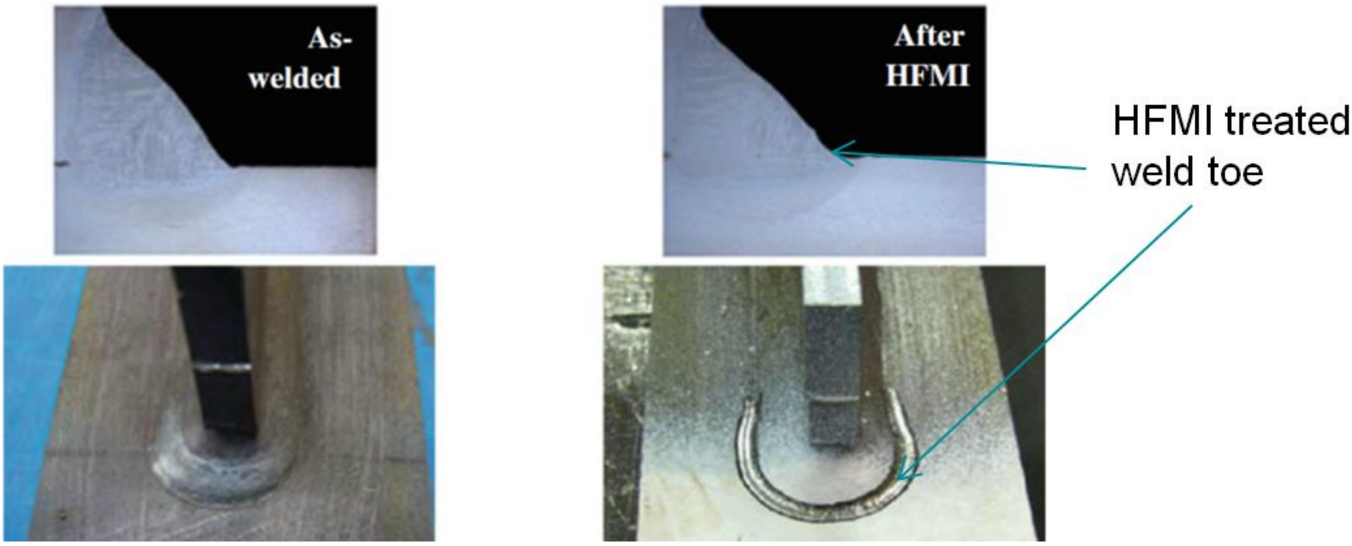


Figure 1. Typical application of post-weld treatment HFMI; Left: a MAG fillet weld in as-welded condition and Right: after HFMI treatment (from [2])

During a HFMI treatment, one (or several) cylindrical indenter is accelerated against and indented into the weld toe transition region with a frequency of typically around 90 Hz. The impact energy of the indenter, which is the indenter mass multiplied with its velocity, is causing a beneficial effect of weld toe geometry modification (enlarged transition radii) and a significant change in residual stress state. Typically, compressive stress fields are created in the surface region around the HFMI treatment, which enhances the endurance towards fatigue loading. Different power sources such as compressed air, ultrasonic piezoelectric elements etc. are used to accelerate the indenter. In 2016, the International Institute of Welding (IIW) published recommendations for HFMI suggesting that the weld prior to HFMI treatment must meet the acceptance limits of quality B in ISO 5817 (highest weld quality class) [2]. This requirement does not imply that the weld must fulfill all quality level B criteria in ISO 5817; only weld profile-related quality criteria need to be evaluated. These include undercuts, excessive overfill, excessive concavity and overlaps. If the weld profile does not meet the requirements of weld class B in this context, light grinding is suggested until class B can be met.

As mentioned above, different power sources are used to accelerate the indenter that is treating the weld toe. These indenters do have different mass, diameter, tip geometry and accelerators. The HFMI guideline is referring to a recent round robin exercise [2] which came to the conclusion that different HFMI equipment, when properly used, provide approximately the same fatigue life improvement when correctly applied. Recent published studies concluded that the compressive residual stresses induced by HFMI play a major role whereas geometry and microstructure are of lower importance [3] However, all these experiments were performed on welds with weld quality level B (high quality). A recent Vinnova project (pre-study ROMI) [6] studied the possibility to treat welds with lower weld quality and the results indicate that the sensitivity to a varying geometrical weld quality is not large, and therefore could also lower quality welds be possible to treat with HFMI with good results. With an increased HFMI tool radius, the mass of the tool increases leading to higher impact forces during the HFMI process creating greater indentation depths and increased compressive residual stresses, as indicated by Leitner et al. [7].
However, the benefit in fatigue life from compressive stresses in the HFMI treated area may be lost due to overloading and such structures may risk an earlier failure. Hence, the recommendations for HFMI [2] states that for structures with R > 0.5 or when σmax > 0.8 f_y may lead to situations where the residual compressive stresses from HFMI is not stable, which can result in a too early fatigue failure. The R-value is defined as σ_{max} divided by σ_{min}, where σ_{max} is the maximum stress and σ_{min} is minimum stress in the fatigue cycle. f_y is the yield strength of the treated material.

TIG-treatment

A classic TIG-treatment consists of a local remelting (re-welding) of the weld fusion line in the weld toe. This region often contains small discontinuities where fatigue cracks may find initiation points. By remelting this fusion line with a TIG-arc, the discontinuities are removed and an improved geometrical transition (larger weld toe radii) between weld and base metal is created. See Figure 2.

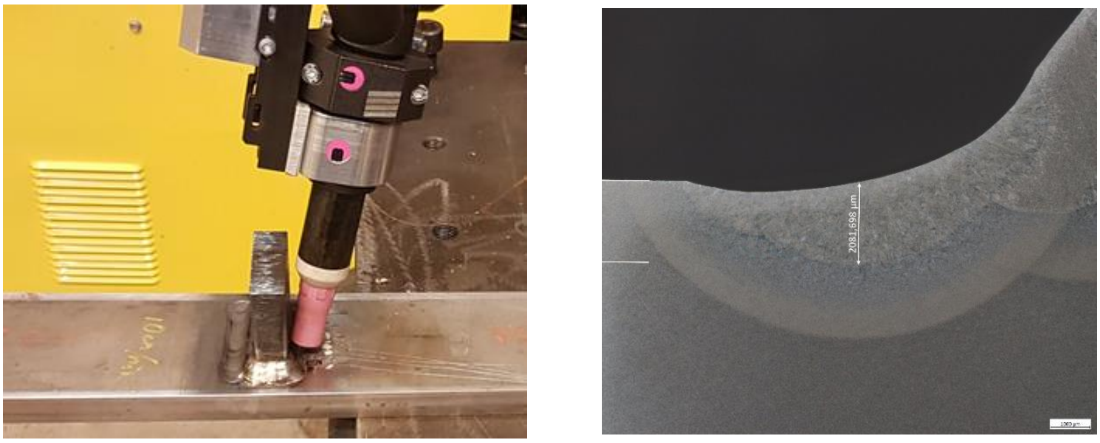


Figure 2. Left: TIG-torch direction for fatigue crack repair. Right: TIG-reweld transition region.

3.2 LifeExt-1 project

Here, a condensed description of the tests and main results in LifeExt-1 is given.

Study and verification of LifeExt methods in LifeExt-1

Three different test specimens were selected, resembling the “worst” positions in a load carrying beam in a bridge. These are (with corresponding numbers in Figure 3 below):
1- Rat-hole (also called cope-hole or notch) detail, usually present at beam splices used to join two bridge girders.
2- The welded detail between vertical stiffener and girder flange. This detail exists in all bridges and appears typically each 3-4 m in composite girder bridges.
3- The gusset plate connection to girder flange which is used in some old bridges to connect wind braces to main girders.

Post-weld treatment methods that can treat the material locally to enhance the fatigue strength in these regions were investigated. The methods with highest potential for local repair are TIG-dressing (or re-melting) and HFMI-treatment (High Frequency Mechanical Impact). Therefore, investigations in the project were made mainly with these two treatments.
In the fatigue testing, the specimens were initially pre-fatigued to different levels, then treated with intended LifeExt technique and run in continued fatigue until failure. With this methodology, investigations could be made on the possible life gain for different situations for each geometry.

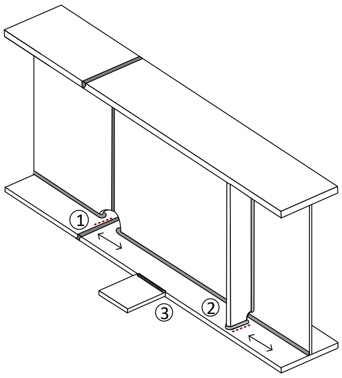


Figure 3. The selected critical parts determining the fatigue life for a bridge.

In the fatigue testing, the specimens were initially pre-fatigued to different levels, subsequently treated with intended LifeExt technique and thereafter run in continued fatigue until failure. With this methodology, investigations could be made on the possible life gain for each geometry and treatment.
All the cases evaluated in LifeExt-1, and found in literature, are shown in Figure 4 below.

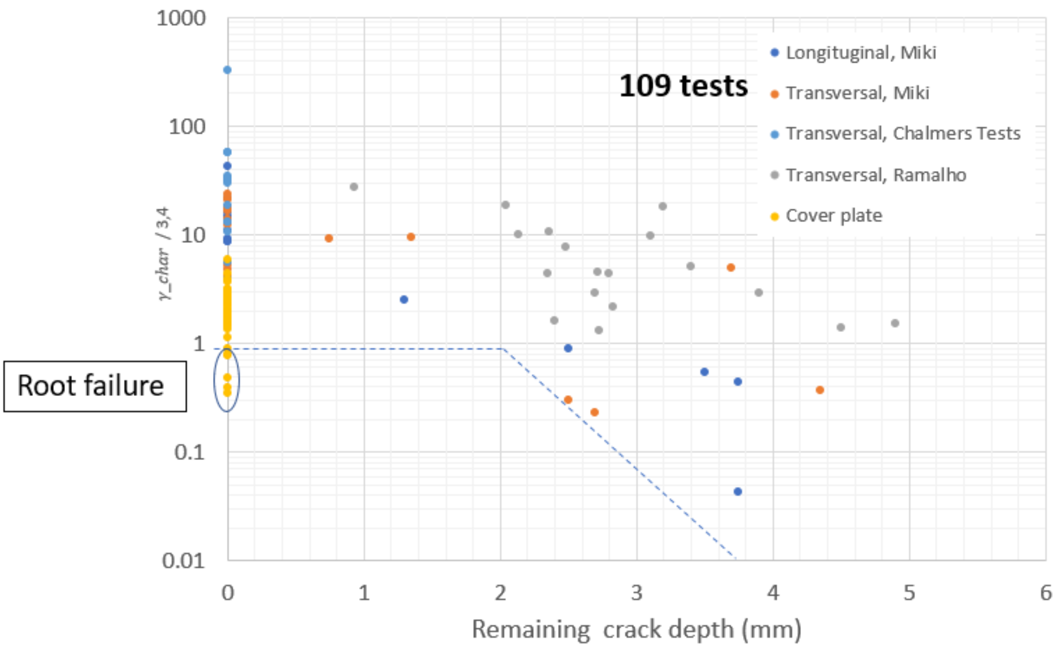


Figure 4. The fatigue life gain factor as function of (eventual) remaining crack after treatment.

Summary of the findings from the experimental program
Both HFMI- and TIG-treatments were successful not only in full restauration of the fatigue strength of fatigued welded details, but also in increasing the fatigue strength up to that of an equivalent new treated detail.

HFMI-treatment gives superior results when fatigued welded details contain no fatigue cracks or when existing fatigue cracks are shallower than 1.5 mm through plate thickness.
TIG-treatment can be used to restore the fatigue strength of welded details if the treatment can be performed with a penetration depth larger than the depth of any existing cracks. A combination of TIG, followed by HFMI gives superior fatigue life extension, equivalent to that obtained for new HFMI-treated details.
An interesting NDT method was identified (UT-TOFD) and adapted to the needs to find and follow a fatigue crack. This method was used to analyze and quantify the crack situation for different cases and improve reliability (reduce scatter) in testing and judgements.

3.3 Objectives for LifeExt-2

Not addressed in LifeExt-1 was how to quality assure the life-prolonging methods, this became an important task in the LifeExt-2-Implementation project together with developing important missing design data for HFMI to the coming Eurocode revision, and continued field investigations with the modified UT-TOFD and laser scanning of welds. Also added in LifeExt-2 was a course development for HFMI operators - there are more or less no HFMI operators available in Sweden today, a pool of operators needs to be developed (educated) before full implementation and utilization of HFMI can be made possible.

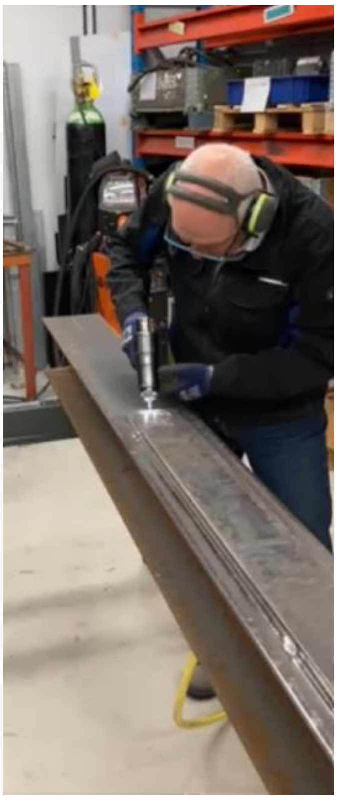
The objectives for LifeExt-2 were:

- To develop methods for quality assurance of life-enhancing methods; HFMI & TIG and to study these with new NDT and digitized scanning methods.
- To develop treatment strategies and procedures for treatment with HFMI & TIG on bridge.
- To incorporate statistical assessments to improve assessment techniques before treatment, and measurement and treatment techniques.
- To test-implement on a bridge, i.e. assess the status, plan, treat and quality-assure a bridge with the LifeExt methods.
- To test and further develop UT-TOFD (crack detection and characterization) on bridges.
- To produce data for and work on updating TRV's regulations (include the methods for life extension and quality assurance of these in the regulations).
- Develop Guidelines for quality assurance and training on the methods and spread knowledge.

4 Experimental work, modelling, and verification

4.1 Fatigue testing of HFMI-treatment of welded cover plate

3m long HEA-beams were supplied with a 1m long cover plate welded to the bottom flange of the beam, in the mid of the beam. 4 of these were fatigue tested in as-welded condition, and 8 of them were fatigue tested after HFMI-treatment (Figure 5) of the end sections of the cover plate weldment. These beams were welded at Swerim and HFMI-treated with the aid of HiFit, then fatigue tested at Chalmers. The fatigue test results were as expected and in line (4 FAT classes improvement) with the HFMI-Guideline. The results shown in Figure 5 (right) below, FAT 80 reached for this geometry, will be incorporated in the coming revision of Eurocode 3. There are multiple thickness combinations that remain to be tested for the cover plate though.



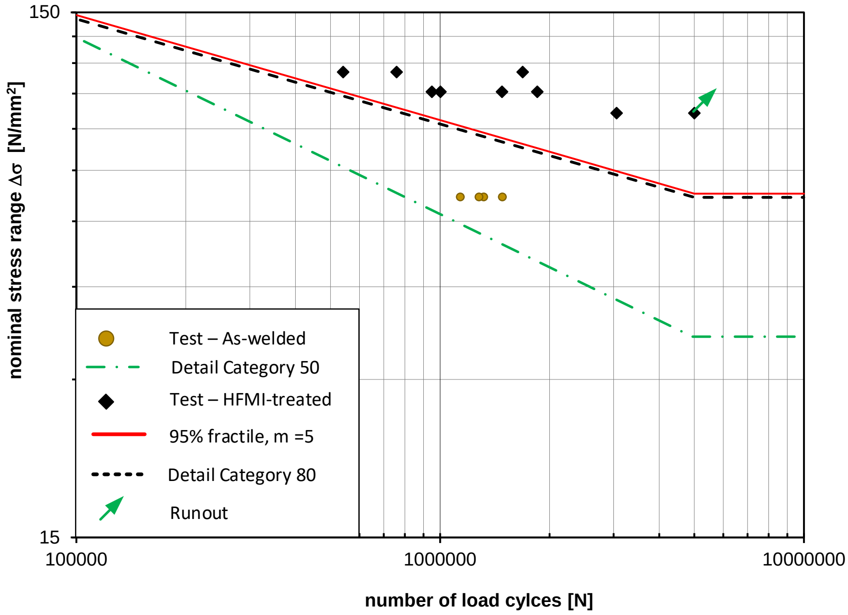


Figure 5. HFMI-treated end section of the cover plate weld for the HEA-beam (left), and the fatigue results (right).

4.2 Fatigue testing of HFMI-treated cope-hole details and longitudinal gusset plates

The welded rat-hole specimen, or cope-hole as it is also denominated, was developed and tested (Figure 6) with and without HFMI treatment in LifeExt-1 in cooperation between Swerim, Dekra, Chalmers and KTH, and further analysis has been made in LifeExt-2. It was shown that HFMI can rehabilitate fatigue cracks with depths below 1.5mm and receive the same result as if the fatigue crack was not present (new structure). These results are however slightly conservative for this type of geometry and new results will be presented at the coming IIW conference in Rhodes in July. See Figure 7 where some of the fatigue results are shown (welding + HFMI treatment, no pre-fatigue before HFMI, compared to results for specimens with 0.5mm fatigue crack present when HFMI-treated). The fatigue test results were in line (4-5 FAT classes improvement for S355 steel) with the HFMI-Guideline, -and also when a fatigue crack (with depth below 1.5mm) was present before the HFMI-treatment. This shows the robustness of an HFMI-treatment given that it is correctly applied.

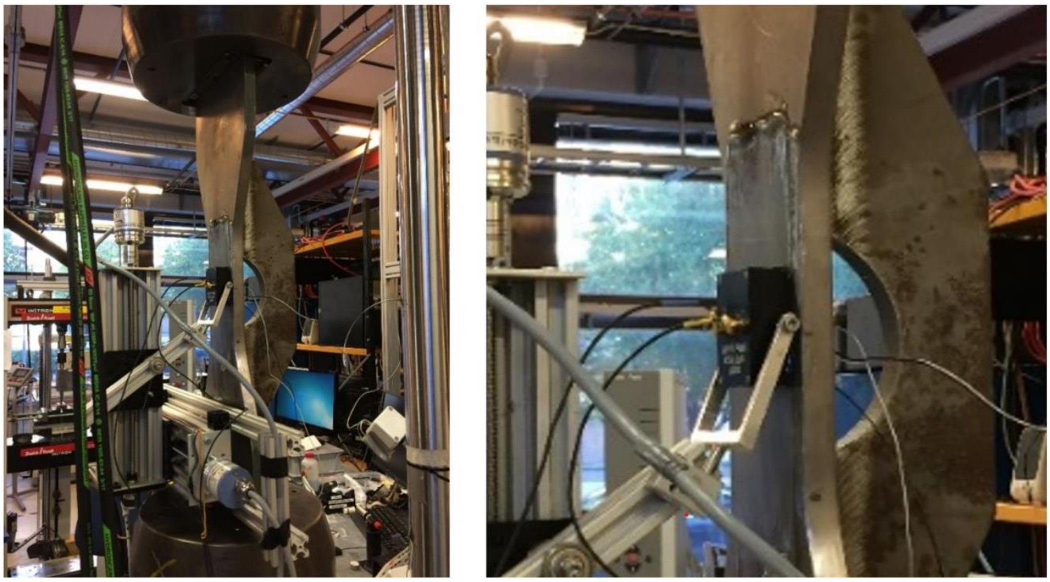


Figure 6. A rat-hole specimen with the TOFD equipment evaluating the fatigue crack development.

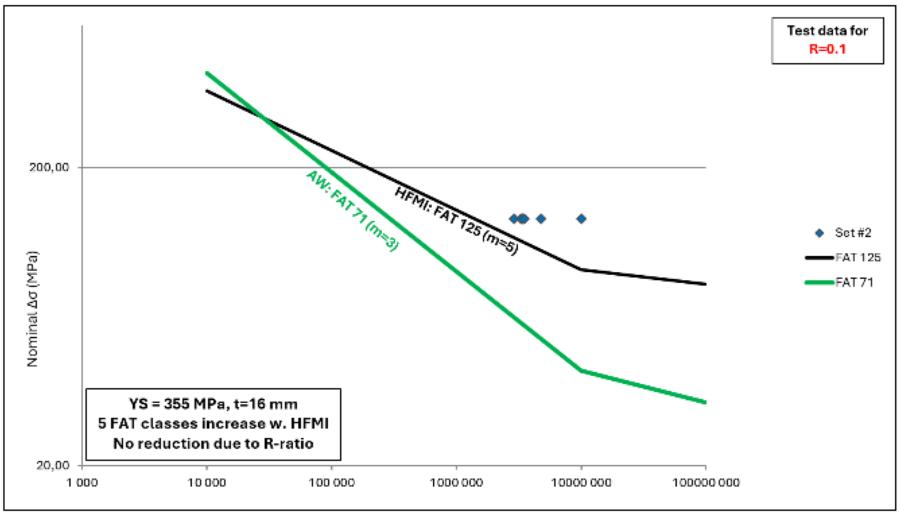


Figure 7. Fatigue results for welded + prefatigued to 0.5mm crack depth & HFMI treated, specimens with longitudinal gusset with cope hole (rat-hole). Different levels of pre-fatigue before HFMI have also been evaluated and will be presented at IIW in Rhodes in July 2024.

To facilitate the fatigue crack size and growth evaluations with and without HFMI in the lab more efficiently, a new manipulator was developed in conjunction with a stand-alone control system, both originates from the DIY industry. The off-the-shelf high resolution building blocks sped up the development and accessibility using the TOFD technique. The evaluation of HFMI as a PWT and rehabilitation method continued with an additional specimen type, the Longitudinal gusset plate (Figure 8). The detail number and detail category are No. 521 and 71MPa respectively, according to the recommendations for Fatigue Design of Welded Joints and Components. It should be noted that the detail category changes with the length of the longitudinal gusset plate. In this study the gusset plate was 120mm, yielding a detail category of 71MPa (FAT 71 for 50mm< l < 150mm).

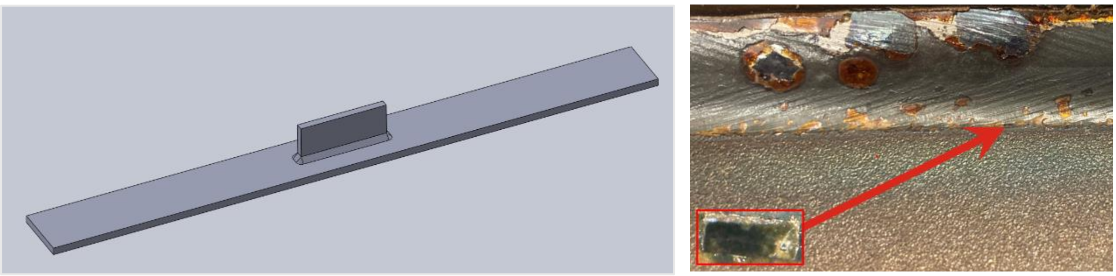


Figure 8. Left: Longitudinal gusset plate, and Right: enlargement of the notch placed in the weld toe region.

This fatigue testing was performed on welded specimens where one short end of the weldment was artificially notched (a glow discharged rectangular notch was made in the weld toe 0.2 x 0.8mm and 0.4mm deep, see right image in Figure 8), and the other side of the weldment was TIG post weld treated. This setup was chosen to force the crack initiation to one short-end of the weld of the gusset plate, at a predefined position. As observed in earlier LifeExt-studies, multiple crack starts can occur, even in a weld with a small footprint (see Figure 9).

Fracture mechanics was utilised to calculate the projected life, and the approach aligned well with the fatigue life from the test results.
In general, the results showed that the findings from the cope-hole specimens is true also for this specimen type. Also, it was concluded that the main difference for the longitudinal specimen type is that there is no redundancy, i.e. no other way for the force to be distributed through the specimen. This basically means that the strain range drop curve has a different shape. However, the method of strain range drop is still applicable to the specimen type and has been used as crack depth monitoring feedback to minimize the number of TOFD scans needed per specimen.
Some crack-growth studies with the longitudinal gusset plate specimen are ongoing and will be completed after the summer as part of PhD studies.

4.3 Verification of NDT method for fatigue crack detection

The Longitudinal gusset plate and cope-hole specimens were also used to verify the accuracy for TOFD as a crack depth characterization tool, via combined detection and destructive testing and evaluation. It was shown that the method is within 0.1mm for the estimation of the crack depths for the specimens. It was also noted that this accuracy is valid for identifying cracks emanating in fatigue. UT-TOFD has thereby been shown to be a powerful tool in aiding with estimation of crack depths and finding defects in welds. The technology has been further developed in the project and adapted with new probes and manipulators for field work, adaptations and preparations are further described below.

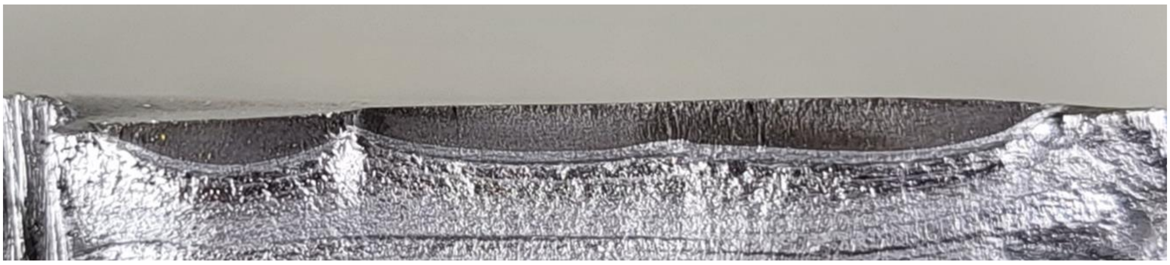


Figure 9. Cut out from cope-hole specimen for verification of TOFD accuracy. Multiple crack-starts (black areas) visible in the upper part of the image (the image is a cross-section from “the inside” of the cope-hole, where the fatigue cracks have initiated in the weld toe).

Within the framework of the LifeExt-2 program, the initial objective for TOFD was to conduct testing on pre-fatigued positions to verify suitability for HFMI treatment. During the course of the project, due to the conditions on the selected test bridge, the TOFD testing was directed to examining the condition of important flange joints (X-joints close to the bridge supports), see Figure 10 below.

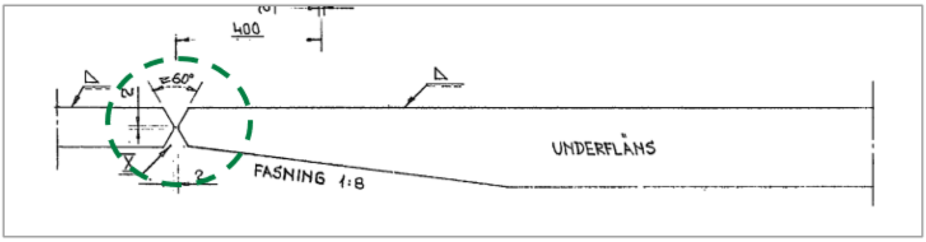


Figure 10. Example of examined X-joint with TOFD on the bridge (flange joints).

During the preparations for the field tests, it was found that the drawings were incorrect (welds not grinded flush to base material), which necessitated preparations to surface grind the weld flush to the material. However, to be able to perform TOFD scan the paint had to be removed in any case, so the delay and amount of extra work was limited.
The flanges of the bridge were between 44 and 50 mm. A calibration block for TOFD was therefore manufactured in advance with a thickness of 44 mm. The calibration block had notches that were 0.4 mm x 1.5 mm and were made with six different depths (0.8 mm, 1.0 mm, 1.5 mm, 2.0 mm, and 2.5 mm). The notches were manufactured very accurately using the EDM in Swerim.

A TOFD system for the flange configuration was developed. Similar to previous TOFD testing within LifeExt, a system with a focus closer to the opposing scan surface was chosen. A probe distance of 100 mm was selected, providing a focus approximately 37 mm into the material. The system was tested using the calibration block, and the notches of 1.0 mm depth and larger could clearly be identified, see Figure 11 below (leading to that a 1mm crack size can be detected and determined in size with a ±0.1mm resolution). The following characteristics were used for the setup: PCS 100mm, data acquisition 43Hz, range 18-25µs, pulser was set at 250V and 100ns pulse width, sound velocity 5920m/s and gain for backwall set to 30dB and for indication to 60dB.

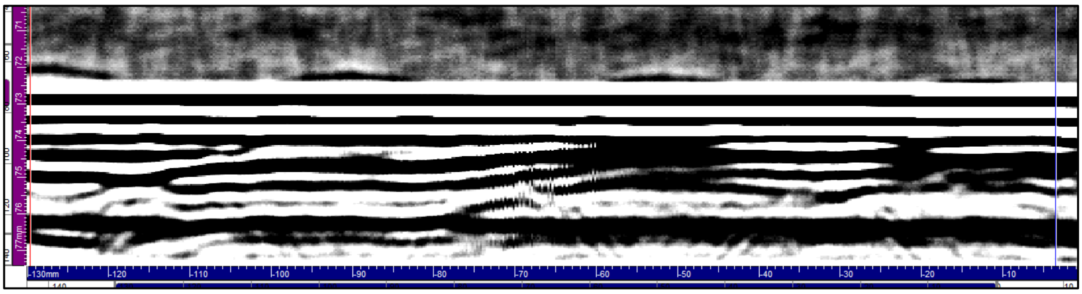


Figure 11. Crack sizing with TOFD, the notches in the calibration block: 0.81mm, 0.95mm, 1.08mm 1.31mm.

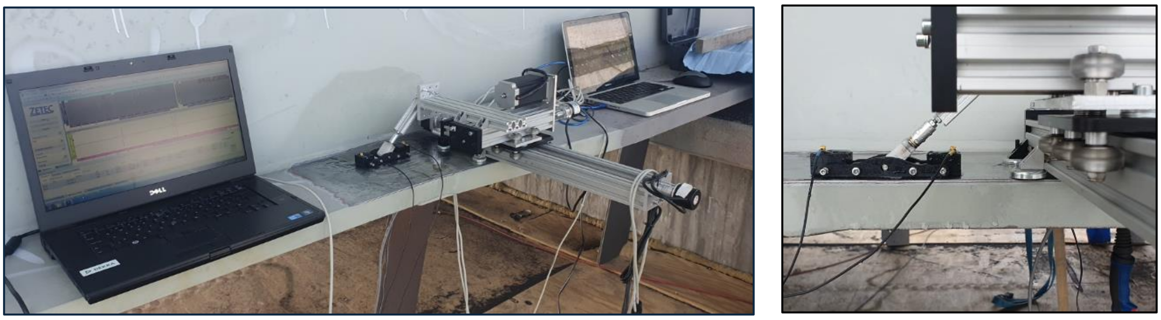
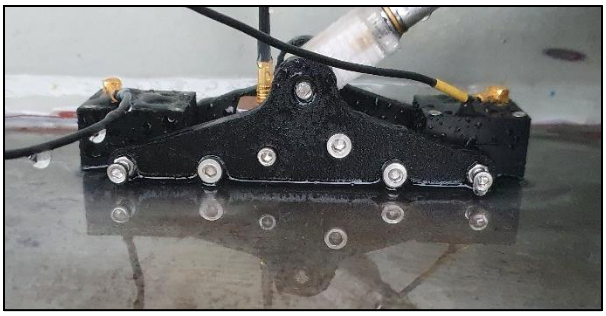


Figure 12. Field application of TOFD in LifeExt-2, with the new larger manipulator.

For the field application of TOFD within LifeExt-2, a new larger manipulator was developed (Figure 12). The manipulator was built to be able to scan the full width of the flange according to the drawing provided. However, the scan was of practical reasons (on-site limitations) divided into two separate scans performed which were performed from the top side of the flange.

A prototyping method for validating and developing probe holders has also been developed with additive manufacturing techniques (FDM, see Figure 13). This enables rapid prototyping and production of new probe holder variants with high precision in terms of PCS distance and the placement of additional probes. As an example of the prototyping speed, the final configuration was tested, verified, and manufactured within one day, and subsequently utilized for testing on the bridge in Stöde the following day.



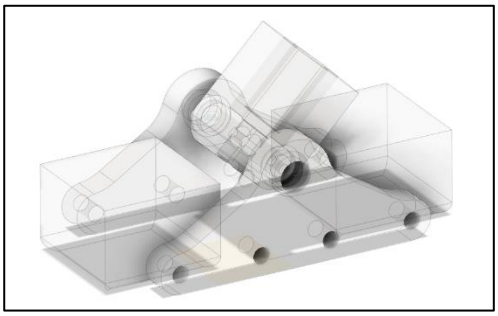


Figure 13. Probe holder developed using fast prototype method based on additive manufacturing. To the left - a zero-degree probe was added to the holder. To the right - the first 50mm PCS holder within the design envelop.

The results from verification tests showed that the detectability level is within the specification.

4.4 Modelling in LifeExt projects

In addition to the experimental research, numerical models have been created to model the post weld treatments and predict the new fatigue life. As TIG remelting enables crack removal in the fusion zone, the life prediction models could be crack-free. However, HFMI treatment does not remove eventual fatigue cracks which implies that these models could also include cracks (to be on the safe side). Table 1 summarizes the models used in LifeExt projects. A presentation of this work is also given at the Nordic Steel Construction Conference in Luleå June 26-28th 2024 and described in [9]. An example is shown in Figure 14 below, where fatigue crack growth in existing, compared to new, welded structures are modelled for HFMI-treatment and combined TIG-HFMI.

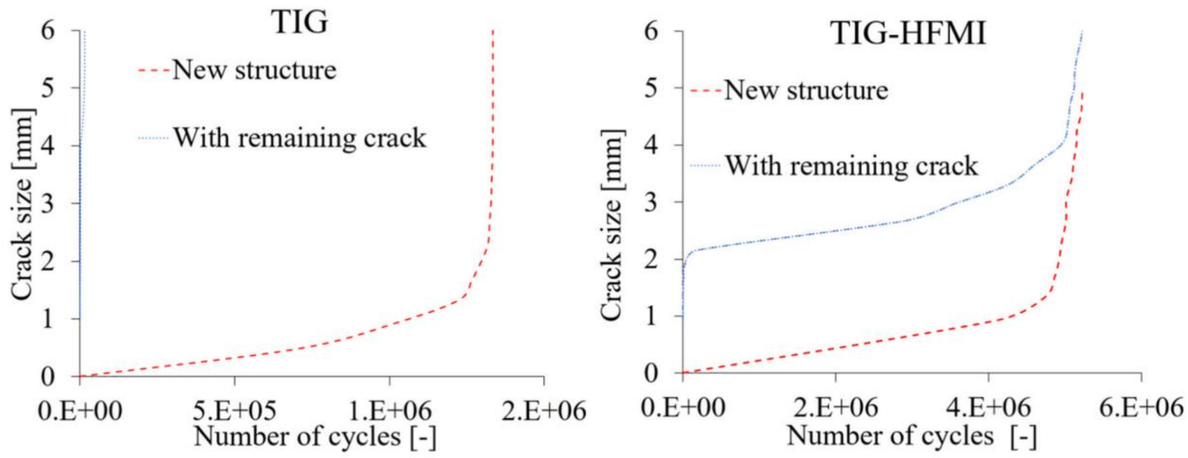


Figure 14. Comparison of fatigue crack growth of new, vs existing, structures treated by TIG remelting or a combined treatment with TIG+HFMI. [9]

Table 1. An overview of the modelling of post-weld treatments utilised for predictions of achieved fatigue life [9].

Description	Governing equations
A simplified model based on Basquin equation to explain the outstanding fatigue strength of TIG treated specimens by incorporating the several changes induced by a treatment (residual stress, local geometry, hardness and distortions). The model is verified with existing experimental results.	$\Delta\sigma_l = k_t \Delta\sigma_g$ $\Delta\sigma_{m,l} = k_t \Delta\sigma_{m,g}$ $\Delta\sigma_{m,tot} = \Delta\sigma_{m,l} + \sigma_{RS} + \sigma_{clamp}$ $\Delta\sigma_{ar} = \frac{\Delta\sigma_l}{1 - \frac{\sigma_{m,tot}}{\sigma_{u,l}}}$
Stress intensities together with weight functions are used to construct the crack growth curves of HFMI treated detail containing cracks. The local changes are incorporated in the definition of the effective R -ratio, and Paris law is employed to construct the propagation curves. The effect of residual stress field and remaining crack size are investigated through a parametric study.	$K = \int_0^a m(x,a).\sigma(x)dx$ $R_{eff} = \frac{K_{min} + K_{RS} + K_{CS}}{K_{max} + K_{RS} + K_{CS}}$ $da = \begin{cases} C.\frac{(K_{max} - K_{min})^m}{(1.5 - R_{eff})^m} dN, & K_{max} - K_{min} > K_{th} \\ 0 \quad , & Otherwise \end{cases}$
Mechanical elasto-plastic finite element model to study the crack closure and introduced compression at the crack tip. Parametric study is performed for the crack size, the impact of position and the angle of indentation.	-
Thermo mechanical elasto-plastic finite element modeling of the combined treatment (TIG remelting followed by HFMI treatment). Crack initiation and propagation models are used. Fatigue damage is calculated based on the resulted strains, and the elements are deleted when the fatigue damage reaches unity. The scanned geometry and local hardness are introduced in the model, and residual stress relaxation during cracking is considered in the model	$\frac{\sigma_{RS}}{\sigma_{RS_{1Cycle}}} = N_i^k$ $\Delta\sigma_{ar} = \frac{\Delta\sigma_{Loc}}{1 - \frac{\sigma_{mLoc} + \sigma_{RS}}{\sigma_{u,L}}}$ $\Delta\epsilon = \frac{\Delta\sigma_{ar}}{E} + K.\left(\frac{\Delta\sigma_{ar}}{E}\right)^n$ $\frac{\Delta\epsilon}{2} = \frac{\sigma_f'}{E}(2.N_f)^b + \epsilon_f'(2N_{.f})^c$

5 Field application

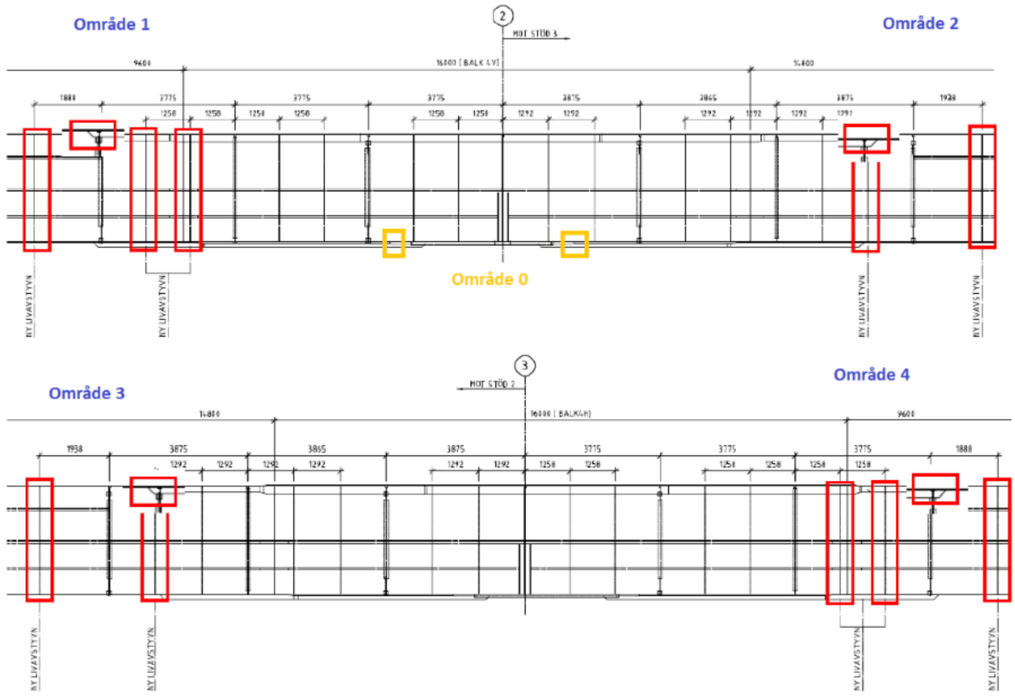
5.1 Selection of bridge and treatment methods

TRV selected the bridge for test implementation. It was a road bridge in Stöde, 42km west of Sundsvall, see Figure 15 below. The bridge was built 1964 and the renovation was established through public procurement by TRV. The contract was wan by Svevia who together with TRV established a “bridge renovation project” that the “research project” LifeExt-2 could connect to and interact with in frequent “status and planning meetings”. HFMI was selected in conjunction with reinforcing stiffeners as a solution to reach the BK4 classing and prolonged fatigue life.

Figure 15. The road bridge in Stöde over the water between Stödesjön and Ede. Note the weather protected platform mounted under the bridge that together with the permanent inspection path between the I-beams gave good work access. Photo taken from north end, I-beams are denominated “west” and “east” beam.

5.2 Description of the test-implementation bridge, strengthening schemes and HFMI-treated details

The bridge is mounted in a north-south direction over the water between Stödesjön and Ede and it has 2 parallel load-carrying beams (“east beam” and “west beam”, 3 m high welded I-beams that should be reinforced to manage a load increase from BK3 to BK4 class. As part of that load capacity increase and also life enhancement work, HFMI was selected to be used on new and existing vertical web stiffeners and also on new longitudinal stiffeners mounted on the upper and lower flanges. The designer contracted had calculated that the most critical parts were the start-and-end sections of the stiffeners. Therefore, it was decided to treat with HFMI 2dm long stretches around the start and end parts of the stiffeners. In total it was 256 positions planned to be treated with HFMI. The technical descriptions of the work needed with HFMI on the bridge was developed in cooperation with the research project LifeExt-2. A dedicated description of the work that the research project needed to perform on the bridge was also developed and coordinated with the bridge renovation project. Here, activities and time needed on the bridge for these activities and the order in which to perform them were described, an example is shown in Figure 16 below.



Operation	Day 1 (h = hour) (Area = "Område" in image above)			
	h1 - h2	h3-h4	h5-h6	h7-h8
Scanning (before HFMI)	Area 1	Area 2		
NDT	Area 0	Ev. Area 0		
HFMI		Area 1	Area 2	
Scanning (after HFMI)			Area 1	Area 2

Figure 16. An illustration of some of the work and timing on the bridge. Shown here are plans for HFMI (red areas, vertical and longitudinal stiffeners) and TOFD (yellow areas, flange joints) that needed a coordinated action between the two projects, the bridge renovation- and the research project.

5.3 Description of work performed on the bridge

Bridge status check and weldability

Before any practical work is launched on a bridge, a status check should be done to investigate the status of the bridge. Included here are investigations on weldability and toughness of the new and existing steels, and checks with NDT (non-destructive testing) that there are no cracks or other unpermitted defects present on the load-carrying parts of the bridge.

Checks of existing steels and welds gave that both the weldability and toughness of the steels were OK, but some center cracks (hot cracks or possibly slag inclusions diminishing with time) were found in the main weld in the lower flange (the weld holding the flange to the web). These cracks were found repeatedly in intervals on one side of the east I-beam between two beam supports and had likely been present since first manufacturing in 1964. These defects could have become more visible in time, for instance when blasting and repainting the bridge. See Figure 17 below. The cracks were repaired by the bridge renovation project by grinding out segments of the weld and re-welding.

Figure 17. Centre cracks found in the main weld holding the lower flange to the web.

It was also found that the web straightness was not according to the quality demands today. The 3m long vertical stiffeners that should be welded to the 3m high web plate were therefore cut into 3 sections, 1m long each, and mounted and welded by the bridge renovation project in 1m sections first to the web. Whereafter the 3 parts of a stiffener were welded together. This way, allowable gap sizes according to EN 1090 could be maintained.

The flange straightness could also in some positions vary too much to be within allowable gap tolerances when the longitudinal stiffeners should be welded to these flanges. This was managed by the bridge renovation project by flame-heating and adjusting the parts before final welding. Some thicker sections also needed pre-heating before welding and the work could be coordinated. See Figure 18.

Figure 18. Pre-heating of a longitudinal stiffener before welding. The outer end (near camera) later to be HFMI-treated at the weld toe around the end section (2dm on each side plus at the corner).

Welding

All welding was made in the bridge renovation project by Timrå Rostfria AB, subcontractor to Svevia. An efficient flow of information was established with good discussions between the research project and the bridge renovation project. The welds needed to have high quality and a good access for HFMI was needed on the actual positions for HFMI. This led to that some longitudinal stiffeners were moved slightly sideways to enable improved access for HFMI. This solution was discussed among the projects and approved by the designer before implementation. Approved WPS:es were used for the welding in all cases.

Scanning and weld quality documentation

The welds were examined by third party (Dekra) before HFMI and in some cases, adjustments such as grinding a part of the weld reinforcement or minor re-welding were needed. After these adjustments, third party was re-examining and approving the welds. Some welds were also laser scanned to evaluate the laser scanning method on a bridge and for detailed measurements of the HFMI treatment. Laser scanning was in these cases done both before and after HFMI, to be able to make comparisons and measure the HFMI groove along the whole HFMI length. The HFMI groove depth is an important quality parameter. See Figure 19.

Figure 19. Laser scanning of weld of vertical reinforcement in conjunction with HFMI-treatment. This was done with the Winteria Flex system both before and after HFMI-treatment, which gave precise measurements of the whole HFMI groove.

The laser scans can be analyzed after approximately 30-60 seconds but are also stored and can be saved as documentation. A deeper analysis can also be made later, or when wished.

Non-Destructive-Testing

Apart from the third-party NDT examinations, tests were also made with the UT-TOFD method. This was further developed by making other transducers and manipulators to be able to use it in the field, i.e. on the bridge. It was decided to focus on examining the butt joints of the lower flanges in conjunction to where the bridge supports are in the water. These positions are very important, and it was of interest to see if the TOFD could find indications here in these old welds. The tests were successful, internal indications that indicated slag inclusions or other internal discontinuities or defects were found. This will be followed-up to see if and when a repair action can be needed. UT-TOFD tests are described more in the following text and shown in Figures 20-21.

The TOFD scanning activities were performed over two separate occasions. On the first occasion only the TOFD approach was used for scanning the weld. For the second visit a zero-degree probe was added to the setup. TOFD is a very sensitive method and can easily pick up any defects through the material thickness. The motivation for a zero-degree probe (0TRL) is to identify and distinguish volumetric defects such as delamination and pores from cracks.
Several conclusions were made during the two occasions, and not only with regards to interpreting the results of the scans.

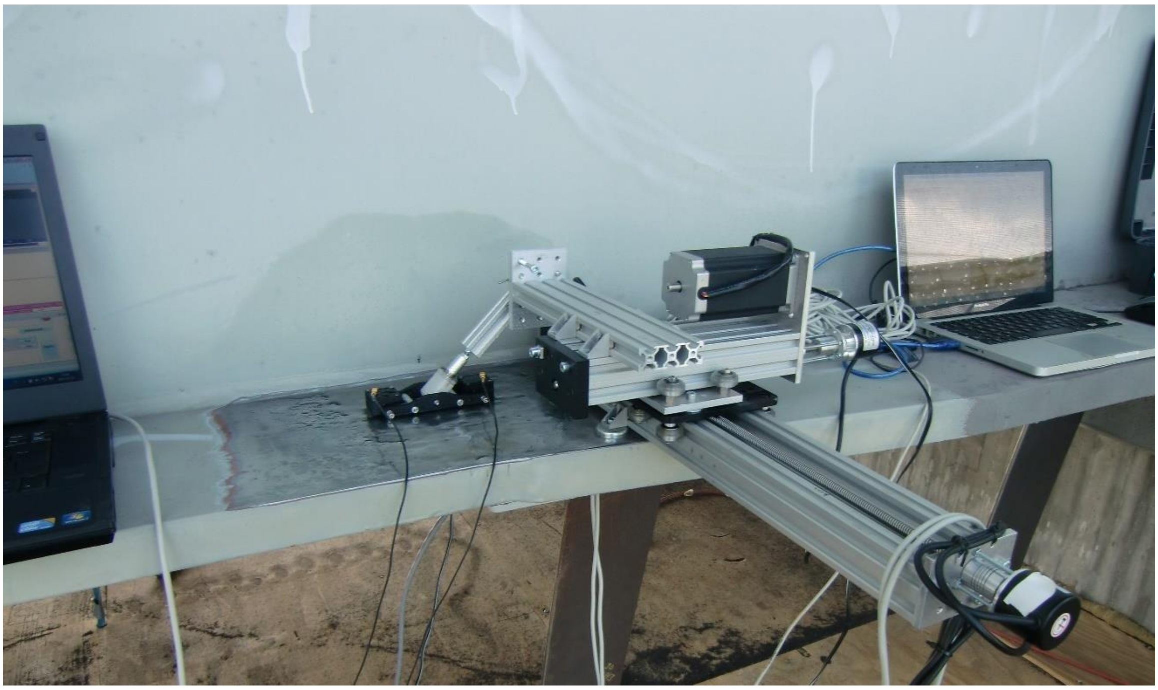


Figure 20. Examining butt-welds in the lower flanges with UT-TOFD. The top side weld region has been grinded flat and blasted (similar to other parts of the bridge where new stiffeners should be welded) to enable a clean and smooth surface to run the transducer on.

Typical findings for the scan with the zero-degree probe, for the field data collection, can be seen in Figure 21 below.

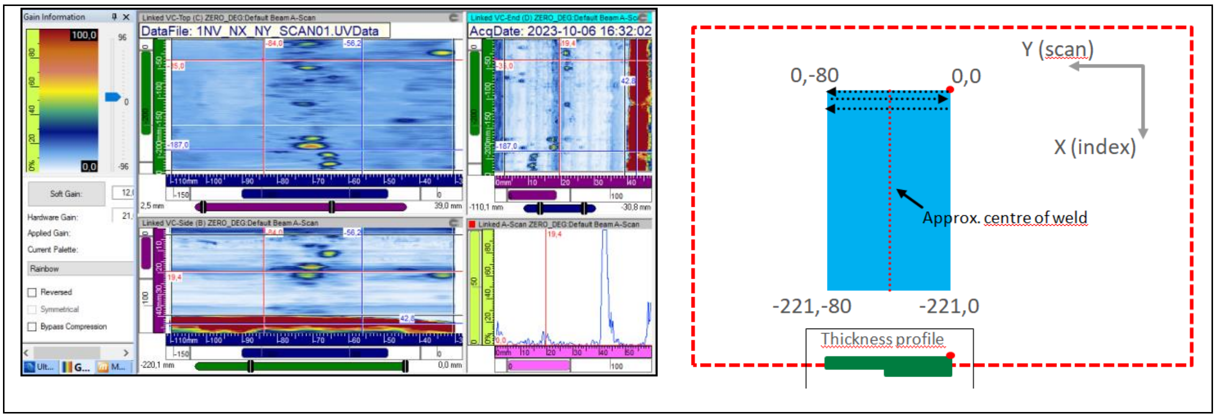


Figure 21. Zero-degree probe scan (0TRL) and coordinate system of the scan data, support no.1 North-West position on bridge.

The Top(C)-view, Side (B)-view and End (D)-view data present full tested volume. This data offers insights into the object's geometry and quality. It is particularly effective in detecting laminar and volumetric defects. Common issues like slag inclusions, large pores, and laminations are easily identified due to their high amplitude responses visible across all views. However, smaller imperfections and vertical planar defects such as lack of fusion and cracks may exhibit low amplitude responses and might not be visible. For a more detailed analysis of defects, Ultrasonic Testing (UT) data is examined as sectional views through the defects. The overall view from Time-of-Flight Diffraction (TOFD) data is less informative, requiring a step-by-step assessment through the entire volume to gather meaningful insights. From the data, it is evident that the tested weld contains several significant volumetric defects and one laminar defect in the parent material.

Conclusions from these TOFD investigations will be compiled and sent to TRV for documentation and follow-up.

HFMI-treatment

HFMI treatment of all actual positions was performed by HiFit in the bridge renovation project and the quality assurance of HFMI was evaluated by the research project. The fact that all parties were on the bridge at the same time and the good dialogue and discussions that this enabled led to efficient adjustments of accessibility and when to re-run a part of a section. In all, the HFMI took 3-4 days to complete for 1 operator (256 positions but short runs). Figure 22 illustrates a typical HFMI treatment on a bridge, a vertical stiffener.

When HFMI-treating the longitudinal stiffeners on the flanges, a not uncommon situation occurred – the welder had in some places grinded the weld around the short end of the stiffener too much and partly grinded the weld toe away (flush to the steel plate). The solution that HiFit had used several times before was utilised. It is a double treatment where the area where the weld toe was is first HFMI-treated with a 10mm flat-pin to build-in a field of compressive stresses, and subsequently followed by the treatment with the 3mm standard pin on the positions where the weld toe is estimated to have been.

Figure 22. HFMI treatment of a vertical stiffener on the west I-beam of the bridge. The weather protected platform mounted under the bridge gave a good work environment, good access.

Scanning and quality documentation of HFMI

The HFMI groove depth is normally measured with a mechanical measuring tool, and it should typically be around 0.2mm deep for a S355 steel (0.15-0.25mm). Most important parameters to achieve the HFMI groove depth are the intensity setting on the machine (which sets the amplitude for the hammer pin) and the travel speed (movement forward of the machine that the operator influences). To some extent is also the pressure that the operator applies on the machine also influencing the indentation depth and of course also the type of pin used (its hardness, diameter and shape). As the technology is used today, the machine is run-in in its settings on positions on the actual bridge where it is allowed to do so. Here, the pin is selected, the machine intensity is tuned-in and a good way of working in terms of pressure and travel speed is established. Then transferred to the actual positions that shall be treated. This was the methodology used on the bridge in Stöde, the settings and technique were run-in on positions allowed by the designer and Svevia.

The laser scanning (Figure 19) was evaluated on a number of selected positions that should be HFMI-treated. The welds on these positions were measured before, and after, HFMI. This gave good and continuous measurements of the complete groove length, and this led to that, in one or two occasions, the identification of the need for a higher intensity setting on the HFMI-machine since some short stretches of the treatment had a too low groove depth. The laser scanner measure with 7 micrometer accuracy and can also be used to analyze the depth distribution (variation) along the run, i.e. be used for both fine tuning the HFMI-process and a quality documentation of it.

Also important for the quality assurance of a HFMI-treatment is the positioning of the “hammering” – the pin shall hit in the weld toe region, the transition between the weld and the base material. This means that it should not only hit on the base material and not only on the weld metal. It needs to hit in-between, and the direction of the pin should be directly downwards (perpendicular to the base plate / steel) and NOT directed towards a position under the weld itself. The reason is that the compressive stresses created by this treatment will make best use when positioned directly under the weld toe and heat-affected zone (i.e. not under the weld). If the pin has been used with erratic angles (more angled towards one side for instance), it can often be seen by a “wall” of material pushed up by the pin on one of the sides of the groove. The HFMI-groove should be even and smooth and not have a wall or “chips” on either side. And the weld toe should not be visible as a thin line in the bottom of the groove, in that case has the plasticization been too low and a re-run with HFMI should be performed, possibly with a higher intensity setting. These aspects are also described in the HFMI-guideline [2].

An example from the QA-documentation with all the parameters noted is shown in Figure 23 below together with a page from the HFMI-treatment-checklist. The checklist is used to ensure the positions globally and locally and to verify that the groove is smooth and has the right depth and no visible weld toe line.

A preliminary document describing aspects on the quality assurance of HFMI: machine types, operator’s training and experience, equipment selections and settings, treatment procedures, etc. has been written in Swedish and will after a referral round be submitted to TRV. The intention is that it could be used when planning or purchasing work with HFMI and also TIG.

HiFIT **QUALITY CONTROL PROTOCOL** **Project:** Bro 22-265-1 över Ljungan

Part 1	**To be filled by the HFMI operator**
Specifications	
Base Material:	To be specified
Thickness:	Web 14mm
Filler material:	According to client's specifications
Weld procedure:	According to client's specifications
Type of weld:	Fillet weld
Location:	East girder
Identification:	W1.B1.E
Equipment:	HIFIT
Make and model:	HFM 12P1-S
Pin radius [mm]:	3/10 mm
Treatment data [bar]:	6
Position:	Weld toe (and if necessary, surface treatment with large radius pin)
Work angle side [degree]:	60-80
Work angle ahead [degree]:	70-90
Travel speed [mm/s]:	3-5
Number of passes:	1 (second pass is applicable if undertreated)
Treatment length [m]:	0.2x2
Time of treatment [h]:	NA
Tool changes:	10 mm
Reason for tool change:	Grinding
HFMI operator	
Name:	Thomas Merkl
Experience [h]:	>5 years
Total length of treated welds [m]:	0.4
Date of treatment:	31/08/2023

Part 2	**To be filled by the controller**
Visual inspection	OK
Photo, enter the name of the photo	W1.B1.E-W1.B2.E
Measurement, description	With Gauge
Equipment for measurement	HIFIT Gauge
Result	OK
Radius of toe [mm]	
Weld angle	OK
Depth of treatment [mm]	0.15-0.35
Remarks	-

Approval	**Contractor**	**Inspector**	**Client**
Company	HiFIT	HiFIT	
Representative name	T Merkl	T Merkl	
Date	31/08/2023	31/08/2023	
Responsible person	Michael Neher	Michael Neher	
Signature			

HiFIT
High Frequency Impact Treatment

Information for Quality assurance of the Post Weld Treatment:

Treated Construction: ______________________________

____

Treated Weld Detail or Protocol No.:

____

Are all Post Weld Treatments at the correct place?	☐ yes	☐ no
Is the position over the weld seam transition?	☐ yes	☐ no
Is the Post Weld Trace uniform and consistent?	☐ yes	☐ no
Are all heat treatment zones completely treated?	☐ yes	☐ no
Is the examined depth of the groove between 0.15 and 0.25mm?	☐ yes	☐ no

Remarks:

____

The HiFIT Post Weld Treatment was checked by:

______________________ ______________________
Name in block letters Signature

____
Date Time:

Figure 23. Example of QA documentation from the bridge (left) and checklist for the HFMI-operator (right)

6 Preparing industry for application

6.1 HFMI course development for operators and Pilot course test education

During LifeExt-2 it was identified that a course for HFMI operators was needed to develop, and a chance to apply for extra funding was given, taken, and granted. A work group consisting of HiFit, Swedish Welding Commission and Swerim was created and after several meetings and programme versions, a 2-day pilot course intended for basic training of HFMI-operators emerged. It consisted of 1 day theory (information about HFMI treatment, how it behaves and should be run, examples of good and bad results and the reasons for it, residual stresses, equipment aspects, needle types, parameters, documentation) and 1 day of practice (learning how to set and run the machine, treating different types of welds and geometries, measurement, visual inspection and judgement of treatments). Weld types used for the HFMI-training in the practical education were butt welds, fillet welds and "pipe-on-plate, i.e. circular welds. The 2-day course was finalized with a theoretical and a practical test. All were approved and received course certificates after the course.

When this pilot course was test-run with FredrikaBremer Industrigymnasium in Haninge with 5 participating "students" (2 were welding teachers from Fredrika Bremer, 1 was welding engineer student from KTH, 2 were welder-students from FredrikaBremer), see Figure 23, it became evident that the pilot course had too much theory to be suitable for the welder-students. They stated that it would be sufficient with ½ day of theory, and the rest of the time should consist of practical training.

After discussion, it also became clear that the pilot course developed is highly suitable for the welding teachers, to train them on HFMI, and the developed course should be used in the future to continue to spread the knowledge in this way to welding schools, to “train the trainers”. The welding schools can then decide on how to best implement the HFMI among the other training activities. It was concluded that this is probably the best way to teach welding students that are in a welding school already, to integrate these 2 days among the other training days at suitable times for the schools. External other students could be given an extra 2-day course, like this pilot course.

The education of HFMI-operators will need to be continued, at this point it will need new financing since the LifeExt-2 project has reached its final month (new financing will be searched to be able to continue to spread this education in Sweden and create a number of HFMI-operators).

Figure 23. The students in the pilot course, and to the right the teacher from HiFit, Michael Neher with 15 years of experience with HFMI.

6.2 Qualification of HFMI equipment and personnel today and tomorrow

Regarding qualification of personnel, the situation today is that the machine suppliers can arrange basic training courses similar to the pilot course just described in the last chapter. This will give basic knowledge connected to one machine type only. The manufacturer can also emit a course certificate to each student that have passed a final test.

This is a good starting point, but it could be supplemented with a possibility to, after some on-the-job-training with HFMI, take a National or European test on standardized test pieces (with different geometries) and also perform a theoretical test or interview. – A standardized and recognized examination could give a National or European Diploma, which in turn could certify that the Diploma holder has the recognized training and experience that is needed for an advanced operator. Swerim and the Swedish Welding commission will together with other interested parties strive in a continued work that need extra financing to achieve such a system and Diploma.

6.3 Dialogue with designers and QA-personnel

It was also realized during the run-time of LifeExt-2 that not only designers need to be informed and trained on how to calculate and take in HFMI in designs, but also the QA-personnel (the third-party controllers) need information and also training on how to make judgements of a HFMI-treated weld. This dialogue and training has started during LifeExt-2, the QA-staff is participating in the Swedish Welding Commission’s work group AG48 Quality Technology and HFMI has been a topic and discussed in 2 meetings within this group. An info material needs to be developed, directed to third-party staff. Activities with Konstruktionscentrum (Design Centre) at Chalmers, for the designers, are planned this Autum and Chalmers has written a report on HFMI for designers [10].

7 Conclusions

Summary of the findings from the experimental program in both LifeExt-projects

1. Both HFMI- and TIG-treatments were successful, not only in full restauration of the fatigue strength of fatigued welded details, but also in increasing the fatigue strength up to that of an equivalent new treated detail.
2. HFMI-treatment gives superior results when fatigued welded details contain no fatigue cracks or when existing fatigue cracks are shallower than 1.5 mm through plate thickness.
3. TIG-treatment can be used to restore the fatigue strength of welded details if the treatment can be performed with a penetration depth larger than the depth of any existing cracks. A combination of TIG, followed by HFMI gives superior fatigue life extension, equivalent to that obtained for new HFMI-treated details.
4. An interesting NDT method, UT-TOFD, has been identified and adapted to the needs in the projects to find and follow fatigue cracks. This method was used to analyze and quantify the crack development for different cases and improve reliability in testing and judgements.
5. TOFD was also adapted to field use and evaluated on flange joints on the bridge in Stöde. These examinations revealed internal flaws in some of the welds, which will be followed-up. This shows a potential for TOFD for a field use in combination with other NDT methods.
6. Important lacking fatigue data for HFMI treated details have been developed (cope-hole, longitudinal attachment, transversal attachment, I-beam with welded cover plate) and the acquired data delivered to the update of Eurocode 3 and the Guideline for HFMI. Still, more HFMI data are needed, for other material thickness combinations, and other welded details.
7. Test-implementation work with HFMI has been performed on the selected bridge in Stöde. The work – and the cooperation between the renovation project and research project – was very successful. The preparations, documentation and way of working can be used again together with the lessons learned (mainly: more scrutinizing work in the start-up phase, to find the faulty drawings and where the bridge need extra work to reach today’s standard). There is also a possibility to develop a better pre-analysis work, to tailor treatments.
8. Quality assurance of the life enhancement methods has been studied and conclusions made on what to focus on. A document has been compiled in Swedish for TRV to be used when updating their regulations and as a support in their procurement work.
9. A basic course for education of HFMI-operators has been developed and test-run. Evaluation after this pilot-course has shown how to adjust the course to fit operators better – and that the pilot course format used should fit well as a course for the welding teachers (to train the trainers). New financing will be searched to be able to continue to spread this education of HFMI-operators, and to be able to teach third-party staff how to make judgements of HFMI-treated welds, and designers on possibilities with HFMI.
10. There are more challenging tasks that will be encountered when the LifeExt techniques are applied to other bridges during a coming scale-up– a “LifeExt3 scale-up” project that acts similar to LifeExt2 (docking on to and supporting bridge renovation projects with research and connected tests) could better enable and increase the speed of this scale-up. It could also include continued education of HFMI for operators, designers and third-party staff.

8 Future work

The following topics remain to be investigated and further worked with:

- The efficiency of the studied LifeExt methods have been demonstrated for 3 main bridge details: butt welds and longitudinal and transverse attachments. Our studies have shown that this cannot be directly "extrapolated" to other bridge details. Therefore, more research is needed to extend the applicability of the LifeExt techniques to other types of important bridge details, particularly those for which fatigue cracking has more frequently been reported for bridges in service, e.g. details of orthotropic bridge decks. Also other geometries of welded cover plates, etc.

- The superior performance of the techniques studied in LifeExt 1&2 has been demonstrated on modern steel types. An extension of these methods to older steel bridges which could have varying steel strengths and properties need to be verified, before the benefits offered by these methods can be utilized fully on bridges with older steel types.

- More challenging tasks will be encountered when the LifeExt techniques are applied to other bridges during the scale-up phase – a "LifeExt3 scale-up" project that acts similar to LifeExt2 (docking on to and supporting bridge renovation projects with research and connected tests) can assist in eliminating obstacles, enabling and increasing the speed of the scale-up.

- Continued teaching and information of HFMI needs to be performed: to welding teachers, to third-party quality control staff, to designers, and to managers.

- Development of suitable and accepted branch tests (national or European) of both HFMI machines and HFMI operators is highly needed to establish the same type of quality system as in welding.

- Spreading of the developed work and methods to other branches and applications. Many fatigue loaded structures can benefit from LifeExt methods. (Some other branches have started to look into this, but a large number of applications remain to be identified/verified.)

9 Publications and Dissemination

Title	Main author	Co-authors	Journal/Conference	status
Bro i Stöde förstärks med HFMI	H Petursson	M Al-Emrani, J Hedegård	Journal Nyheter om Stålbyggnad, nr 3-2023	Published
Application of high-frequency mechanical impact treatment for fatigue strength improvement of new and existing bridges.	H Al-Karawi		Dissertation: THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY. ISBN 978-91-7905-797-8. Chalmers University of Technology 2023	Published
Verification of the Maximum Stresses in Enhanced Welded Details via High-Frequency Mechanical Impact in Road Bridges, Buildings.	H Al-Karawi	J Leander, M Al-Emrani	Publication: Buildings 2023 https://www.mdpi.com/2075-5309/13/2/364	Published
Framgångsrika försök att förlänga livslängden på broar	J M Högberg		Journal Dagens Infrastruktur Feb-2024 Framgångsrika försök att förlänga livslängden på broar - dagensinfrastruktur	Published
Fatigue improvement of welded cover-plates using High Frequency Mechanical Impact Treatment.	M Al-Emrani,	J Hedegård, J-P Anttonen, H Petursson	Conference: NORDIC STEEL 2024, 15th Nordic Steel Construction Conference, June 26–28, 2024, Luleå, Sweden	Published
Fatigue life extension of welded steel structures - Summary of LifeExt research projects conducted 2017 - 2024	H Al-Karawi	M Al-Emrani, J Hedegård	Conference: NORDIC STEEL 2024, 15th Nordic Steel Construction Conference, June 26–28, 2024, Luleå, Sweden	Published
Evaluation of HFMI in welded cover-plates for strengthening of steel bridges.	A Engdahl,	N Khoulani	Master's thesis in Structural engineering and building technology. Department of Architecture and Civil Engineering, CHALMERS UNIVERSITY OF TECHNOLOGY, Master's thesis ACEX30 2024	Published

Life Extension of Welded Steel Details in Bridges	Z Jin		Master of Science Thesis in Lightweight Structures SD241X School of Engineering Science SE-100 44 STOCKHOLM	Published
High Frequency Mechanical Impact Treatment - Recommendations for the design of welded details in road and railway bridges	M Al-Emrani	P Shams-Hakimi, H Al-Karawi	Chalmers Report ACE 2024:3	Published
Fatigue life improvement of welded cover-plates using High Frequency Mechanical Impact treatment	M Al-Emrani	J Hedegård, H Petursson	Conference: IABSE 2024, San José Sept 25-27th 2024	Accepted

Dissemination events

J Hedegård, A Lundstjälk, H Petursson, participation and presentations at InfraSweden2030 annual workshops.

J Hedegård, "LifeExt-project", presentation at Elmia Production Technology Exhibitions, May 11th 2022.

J Wahlsten, "About HFMI and LifeExt", presentation at the CJS Conference, May 22-23rd 2022.

M. Edgren in NDT Autumn Assembly 2022: "Sensor technology within research and customer assignments", NDT Sweden - Föreningen för Oförstörande Provning (FOP), Stockholm, Sweden, November 8th 2022.

A Lundstjälk, "OM HFMI och LifeExt" presentation at Fogningsdagarna, March 30th 2023.

J Hedegård, "Om HFMI och LifeExt" presentation for Svevia, April 12th 2023.

A Lundstjälk, "Öka utmattningslivslängden med HFMI", InfraSweden2030 Innovation workshop May 25th 2023.

J Hedegård, "Om HFMI och LifeExt-projekten", presentation for Swedish Welding Commission WG48, Sept 25th 2023.

M Al-Emrani, chairing " Ökad Livslängd med HFMI", a session at Stålbyggnadsdagen (Steel Building Day) at Älvsjömässan, Oct 19th 2023, with presentations by M Al-Emrani (Chalmers), H Petursson (TRV), A Björnsson (HiFit Scandinavia), P Shams-Hakimi (WSP) giving information on how to use HFMI, what to consider when procuring HFMI, the coming updates on HFMI in EC3, and the work made on the bridge in Stöde. https://www.sbi.se/presentationer-stalbyggnadsdagen/ - HFMI equipment and HFMI-treated welds were also exhibited in the Meet, Eat & Mingle area of the conference.

J Hedegård, “LifeExt-projects” a presentation for the FFI Geometry Cluster Nov 29th 2023.

Z Barsoum et al, Possibilities with High Frequency Mechanical Impact (HFMI) Treatment and Digitized Quality Assurance in Fatigue Life Extension of Welded Structures, Opening Keynote Lecture, 10th International Conference on Fatigue Design, Senlis, France, November 29-30th 2023.

J Wahlsten, A Lundstjälk and J Hedegård, presentation of HFMI and practical demo, SBI Young Designer’s Network meeting “About HFMI” at Swerim Feb 20th 2024.

J Hedegård, “Om HFM” presentation for Swedish Welding Commission WG14, March 20th 2024.

M Edgren in NDT Spring Assembly 2024, ToFD – Data acquisition and evaluation of the PWT-method HFMI, NDT Sweden - Föreningen för Oförstörande Provning (FOP), Stockholm, Sweden, 12-13 April 2024.

J Hedegård, ”Nya möjligheter med HFMI” (New possibilities with HFMI), presentation at Elmia Production Technology Exhibitions, May 16th 2024 .

J Hedegård,” Ny operatörsutbildning för HFMI” (New Education for HFMI Operators), presentation at Elmia Production Technology Exhibitions, May 16th 2024 .

H Petursson, A Westerlund, M Al-Emrani, J Hedegård, ”Livslängdsförlängning av befintliga broar – Implementering”, BBT-webinar May 28th 2024. LifeExt 2 Livslängdförlängning av befintliga broar 28 maj 2024 - YouTube

M Al-Emrani, J Hedegård, J-P Anttonen, H Petursson (2024): Fatigue improvement of welded cover-plates using High Frequency Mechanical Impact Treatment. NORDIC STEEL 2024, The 15th Nordic Steel Construction Conference, June 26–28, 2024, Luleå, Sweden.

H Al-Karawi, M Al-Emrani, J Hedegård, Fatigue life extension of welded steel structures - Summary of LifeExt research projects conducted 2017 -2024. NORDIC STEEL 2024, The 15th Nordic Steel Construction Conference, June 26–28, 2024, Luleå, Sweden.

Coming events:

M Edgren et Al., Evaluation of crack depth impact on HFMI treated pre-fatigued welded bridge details, presentation at 77th IIW Annual Assembly, Rhodes, Greece, 7-13 July 2024.

J Hedegård & J Wahlsten, workshop in Swerim on HFMI for Swedish Welding Commission WG14, Sept 25th 2024.

M Al-Emrani et Al, Konstruktionscentrum Seminar on HFMI for Designers, planned for Autumn 2024.

M Al-Emrani et Al, “Fatigue life improvement of welded cover-plates using High Frequency Mechanical Impact treatment”, IABSE 2024, San José Sept 25-27th 2024.

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[10] M. Al-Emrani, P Shams-Hakimi, H Al-Karawi, “High Frequency Mechanical Impact Treatment - Recommendations for the design of welded details in road and railway bridges.”, Chalmers Report: ACE 2024:3.
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