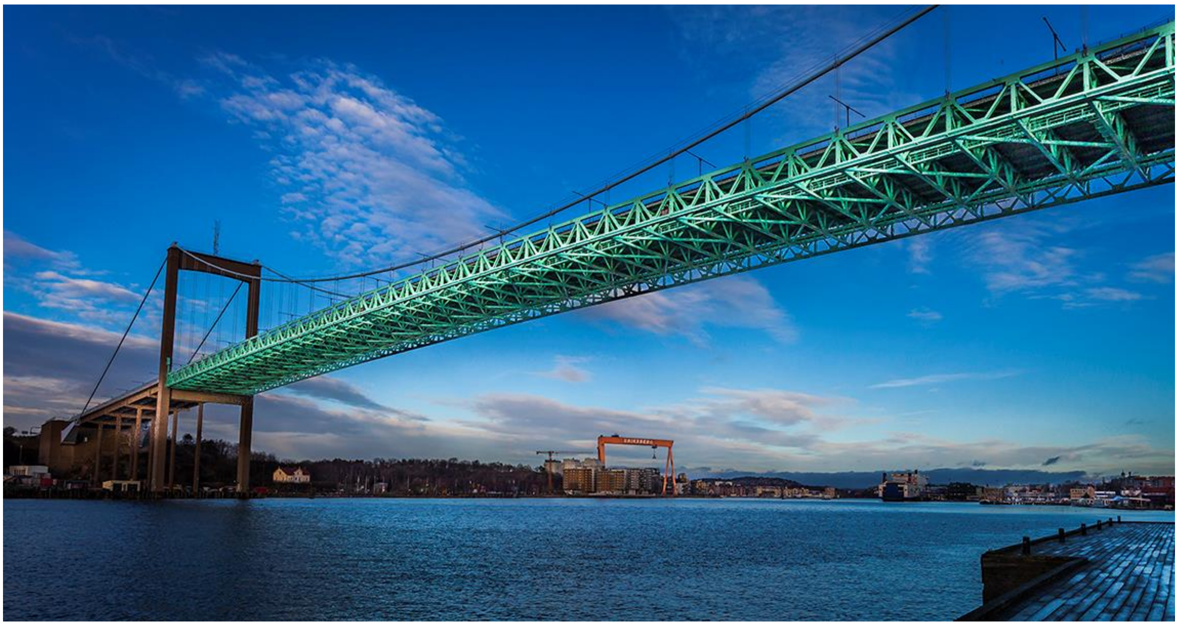
LifeExt – Prolonged life for existing steel bridges

– Livslängdsförlängning av befintliga stålbroar

Open report / Publik rapport



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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 because their theoretical life span is reached is not a sustainable solution, neither from societal nor economical point of view. Therefore, methods for accurate assessment and techniques for extending the service life of existing infrastructures are top priorities for all industrial countries. The LifeExt project reported here was created to address these issues, to enable substantial life extension for existing bridges by applying weld improvement techniques locally on selected (most critical) positions on a bridge. These critical areas receive faster damage accumulation 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 in a very local area, the LifeExt project set the objectives for life extension investigations:

- The possibility to infuse (remove) a fatigue crack should be studied, with the aim to investigate which crack sizes that are possible to remove by TIG-treatment directed more into the base material, i.e. along the crack depth direction instead of the classic treatment direction towards the weld toe and lower part of the weld. Focus would be within the manual TIG-welding (treatment outdoors on a bridge should be possible).
- Suitable NDT methods for identification and quantification of actual fatigue damage should be evaluated.
- The possibility for HFMI techniques to restore the fatigue life of a fatigue damaged welded detail should be investigated for different levels of "pre-fatigue". The extension in fatigue life gained should be investigated.
- A fatigue damage model should be developed that incorporates repair techniques.
- A method should be developed for judgement of suitability for LifeExt treatments, and selection of suitable techniques.

Study and verification of LifeExt methods

Three different test specimens were selected. These are:

1- Rat-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, the 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.

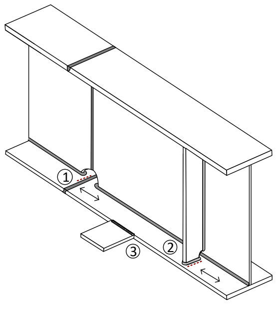


Figure 1. The selected critical parts determining the fatigue life for a bridge

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, and found in literature, are shown in Figure 2 below.

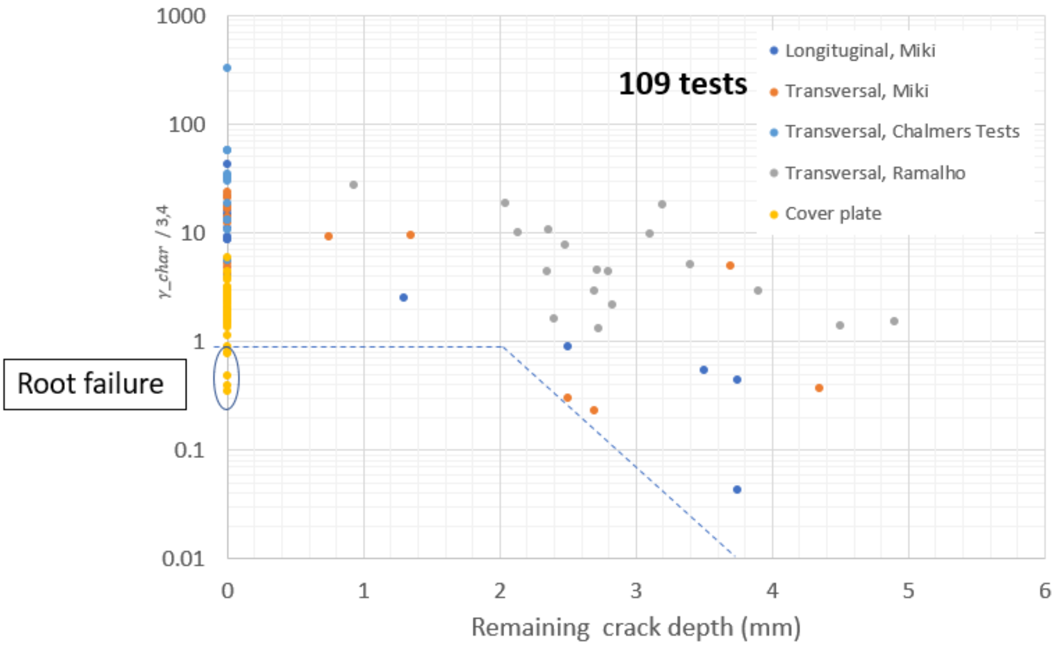


Figure 2. The fatigue life gain factor as function of (eventual) remaining crack after treatment.

Summary of the findings from the experimental program

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 has been 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.

Recommendations

Based on the extensive experimental and theoretical work performed in LifeExt, initial recommendations for the use of LifeExt-project results has been formulated. However, for the full potential of the project results to be utilized in practice, i.e. implemented in a complete guideline, several technical questions need to be studied in more detail. These are further described in the report.

2 Sammanfattning på svenska

Många broar i världen har nått sin kalkylerade livslängd, eller överskridit den.
Det är en samhällelig utmaning att hitta bra och kostnadseffektiva metoder för att åstadkomma livslängdsförlängning för de broar som klarar detta. Därför är nya metoder för statusbedömning, mätning, behandling av stort intresse att utveckla och implementera.
LifeExt projektet som beskrivs i denna rapport skapades för att adressera dessa frågor, med syftet att möjliggöra väsentlig livslängdsförlängning för befintliga broar genom att applicera anpassade förbättringstekniker på utvalda kritiska detaljer i broar. I dessa positioner fås snabbare skade-ackumulering och genom att förbättra dessa platser nås väsentlig livslängdsökning för hela bron.

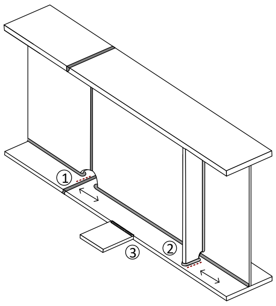
LifeExt projektet satte upp följande mål för att kunna åstadkomma livslängdsförlängning:

- Möjligheten att "lokalt åter-svetsa" (fullt reparera) en spricka ska studeras, med målet att kvantifiera vilka sprickstorlekar som kan "avlägsnas" genom återsvetsning med s.k. TIG-behandling (lokal TIG-svetsning) riktad längs sprickans utbredningsdjup. Manuell TIG-behandling är i fokus eftersom behandling utomhus på en bro ska vara möjligt.
- Möjliga OFP-metoder (oförstörande provning) för identifiering och kvantifiering av utmattningssprickor ska utvärderas.
- Möjligheten att med HFMI (High Frequency Mechanical Impact) metoder kunna återställa utmattningslivslängden för en svetsad detalj ska undersökas, för olika nivåer av ackumulerad delskada (för-utmattning före behandling). Därmed ska nivån på möjlig livslängdsförlängning kunna kvantifieras för olika fall.
- En skademodell ska utvecklas som även kan bedöma livslängdsförlängning.
- En metodik ska utvecklas för bedömning av lämpligheten att applicera LifeExt tekniker, samt vilka tekniker som kan vara aktuella.

Studier med LifeExt metoder

Tre olika provkroppar valdes som representerar de svagaste punkterna i en bro. Dessa är:

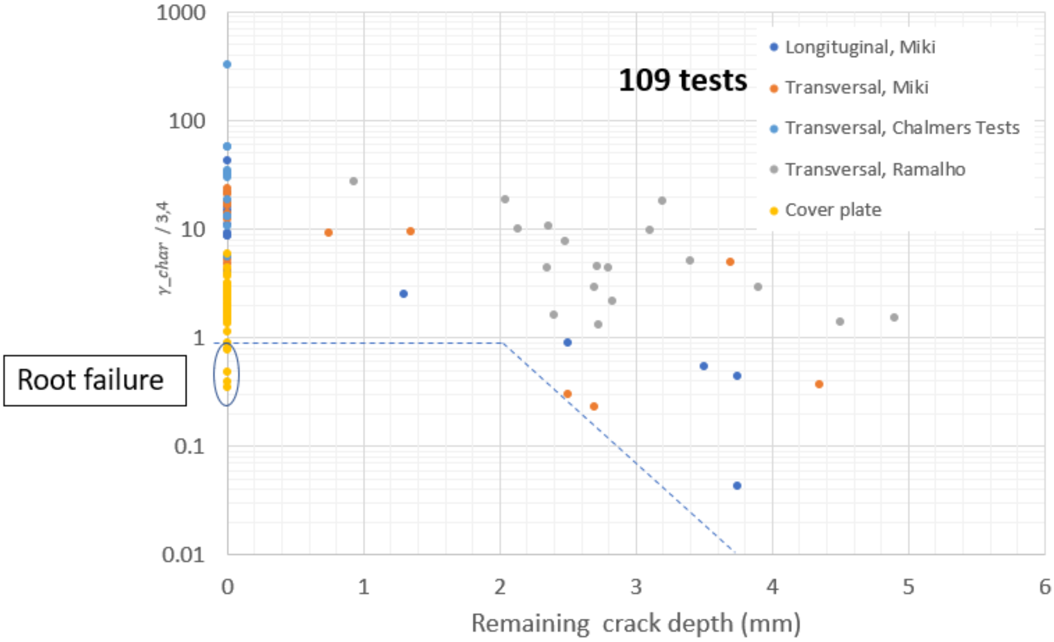
1. "Rat-hole" (eller notch) detalj, denna återfinns vanligen vid balkskarvar.
2. Den svetsade vertikala förstyvningen mellan fläns och liv i en balk.
3. Tvärgående anslutning till nedre balkfläns, ansluter ofta vindstag mellan huvudbalkar.



Figur 1. Illustration av de utvalda kritiska detaljerna som bestämmer utmattningslivet för en brobalk.

Efterbehandlingsmetoder med förmåga att lokalt kunna återställa utmattningsskada vid kritiska detaljer var i fokus att identifiera och två metoder framträdde som mest lämpade:
TIG-behandling samt HFMI-behandling. De undersökningar som gjorts i projektet har därför huvudsakligen skett med dessa metoder.
I utmattningsprovningen med de tre olika provkroppsgeometrierna gjordes först inledande utmattning till olika nivåer av delskada, därefter applicerades aktuell förbättringsmetod, varefter fortsatt utmattningsprovning till brott gjordes. Därefter kunde aktuell livslängdsökning bedömas för de olika fallen.

Samtliga fall utvärderade i LifeExt, samt ytterligare funna i litteraturen, visas i Figur 2 nedan.



Figur 2. Livslängdsförlängningsfaktor som funktion av kvarvarande del av spricka efter behandling.

Summering av erfarenheter från de experimentella försöken

1. Både HFMI- och TIG-behandlingar var framgångsrika, inte bara i att återställa/restaurera skadan från sprickningen utan även i att öka utmattningstäligheten upp till en nivå motsvarande en helt nytillverkad detalj.
2. HFMI-behandling ger överlägsna resultat när utmattad detalj ännu inte innehåller en utmattningsspricka, eller när sprickan är mindre än 1,5 mm i plåtens tjockleksriktning.
3. TIG-behandling kan användas för att återställa skada (en spricka) när processens inbränning kan nå djupare än största sprickdjup i detaljen.
   En kombination av TIG följt av HFMI ger stor livslängdsförlängning, motsvarande en helt ny detalj som HFMI-behandlats direkt efter tillverkningen.
4. En OPF-metod har identifierats (UT-TOFD) och anpassats så att utmattningssprickor kan identifieras och följas. Denna metod användes för att följa spricktillväxten i ett antal fall och användes även för att förbättra förutsägbarheten (minska spridningen).

Rekommendationer

Baserat på det omfattade experimentella och teoretiska arbete som utförts i LifeExt har initiala rekommendationer tagits fram för hur resultat och metoder i LifeExt ska kunna användas. För att kunna nyttja livslängdsförlängande tekniker full ut behövs emellertid uppföljande utvärderingar med fler fall utvärderade och ett antal tekniska frågor utredda. Dessa beskrivs i senare del av rapporten.

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 desired high pace. Therefore, new methods for status judgements and life extension techniques are of high importance to develop and implement.

The LifeExt project reported here was created to address these issues, to enable substantial life extension for existing bridges by applying weld and fatigue life improvement techniques locally on some selected (most critical) positions on a bridge. These areas receive faster damage accumulation and by improving these areas, the whole bridge life will be prolonged.

3.1 Life extension methods

HFMI- High Frequency Mechanical Impact

In 2016, the International Institute of Welding (IIW) published a recommendation/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 $N = 2 \times 10^6$ 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 3.

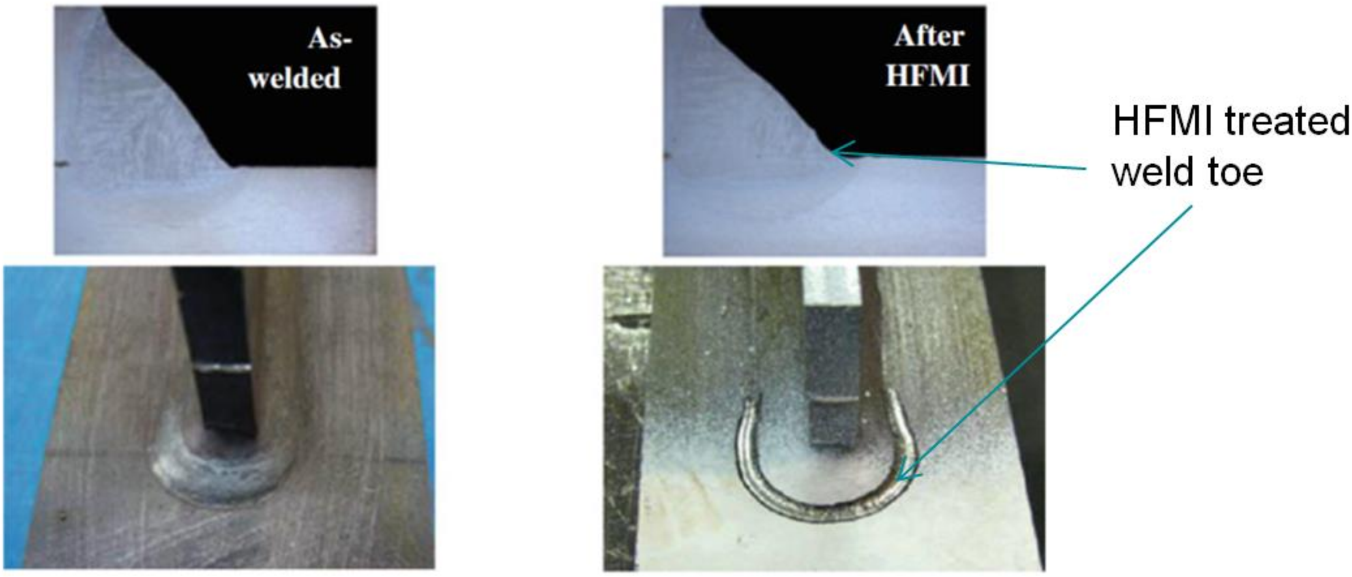


Figure 3. Typical application of post-weld treatment HFMI; Left: a MAG fillet weld in as-welded condition and Right: after HFMI treatment (from [1])

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) [1]. 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) [5] 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. [4].

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 [1] states that for structures with $R > 0.5$ or when $\sigma_{max} > 0.8\ f_y$ 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 toe radii) between weld and base metal is created. See Figure 4.

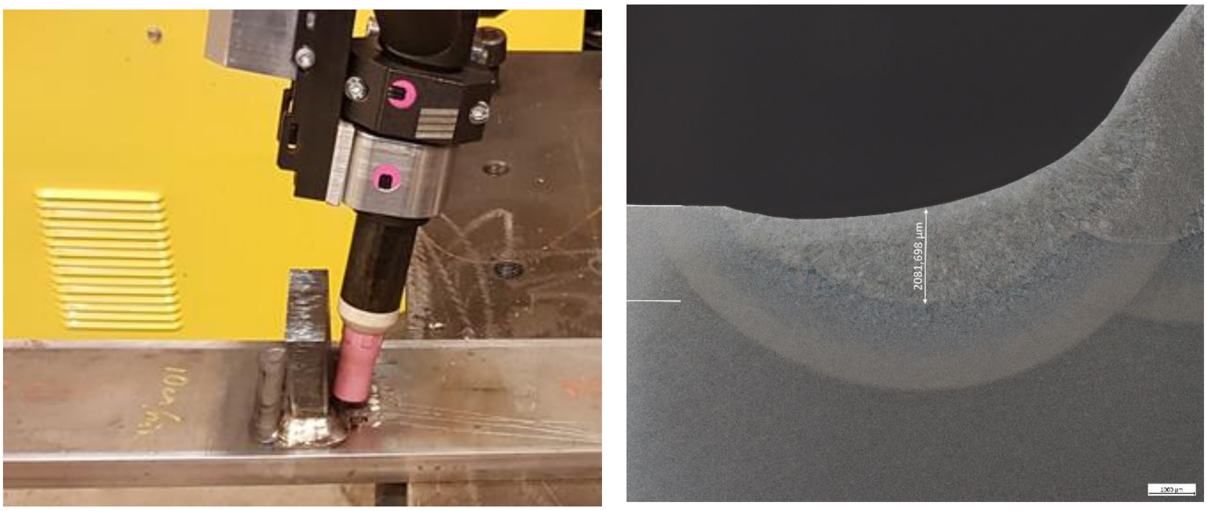


Figure 4. Left: TIG-torch direction for fatigue crack repair. Right: TIG-reweld transition region.

4 Objectives

The LifeExt project set out the goal 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 and by improving these areas, the whole bridge life will be prolonged. And based on the local damage approach, that a fatigue damage on a fatigue loaded structure that has been subjected for fatigue for a certain time is accumulated in a local area, the LifeExt project set the objectives for life extension investigations:

- The possibility to re-weld (repair, remove) a fatigue crack should be studied, with the aim to investigate which crack sizes that are possible to remove by re-welding with a TIG-treatment directed more into the base material, i.e. along the crack depth direction instead of the classic treatment direction towards the weld toe and lower part of the weld. Focus would be within the manual TIG-welding (treatment outdoors on a bridge should be possible).
- Suitable NDT methods for identification and quantification of actual fatigue damage should be evaluated.
- The possibility for HFMI techniques to restore the fatigue life of a fatigue damaged welded detail should be investigated for different levels of "pre-fatigue" before applying the HFMI treatment, and the additional fatigue life gained should be investigated.
- A fatigue damage model should be developed that incorporates repair techniques.
- A method should be developed for judgement of suitability for LifeExt treatments, and selection of suitable techniques.

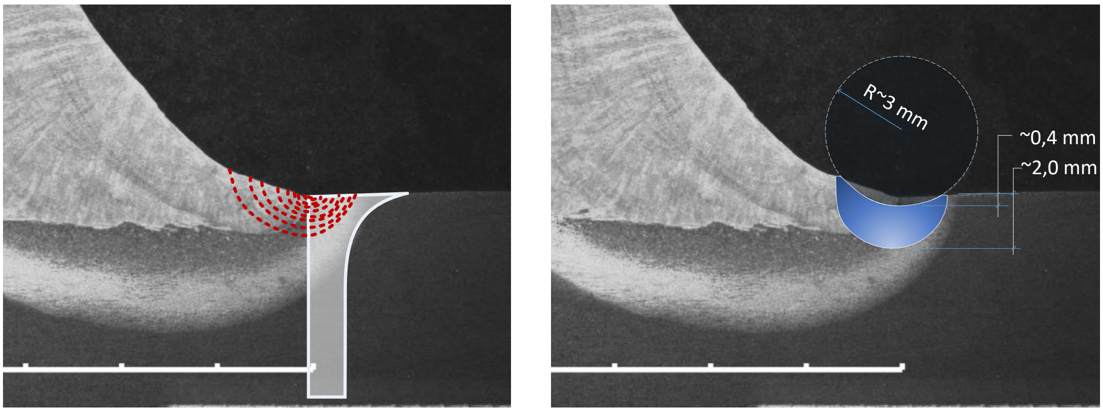


Figure 5. Illustration of the fatigue damage accumulated locally at the weld toe.

5 Experimental and Results

5.1 Selection of specimens and treatment methods

For verification of LifeExt methods, three different test specimen geometries have been selected. These are:

1. Rat-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.

Figure 6 shows these three details in a bridge girder, and the corresponding three types of specimens.

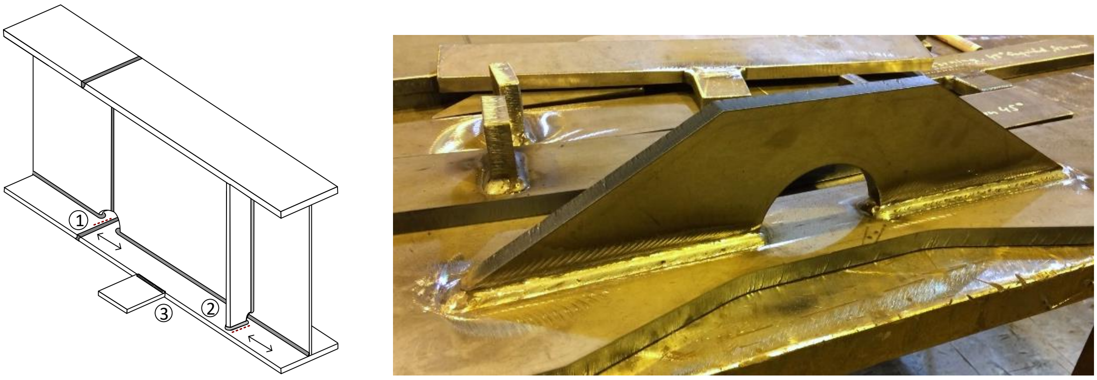


Figure 6. Left: critical details in a bridge; Right: corresponding test specimens.

Life extension methods

The hypothesis that forms the basis for the project is that fatigue damage is accumulated locally in a limited material volume the weld toe. Thus, methods that can treat the material locally at critical areas to enhance the fatigue strength are of interest. Two methods were identified to have the largest potential to fulfil the goals of the project: TIG-dressing (or re-melting) and HFMI-treatment (High Frequency Mechanical Impact). Therefore, most investigations in the project were made with these treatments (although, some investigations were made with other methods: cut-outs and grinding). HFMI was used for treatment of detail 1 (rat-hole). For detail 2, three different alternatives are investigated, HFMI, TIG and a combination of both methods. Detail type 3 (gusset plate) was treated first by cut-outs and grinding followed by HFMI-treatment.

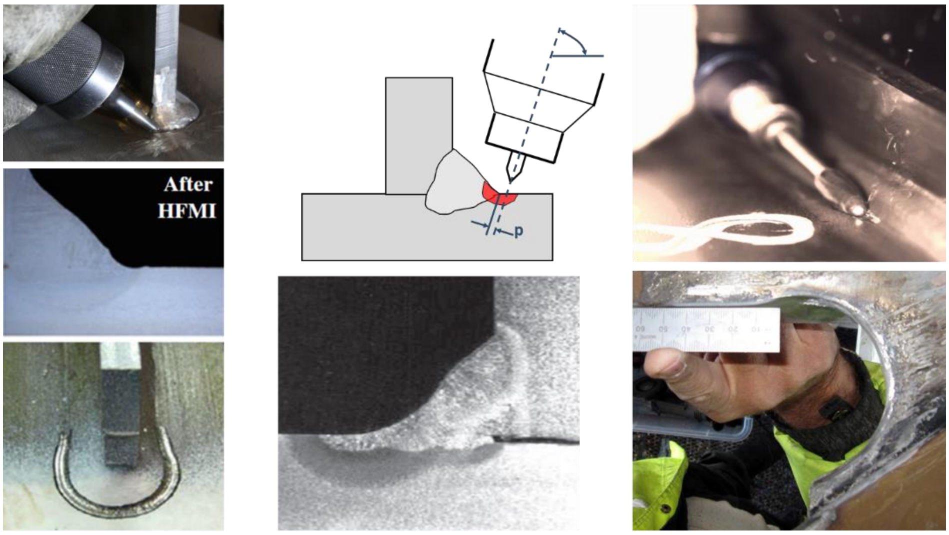


Figure 7. Methods for fatigue life extension used in the LifeExt project.

Analysis of fatigue from traffic loads

It is well-known from previous research on post-weld treatment techniques, that the performance of the treatments is highly dependent on the characteristics of loads to which the treated details are subjected. Therefore, one of the Tasks specified in the project was to study real load effects that can be expected in bridges treated with the methods studied in the project.

The work in this task involved the collection of existing data from several measurements of traffic loads on Swedish roads and analyzing the expected load effects (stresses) in various types of girder bridges using Monte Carlo simulations.

Analysis of the collected data which comprised 55,000 vehicles shows that there is a considerable portion of heavy vehicles that exceed the load models specified in Eurocode and used in the design of steel bridges. These overloads have in principle no major influence on the design of new bridges but can be determinantal for bridges that are treated with HFMI. However, analysis of four case-study bridges (see Figure 8) shows that the stresses generated in existing bridges due to these overloads are still well below the yield stress in local details so that the risk of reducing the efficiency of treatment methods is negligible. The investigation conducted in this task and a detailed description of analysis and results will soon be published in: “Assessment of in-service stresses in steel bridges for high frequency mechanical impact applications, Poja Shams-Hakimi, Fredrik Carlsson, Mohammad Al-Emrani”.

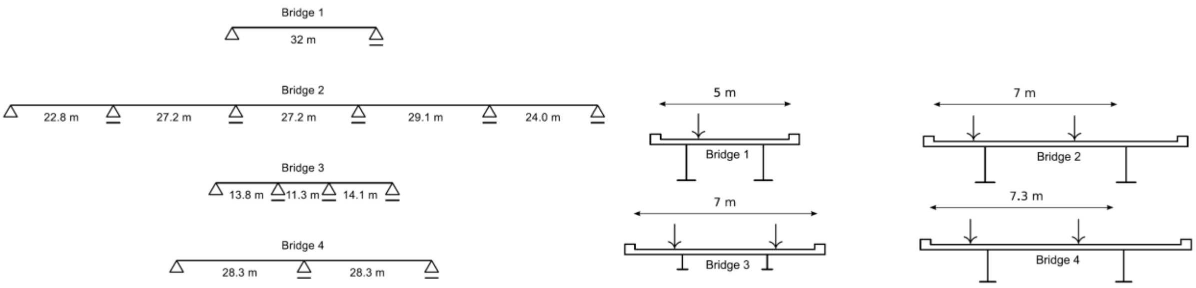


Figure 8. The four case-study bridges.

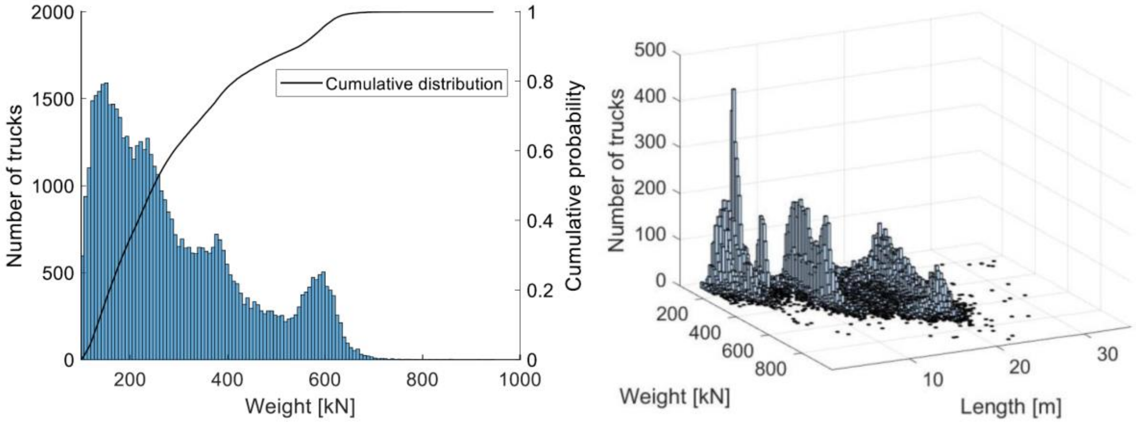


Figure 9. Distribution of vehicle weight from collected traffic measurements in the study.

5.2 Fatigue testing / Description of the experimental program

The principle for the verification by testing used in LifeExt experimental work is shown in Figure 10.

In a first phase, each test specimen is fatigued either until a fatigue crack has initiated or to a percentage of the characteristic fatigue life of the specimen type as obtained by testing on as-welded details. Afterwards, post-weld treatment is applied to the weld toe and fatigue testing is resumed in phase 2 until failure. Comparisons are made with achieved fatigue life for as-welded specimens and the life enhancement can be judged.

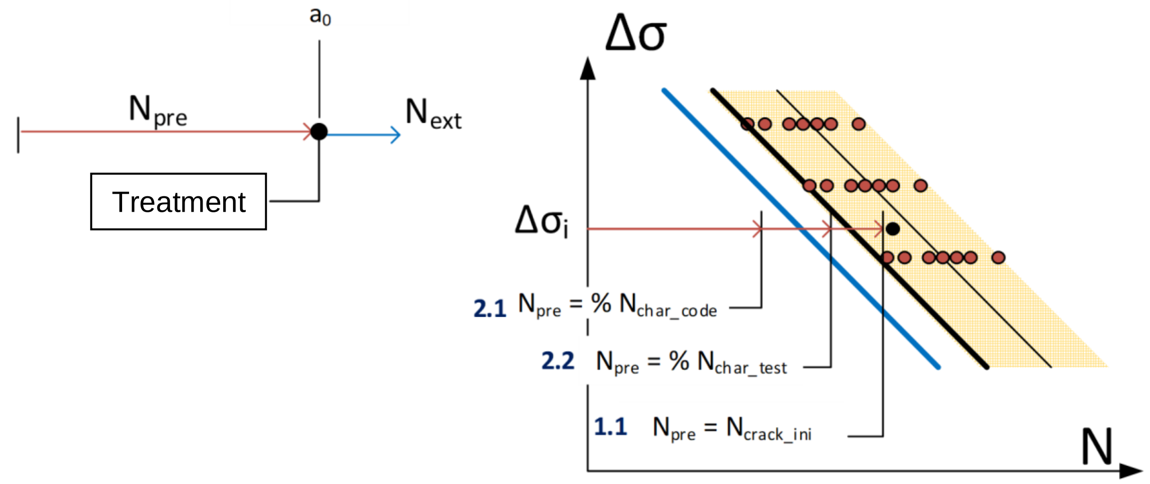


Figure 10. Sequence of pre-fatigue, treatment, and final fatigue.

To detect crack initiation a set of strain gauges is added to each specimen, see Figure 11. The drop in strain is used as a parameter that indicates crack initiation. Fracture mechanics models were used to find a relation between the amount of strain drop and the depth of the crack. In addition, TOFDT was used to verify this relation (see section 5.3). To arrive at a solid and robust correlation, some test specimens were fatigued to various expected crack depth and then sectioned in various ways to verify the dimensions of the real crack. Figure 12 shows two examples of such tests.

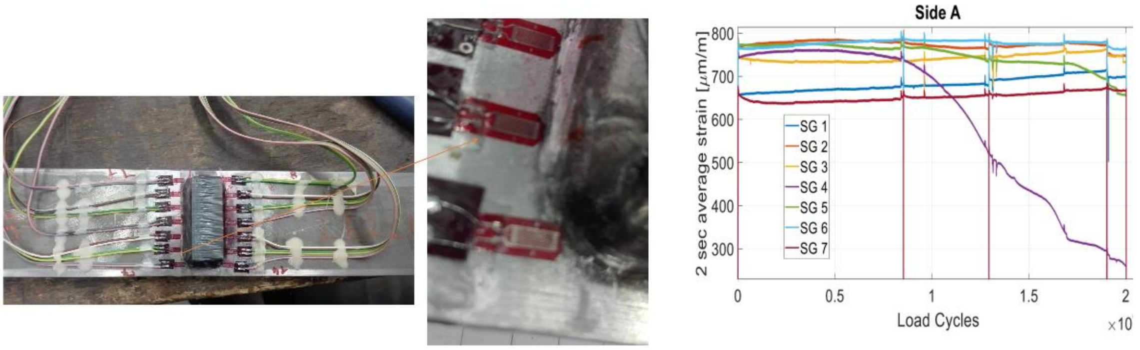


Figure 11: Positioning of strain gauges in specimens type 2 and example of strain drop due to crack initiation and propagation.

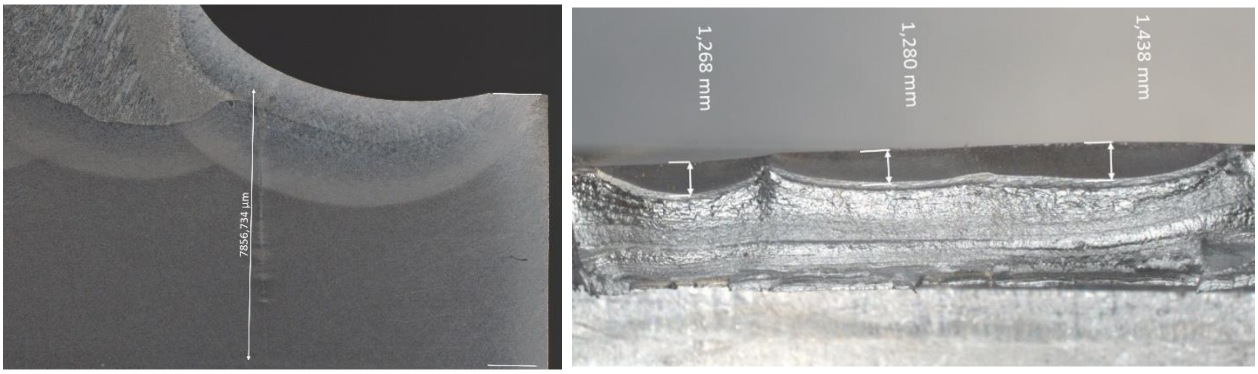


Figure 12: Examples from sectioning and microscopic investigations to verify crack dimensions.

In addition to fatigue testing, comprehensive measurements of residual stresses in Type 2 specimens with and without treatment were conducted. These measurements provided very valuable insight into the effect of various treatment methods on the state of residual stresses and were further used in the development of models for estimating the damage accumulation in these specimens. Figure 13 shows a summary of measured residual stresses in various states of specimen Type 2.

To obtain a detailed view of the effect of various treatment techniques on the local material properties in the welded region, micro-hardness measurements were also conducted. The results are shown in Figure 14. The results clearly show that TIG increases the hardness (and thus the strength and the resistance to fatigue) locally at the weld toe. A greater increase is obtained by HFMI and the best effect on hardness is obtained by a combination of TIG followed by HFMI.

Further, detailed microscopic investigations are performed to study the effect of HFMI-treatment on the existing fatigue crack, see Figure 15. This information is used later in the development of the fracture mechanics models which are used to estimate the effects of HFMI-treatment.

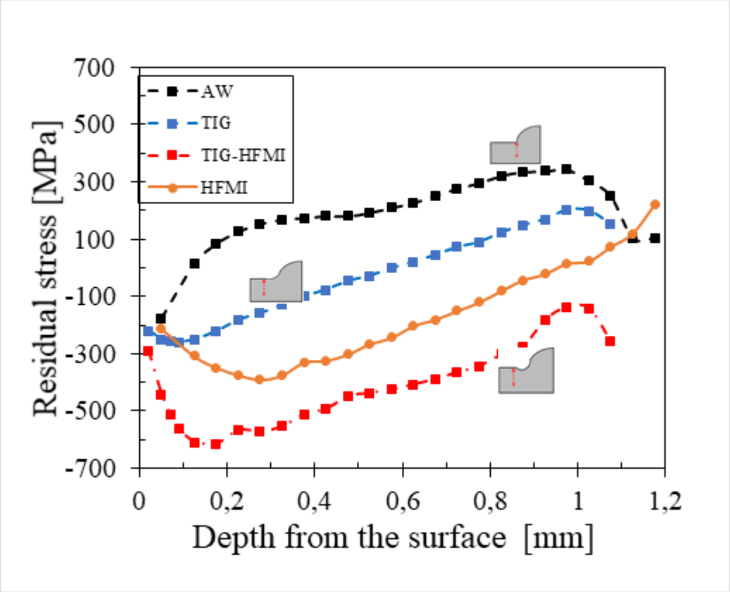


Figure 13: Examples of the results of residual stress measurements in untreated and treated joints.

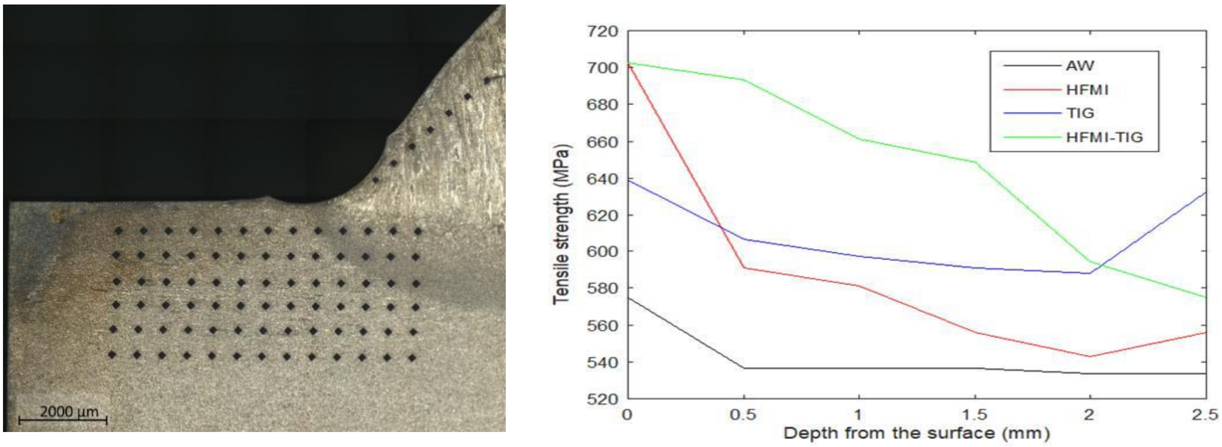


Figure 14: Micro-hardness tests and results.

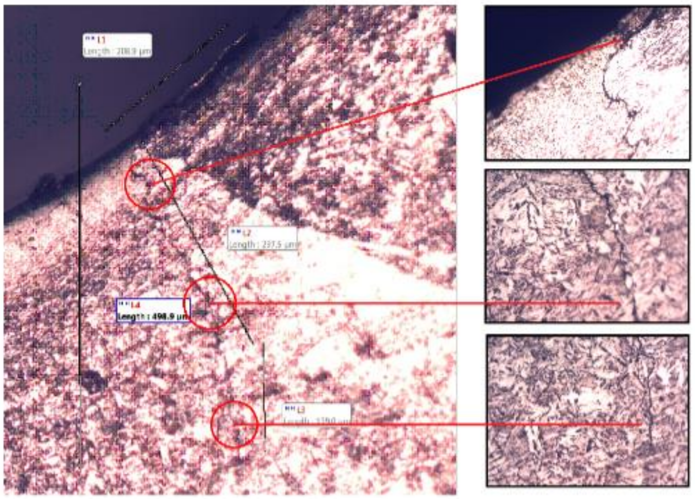


Figure 15. Microscopic investigations to study the effect of HFMI-treatment on existing fatigue crack.

Evaluation of fatigue test results

The results from fatigue testing were evaluated in different ways, i.e. with different fatigue life determinations (e.g. based on characteristic fatigue life, mean fatigue life, etc.).

Here an evaluation based on the degree of enhancement for each specimen expressed as a ratio to the degree of enhancement expected for a totally new (un-fatigued) equivalent detail is presented. This ratio is expressed as:

$$\frac{\rho}{\rho_{new}}$$

Where

$\frac{N_{ext}}{N_{pre}}$ is the ratio of extension of fatigue life obtained from phase 2 divided by the fatigue life to crack initiation obtained from phase 1.

And

$\rho_{new} = \left[\frac{N_{\boldsymbol{treated}}}{N_{AW}}\right]_{new}$ is the ratio between the fatigue life of a new treated detail to that of the same detail in as-welded condition

A ratio $\frac{\rho}{\rho_{new}} \geq 1.0$ means that the treatment results in a life extension equivalent to the fatigue life of a new treated detail.

Figure 16 shows the results obtained for Type 1 specimens. Other results collected from previous studies are also shown. A clear conclusion is that a full extension of fatigue life can be obtained for details that are pre-fatigued even in the presence of cracks up to 1,5 mm deep.

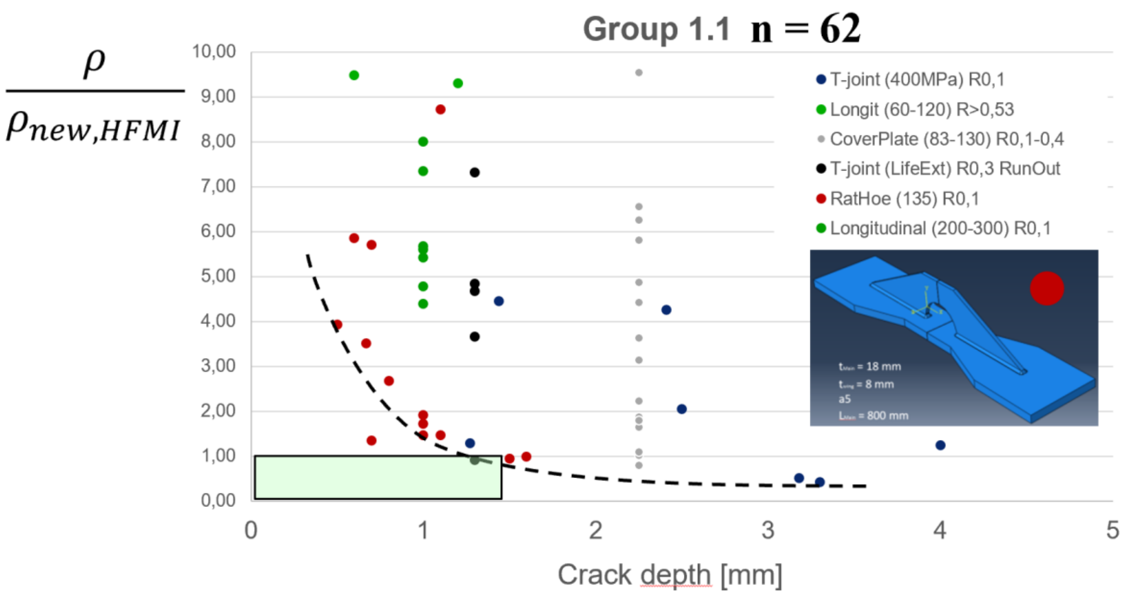


Figure 16. Life extension results obtained for Type 1 specimens. Other results collected from previous studies are also shown.

Specimens Type 2 were prefatigued to cracks of 0,6-1,3 mm deep. None of these specimens failed in the weld in phase 2 testing. They either run-out after 10-30 million cycles or failed in the area where the specimens were gripped by the testing machine. These results clearly show the efficiency of HFMI treatment used both in Type 1 & 2 specimens.

The results from TIG treatment of Type 2 specimens are shown in Figure 17. In all specimens, TIG was performed with a penetration depth larger than the depth of existing cracks. In other words, the crack was totally removed by the re-melting process. The fatigue results are plotted along with test data obtained from the literature on similar TIG-treated details but without prefatigued, i.e. new treated specimens. The results clearly show that TIG-treatment of Type 2 specimens after phase 1 testing gave fatigue strength equivalent to that observed in new specimens.

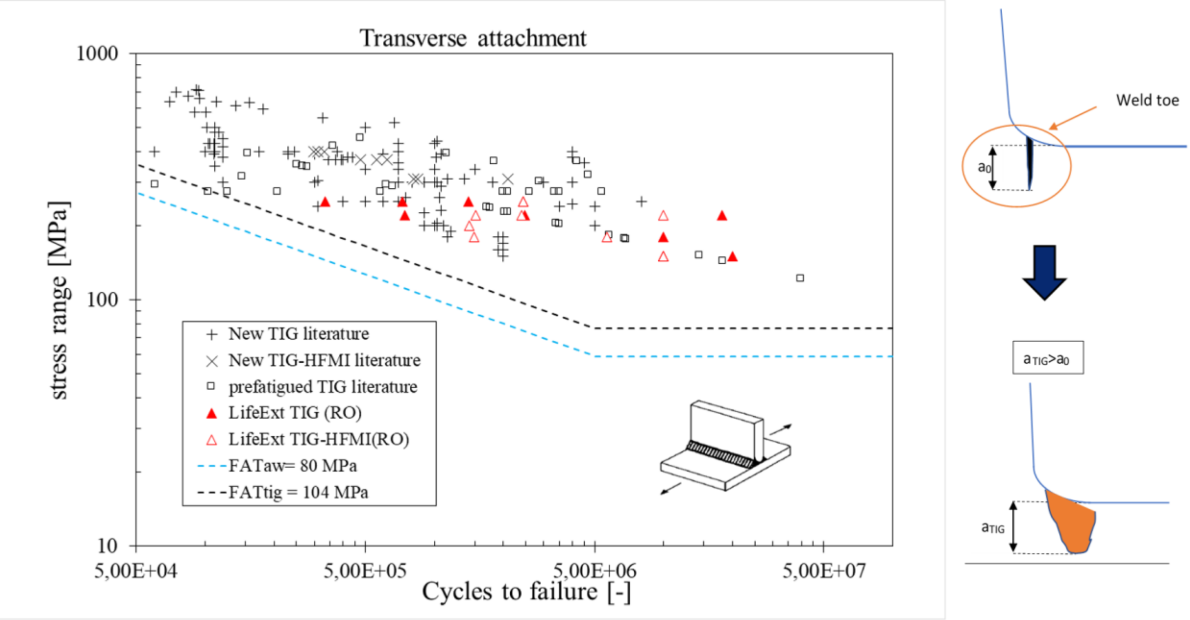


Figure 17. Life extension results obtained for Type 2 specimens. Other results from previous studies are also shown.

Another way of expressing the results for TIG-treated specimens is presented in Figure 18. Here, the ρ-ratio is plotted against the remaining crack after treatment. For LifeExt specimens, the remaining crack depth is zero and all tests are located well above the ratio 1,0. Test results from previous studies on various specimen types with remaining cracks are also included here. It is apparent that TIG produced excellent results even when cracks of up to 2 mm remain after treatment. This demonstrate the robustness of the method and give a “margin of error” for possible missing some of the entire crack depth.

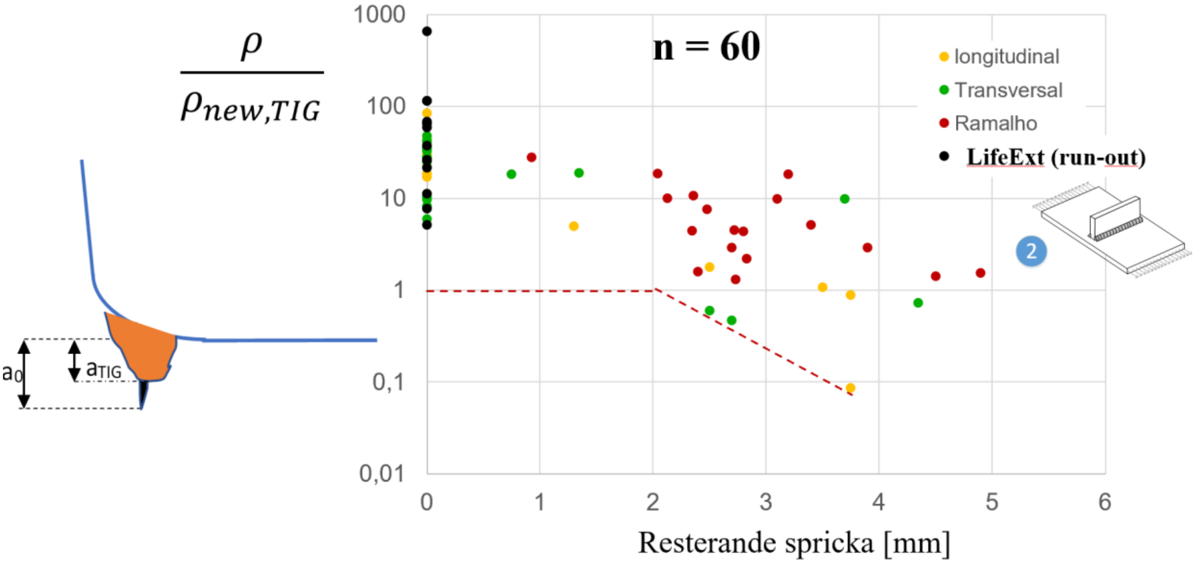


Figure 18. ρ-ratio plotted against the remaining crack after TIG-treatment.

5.3 Development of NDT method and identification of fatigue crack

There are many NDT methods available for reporting (indicating) surface breaking cracks. Typical field methods are used to indicate a surface crack are Magnetic particle Testing (MT), Penetrant Testing (PT) and Eddie current Testing (ET). The main drawback with these techniques is that only the width of the crack is identified (characterized) and no information on the crack depth is reported. With aid of calculations there is a possibility to tie a crack length to a crack depth. However, these approaches rely on single cracks and not multiple crack front growing into each other. Another field method is manually operated Ultrasonic Testing (UT), which was not part of the evaluated methods in this project. However, mechanised UT and UT TOFD (Time Of Flight Diffraction) was used to evaluate the possibility to identify crack depths. The tests showed that it was possible to detect anomalies in the material with mechanised UT, see Figure 19, although the approach is difficult to use for crack depth estimation.

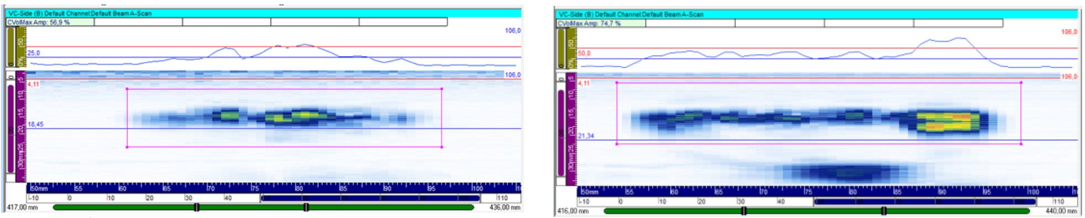
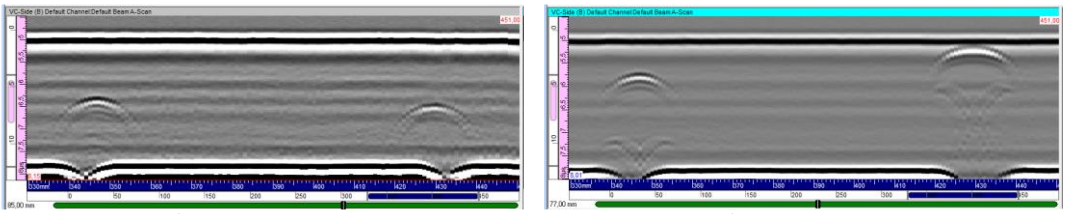


Image of mechanised UT at approximately 75% of characteristic life, test specimen 9, side 2

Image of mechanised UT at approximately 90% of characteristic life, test specimen 8, side 2

Figure 19. Fatigue damage identified with mechanised UT.

Further tests were performed using mechanised UT TOFD, an approach used in e.g. nuclear power plants as NDT method for crack depth estimation. See Figure 20.



Example image of mechanised TOFD at approximately 75% of characteristic life, test specimen 9, side 1 and side 2. Estimated height 6.0mm and 5.2mm respectively.

Example image of mechanised TOFD at approximately 90% of characteristic life, test specimen 8, side 1 and side 2. Estimated height 8.3mm and 12.0mm respectively.

Figure 20. Fatigue damage quantified with UT-TOFD.

UT-TOFD proved to be a powerful tool in aiding with the estimation of crack depth and was further developed within the project.

Ultrasonic TOFD probe

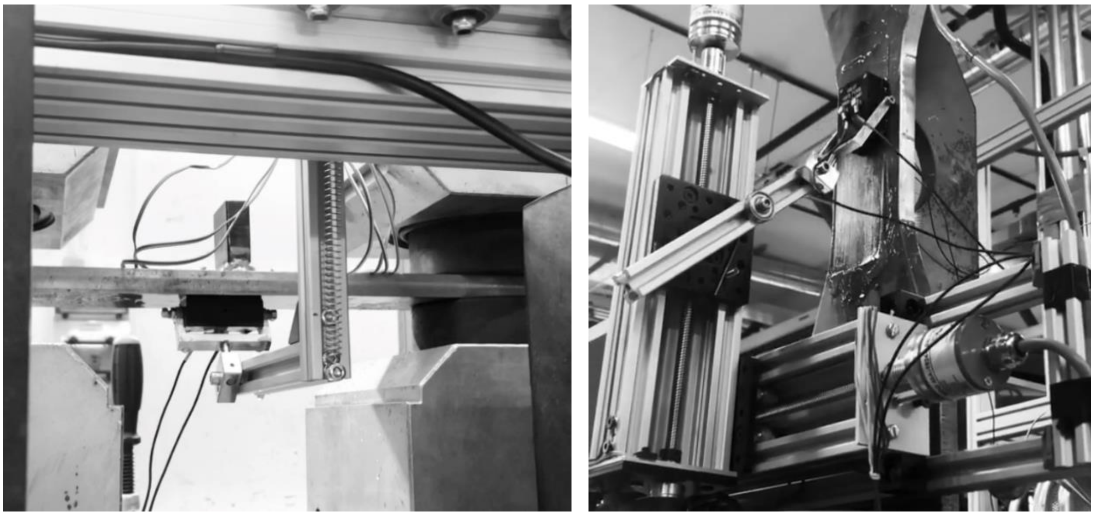
TOFD detects cracks using the signals diffracted from the flaw’s extremities (tips). Two angled compression wave probes (typically between 2 to 10MHz frequency) are used in transmit-receive mode, one probe each side of the weld. The beam divergence is such that the majority of the thickness is inspected, although, for thicker components, more than one probe separation may be required.

Based on results from preliminary testing according to MPR 18-35 an ultrasonic TOFD probe with PCS 35mm wedge angle at 50deg at 5MHz frequency was chosen. Focal depth of the TOFD probe is 14,7mm. This probe was chosen over a standard probe focal depth where the focal depth is 2/3 of the material thickness, i.e. 10,7mm. The strategy to deviate from the common probe focal depth choice was aiming on detecting as small surface cracks as possible. It is noted that for measuring the deeper cracks there was a need for another ultrasonic probe (TOFD PCS 20).

Manipulator

Storing the data collected with the UT TOFD system, a high-resolution positioning feedback system must be used to locate the position of the signal/data when performing scans. These systems are called manipulators and come in different sizes and shapes; however, manipulators are commonly developed per NDT situation/task.

In order to collect data within this project, two different manipulators were developed to enable precise positioning and documentation the scanned data. See Figure 21.



Manipulator developed for test specimen type 2, non-load carrying transverse gusset plate

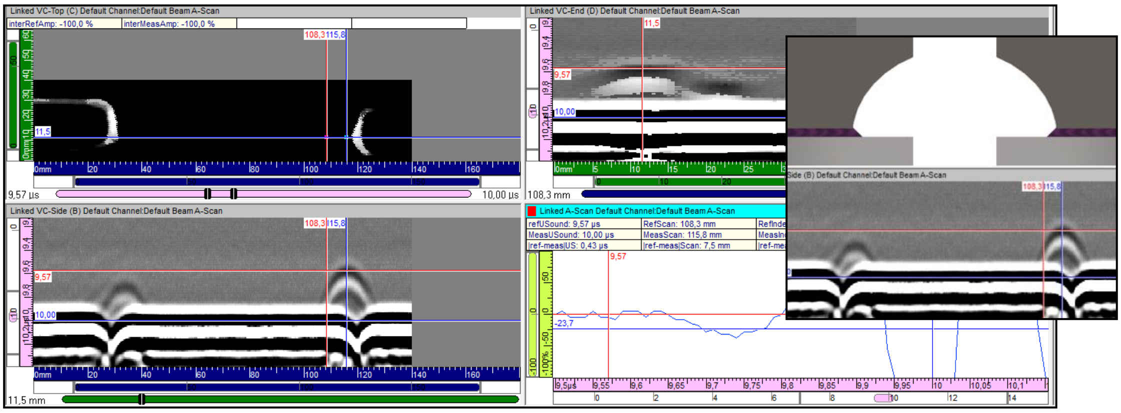
Manipulator developed for test specimen type 1, "rat hole" specimen

Figure 21. Manipulators developed for UT-TOFD.

Scan interpretation and resolution

TOFD scanning involve two ultrasonic probes generating beams in opposite directions: one for transmission and one for reception. This technique allows the sizing of flaws, such as cracks, based on the diffraction echoes due to theirs edges. Many signals are received: lateral wave, top and bottom edges diffraction echoes and geometry echoes (ex: backwall echo).

For mechanised TOFD multiple signals arrays (time – amplitude) are stored in the scanning software and visualized making it possible to estimate crack heights/depths. The depths of the cracks are calculated based on the differences between backwall echo (horizontal black and white stripes) and the crack tip echo. The visualisation software is shown in Figure 22.

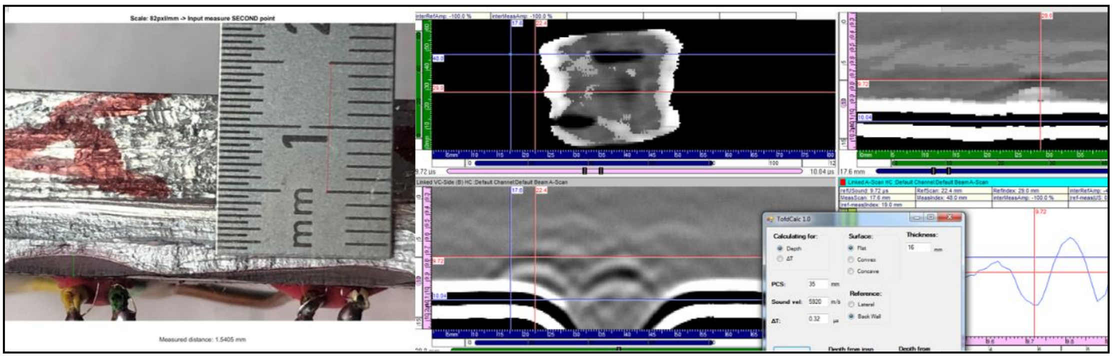


interRefAmp: -100,0 %
interMeasAmp: -100,0 %
refUSound: 9,57 µs
RefScan: 108,3 mm
MeasUSound: 10,00 µs
MeasScan: 115,8 mm
|ref-meas|US: 0,43 µs
|ref-meas|Scan: 7,5 mm

Scanning and visualisation software – two cracks appear in the image, with the shape af an arc. Back wall echo is looking likte horizontal black and white stripes. The positions where the backwall pattern tend to bend downwards in the bottom left pane, are beginning and the end of the fillet welds.

Figure 22. visualisation software for UT-TOFD.

When TOFD is used within accredited inspection and NDT there are multiple error sources to consider when giving a size estimation on a crack indication. Typically, the estimated error for a crack size projection is approximately ±1mm. Within this project many of the contributing error sources could be minimized and in conjunction with an uncomplex geometry the final estimated error was approximately ±0.2mm. A tool for crack depth visualisation and estimation was developed to verify the estimated error. All the verified crack size estimations were within the given error margin of ±0.2mm. It is noted that all the estimations were conservative, i.e. the crack size estimation based on TOFD were all less than the actual crack.



TofdCalc 1.0

Calculating for:
● Depth
○ ΔT

Surface:
● Flat
○ Convex
○ Concave

Thickness: 16 mm

PCS: 35 mm

Sound vel: 5920 m/s

ΔT: 0.32 µs

Reference:
○ Lateral
● Back Wall

Verifiaction of estimated crack size based on TOFD for specimen type 2. In the scan image (bottom middle) an arc is visualized in the middle indicating a void within the weld.

Figure 23. Illustration of verification work for UT-TOFD.

Scans performed on specimens after post weld treatment (PWT) with HFMI contained detailed information, indicating the possibility for TOFD to also be used as a quality assurance tool for PWT methods. This insight was very interesting but due to resources available, it was not possible to further investigate this area within the project.

The TOFD method was used to estimate crack depth on prefatigued specimen before PWT methods were applied. Within the testing of test specimen of type 1, “Rat-hole specimen”, TOFD was used to stop the testing at a certain crack depth during fatigue testing before applying HFMI, making it possible to test the effect of HFMI on prefatigued test specimen with a well-defined crack size.

UT TOFD can be implemented for crack size characterisation in laboratory environment with good results in terms of relatively low error (±0.2mm). However, there are possibilities to find cracks closer to surface than within this project, with a minimum crack depth down to 0.5-0.7mm, because of the backwall echo. The effect of the backwall echo can be reduced using a probe with a higher frequency. A 10MHz probe instead of a 5MHz could possibly detect cracks less than 0.5mm and down to 0.3mm. It is also noted that an automized process for evaluating the produced scans is preferable to reduce scatter in the crack characterisation process. Finally, there would be time and resource savings in development of a semiautomated system for data collection, i.e. perform scans without having NDT operators on site. A development in this direction could give valuable information on crack growth rate and insight in the specimen (detail) behaviour.

5.4 Damage models

Proposed model

The proposed model is applicable to deterministic approaches that involve the use of design values (mean values) of the input parameters (from the pre-fatigued and treatment phases). The framework is divided into three blocks: block A, block B and block C.

- Block A: Assessment and evaluation of the pre-fatigued state of the structure

The aim of this block is to more accurately assess the state of the pre-fatigued welded steel structure by providing damage models and theories of fracture mechanics.

- Block A.1. Data collection

Data collection is the most important step in this framework. Documents that detail the design phase, in-service phase and current state of the structure (which is to be treated) are needed to assess the structure.

- Block A.2. Selection of the fatigue assessment approach

The collected data should be analyzed to quantify the degree of structural degradation, such as the crack depth and the amount of accumulated fatigue damage. Two cases are discussed: the first case involves cracked pre-fatigued structures, and the second case involves uncracked structures with accumulated microscopic damage due to fatigue. The selection of the suitable fatigue assessment approach is crucial to the assessment process; therefore, two distinct fatigue assessments are selected to address each case according to the IIW recommendation [7] and Eurocode [11].

a. Damage tolerance approach [1,7, 16]

This approach is applicable to cases in which the pre-fatigued structures contain cracks.

b. Safe life approach- S-N method [1,7, 16]

The safe life approach is selected for pre-fatigued structures that do not show any cracks to predict the crack initiation life. [14]

- Block B: treatment analysis and estimation of the extended fatigue life

The state of the repaired pre-fatigued structures depends on the state of the pre-fatigued structure before repair and on the treatment itself. In one case, the treatment re-melts the damaged area, completely removes the weld defects and the cracks (if they exist), leading to structure without cracks. While in the second case, the treatment does not completely remove the cracks and there remain subsurface cracks in the structure after treatment.

Damage distribution

The damage distribution in the prefatigued phase is strongly dependent on the weld residual stress distribution. The location of crack initiation depends on the damage distribution which could be surface or subsurface initiation

For different possible weld residual stress, the damage distribution at the weld toe through the thickness direction (for type 2 specimens) is presented in Figure 24. Here can also the number of cycles to detect crack initiation be found.

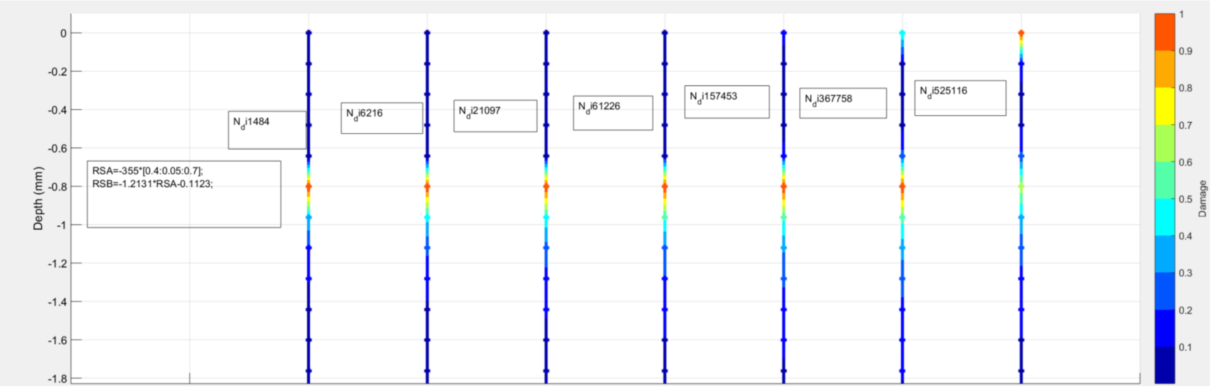


Figure 24: Damage distribution at the weld toe through the thickness direction for the pre-fatigued phase for different possible weld residual stresses.

Treating the pre-fatigued structures and independent of the RSTIG (compressive or tensile), surface crack initiation is detected even if there is remaining subsurface damage (The crack initiation after TIG treatment is not governed by the remaining damage). See Figure 25.

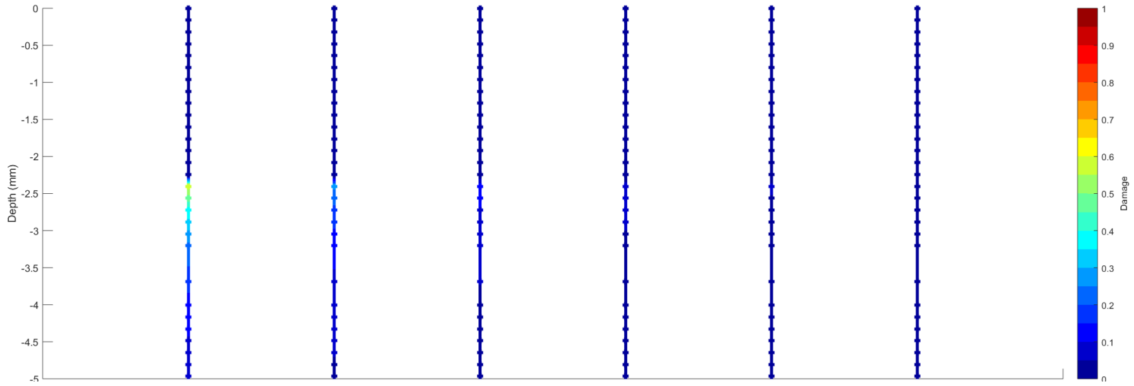


Figure 25: Subsurface remaining damage after TIG treatment.

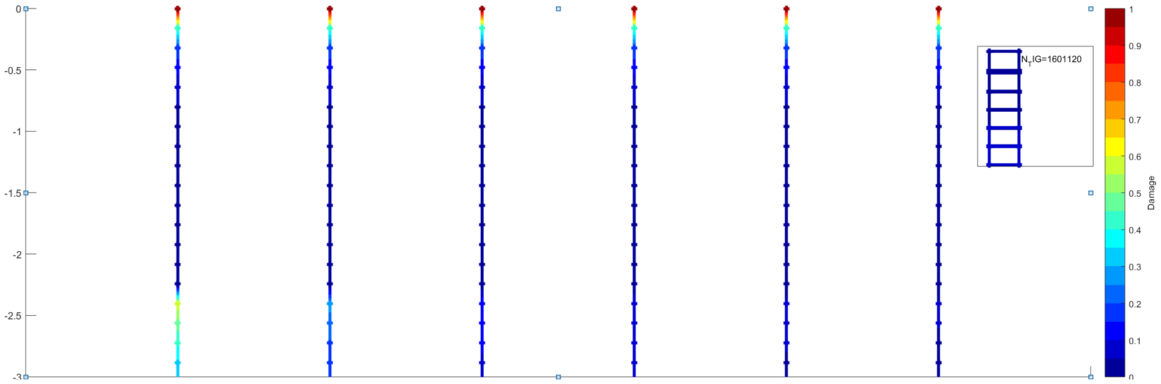


Figure 26: Surface cracks of the prefatigued and treated structures.

Model verification

Figure 27 shows a comparison between the experimental [21] and the predicted extended fatigue lives, for transversal and longitudinal attachments, respectively. The predicted extended fatigue life is within the error band of 25% of the experimental extended fatigue life. Hence, it can easily be concluded that TIG dressing introduced tensile residual stress at the weld toe which is close to the used shape in [22]. The extended fatigue life of cracked structures (after treatment) is low compared to the extended fatigue life of non-cracked structure after treatment.

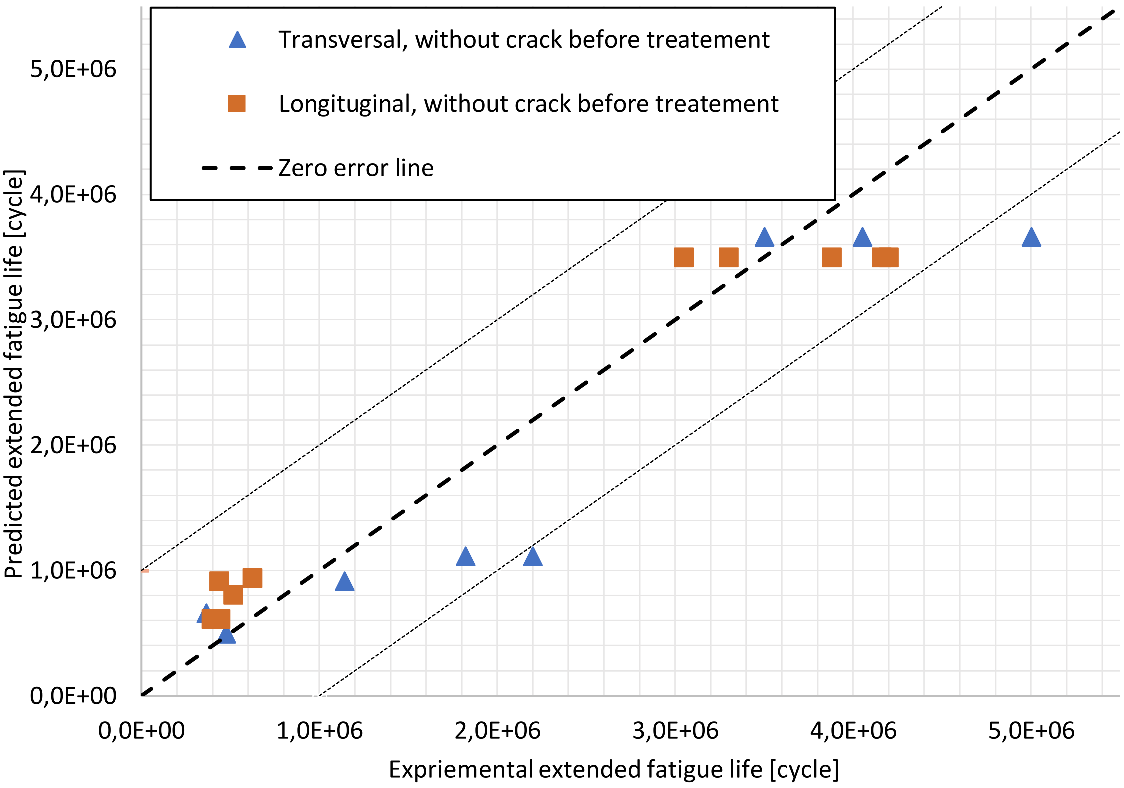


Figure 27: Comparison between experimental and predicted extension in fatigue life for transversal and longitudinal attachments.

The fatigue life of TIG dressed specimens is higher than the fatigue life of the as-welded specimens regardless if the TIG dressing is able to completely remove the crack or not. The highest improvement in the fatigue life is detected when TIG treatment succeeded to completely remove the crack. Thus, the extended fatigue life includes the crack initiation period of the treated structure. It is worth mentioning that all the specimens failed at the welded toe. This leads to the conclusion that fatigue lives are strongly influenced by the state of the weld toe after treatment. As already mentioned, all the TIG parameters were provided in this case study, except for the TIG residual stress which was found by the shape in [22].

6 Conclusions

Summary of the findings from the experimental program

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-treatments reach the best improvement results on fatigue loaded welded details when no fatigue cracks are initiated, or when existing fatigue cracks are shallower than 1,5 mm through plate thickness.
3. TIG-treatment can be used to restore the initial fatigue strength of welded details if the treatment can be performed with a penetration depth larger than the depth of any existing crack. A combination of TIG-treatment followed by HFMI-treatment gives larger fatigue life extension, equivalent to that obtained for new HFMI-treated details.

4. An interesting NDT method has been identified and adapted to the needs in the project 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 judgement

Recommendations

Based on the extensive experimental and theoretical work performed in LifeExt, a formulation of recommendations for the use of LifeExt-project results is illustrated in a flowchart form in Figure 29. The methods developed in LifeExt are of highest relevance and usefulness in two situations:

1. Conventional assessment of the residual fatigue life of a bridge shows that theoretical life span of the bridge is reached or already passed.
2. The expected design fatigue life cannot be reached due to change in traffic load conditions, such as increased allowable vehicle load or traffic intensity.

In both cases, a need to extend the remaining fatigue life of the bridge is identified.

Another outcome of such analysis is the damage accumulation in fatigue-critical details in the bridge. Dependent on the "damage distribution" in various details, and the target life extension required, fatigue-critical details, the fatigue life of which need to be extended are identified. It is worth keeping in mind here that even details with fatigue damage factor < 1.0 may need to be enhanced to ensure the required life extension of the entire bridge.

Examination of the applicability of the methods developed in LifeExt follows the above-mentioned conventional analysis.

In a first step, Critical details are inspected with suitable NDT technique to verify whether the fatigue process in these details has gone so far that fatigue cracks are initiated. The NDT methods in this stage should be capable of detecting surface cracks with good probability of detection.

Two cases can then be met:

1. No surface cracks are present in the inspected details. In such case, HFMI is suggested as a method of treatment. An extension in fatigue life equivalent to that obtained for similar new details treated with HFMI can be assumed in calculation of the remaining fatigue life of the bridge.
2. If surface cracks are detected, an NDT method that is capable of registering the depth of cracks with good reliability should be used to specify crack depths. If the cracks are shallow and if TIG-remitting can be conducted with a penetration depth that guarantees a full fusion of the cracks, then TIG-dressing can be used to restore the fatigue life of the detail. To obtain a higher life extension with more reliable results, TIG-treatment cab be followed by HFMI-treatment of the repaired details. In such case, an extension in fatigue life equivalent to that obtained for similar new details treated with HFMI can be assumed in calculation of the remaining fatigue life of the bridge.

Notes:

1) Details that contain cracks with substantial depth cannot be restored with the methods developed in LifeExt. As a general statement, cracks that have propagated > 2 mm through plate thickness are in this category.
2) Even though, this technique has not been investigated in LifeExt, previous studies and experience from repair of fatigue damaged bridge details show that grinding can be used to remove the material volume containing cracks, followed by HFMI-treatment.
3) Detailed guidelines and recommendations for the application of TIG- and HFMI-treatment for life extension purposes lie outside the scope of LifeExt. This applies as well to workmanship and quality assurance. These topics need further studies and are proposed for future continuation of the LifeExt project. However, both HFMI- and TIG-treatment of new (not fatigued) welded details are well covered in the IIW guidelines and these should be consulted when the methods are used for life extension of existing bridges.

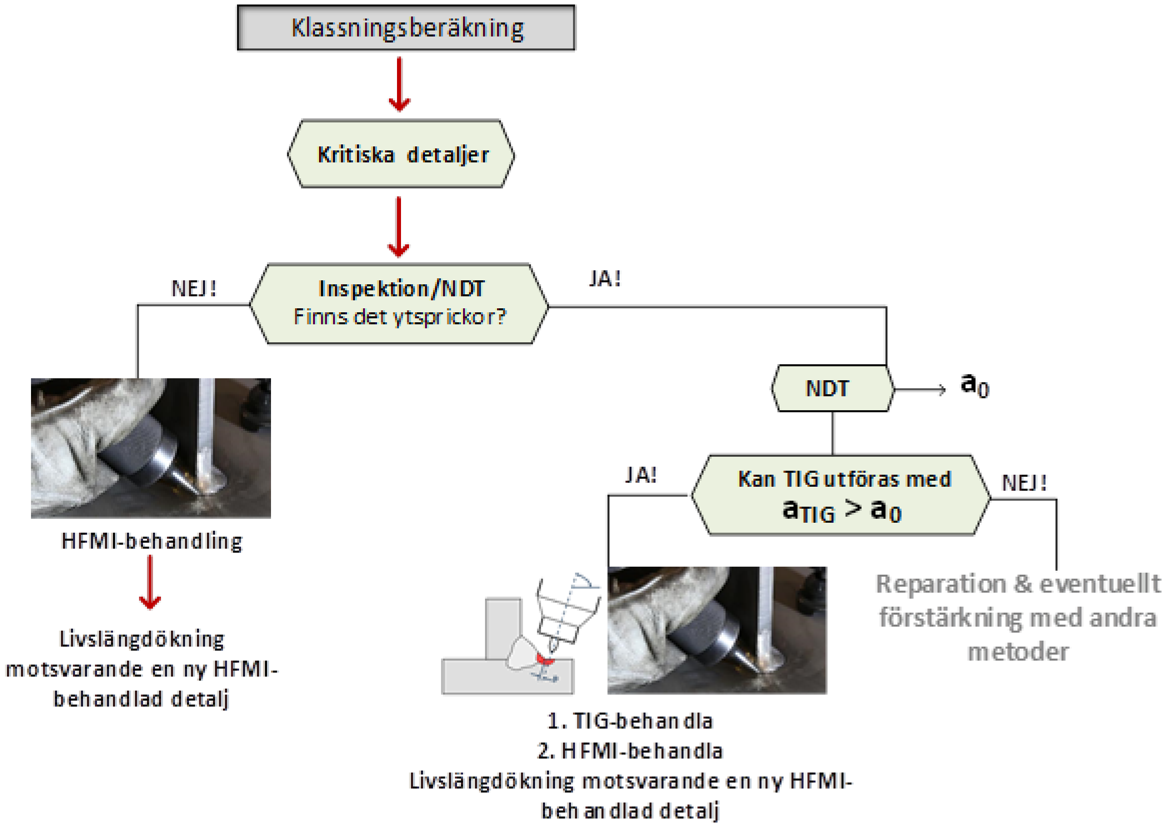


Figure 29. Recommendations for the use of LifeExt-project results illustrated as a flowchart.

7 Continued work

LifeEXT 2 – need for further studies

The work in LifeExt 1 has demonstrated the powerfulness of LifeExt techniques to extend the fatigue life of existing bridges, beyond the best expectations of the project team at the start of the project. The project results are founded on extensive experimental verification and analytical modelling that both gave a detailed and valuable insight as to the mechanisms that govern the fatigue life extension obtained for the studied methods. However, for the full potential of the project results to be utilized in practice, a number of technical questions need to be studied in more detail. These have been identified by the project team as follows:

1. LifeExt has demonstrated the excellent capability of TOFD to detect and characterize very short and shallow cracks (crack depth of ca 0,8 mm). This has been done in laboratory environment. The promising potential of this method should be investigated and verified in “real environment”, i.e. under real conditions in a bridge.
2. As the recommendations from LifeExt are attached to requirements related to crack detection, the reliability of NDT methods usually used in inspection of bridges (dye penetrant, magnetic particles, X-ray, UT) need to be established. This topic has been studied extensively before, but as NDT methods are in continuous development, the *current* state of the art needs to be established.
3. To the same end, there is a need to establish a robust connection between the results obtained in LifeExt (in term of life extension and requirements on fatigued details in bridges) and various relevant uncertainties regarding quality of treatment, probability of crack detection, material and weld qualities, to mention few. These uncertainties should be evaluated in a

probabilistic way to arrive at reliability levels that are comparable or equivalent to those specified for bridges, for example in EN 1990.

4. Finally, there is a need for clear and detailed description for the proposed LifeExt methods with reference to workmanship and quality assurance of treatment. This is another important field that needs to be addressed in future work.

8 Publications and Dissemination

Following publications have been developed in the project:

Title	Main author	Co-authors	Journal/Conference	status
A probabilistic study of welding residual stress distribution and their contribution to the fatigue life	Asma Manai	Franz von Bock und Polach, Mohammad Al-Emrani	Journal	Submitted
A framework to assess and repair pre-fatigued welded steel structures by TIG dressing	Asma Manai		Journal	Accepted
Analysis of the treated pre-fatigued welded steel structures by TIG dressing (it might be changed)	Asma Manai		Journal	Almost Ready for submission
A literature review of pre-fatigued structures treated by TIG dressing	Asma Manai		Conference (IABMAS)	Accepted
A methodology for assessment and retrofitting by TIG dressing of existing pre-fatigued welded steel joints	Asma Manai	F. Von Bock und Polach, J. Hedegård	Conference (IABMAS)	Accepted
Influence of weld residual stress in the fatigue strength	Asma Manai		Conference (Euro Steel)	Submitted
Evaluation of HFMI as a Life Extension Technique for Welded Bridge Details	Martin Edgren	Z. Barsoum, K. Åkerlind, M. Al-Emrani	Conference (Fatigue and Design in Senlis, 2019)	Accepted

Dissemination events

Participation in International Institute of Welding Conference and Annual Assembly, 2018, Bali, Indonesia, presentation of progress in LifeExt project and early results.

Participation in International Institute of Welding Conference and Annual Assembly, 2019, Bratislava, Slovakia, presentation of progress in LifeExt project and early results.

Coming events:
March 26th: Open Seminar in Swerim: The projects LIFEEXT, HIPFAT, and SUNLIGHT: results presentations and discussions.

Nordic Conference on Welded Structures, Spring/Summer 2020 (date to be decided). LIFEEXT will present results.

ELMIA Production in May: LIFEEXT will present results.

9 Acknowledgements

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