Life extension, upgrade and repair of welded structures – Towards the use of High Strength Steels

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Welds have much lower strength than the base materials due to:

- **Stress concentration due to local weld shape and joint geometry**
- **Weld defects and flaw which leads to early crack propagation**
- **High tensile welding stresses**
Improving the Fatigue Strength of Welded Structures

**Increased Service Life**

**Good design practice**
- Minimize fatigue loads, e.g. by avoiding resonance & vibration
- Use low SCF joints
- Avoid corrosion
- Place welds in areas with low stress

**High quality fabrication**
- Good choice of plate and weld materials and process
- Good weld penetration, groove geometry
- Weld quality inspection w. correlation to fatigue life

**Improvement techniques**
- Applied during fabrication
- Post fabrication treatment

**Geometry modification techniques**
- Local stress peaks are reduced
- Lower SCF
- Surface quality is improved
- Tensile welding residual stresses are reduced

**Residual stress techniques**
- High local compressive residual stresses are introduced
- Material work hardening
- Phase changes in weld material gives compressive stresses
- Surface quality is improved
- Lower SCF
High Frequency Mechanical Impact - HFMI

Example of HFMI devices available worldwide

- ultrasonic impact treatment (UIT)
- ultrasonic peening (UP)
- ultrasonic peening treatment (UPT)
- ultrasonic needle peening (UNP)
- pneumatic impact treatment (PIT)
- high frequency impact treatment (HiFiT)
- Etc...
- > 90 Hz
High Frequency Mechanical Impact - HFMI

Example of HFMI indenter sizes and configurations

Typical weld toe profile in the as-welded condition and following HFMI treatment
# What Does the Current IIW Guidelines Say?

## Nominal stress: Existing IIW FAT classes

<table>
<thead>
<tr>
<th>$f_y$ (MPa)</th>
<th>Longitudinal welds</th>
<th>Transverse welds</th>
<th>Butt welds</th>
</tr>
</thead>
<tbody>
<tr>
<td>all $f_y$</td>
<td>71</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td>$f_y \leq 355$</td>
<td>90</td>
<td>100</td>
<td>112</td>
</tr>
<tr>
<td>$355 &lt; f_y$</td>
<td>100</td>
<td>112</td>
<td>125</td>
</tr>
</tbody>
</table>

1. **as-welded, $m = 3$**
2. **Improved by hammer or needle peening, $m = 3$**

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Some of Assumptions:

- The improvement method covered in these studies is applied to the **weld toe**
- All of fatigue design methods for HFMI improved welds are based on an assumed S-N slope of $m = 5$ and fatigue strength improvement factors are defined at $N = 2 \cdot 10^6$ cycles

![Graph showing stress range vs. cycles to failure with examples of joints suitable for improvement]
a design recommendation including one fatigue class increase in strength (about 12.5%) for every 200 MPa increase in static yield strength was proposed and shown to be conservative with respect to all available data.
**Proposed Fatigue Strength Improvement using HFMI**

**Nominal Stress**
Existing IIW FAT classes for as-welded and hammer or needle peened welded joints and the proposed FAT classes for HFMI treated joints as a function of $f_y$

<table>
<thead>
<tr>
<th>$f_y$ (MPa)</th>
<th>Longitudinal welds</th>
<th>Cruciform welds</th>
<th>Butt welds</th>
</tr>
</thead>
<tbody>
<tr>
<td>all $f_y$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>as-welded, $m = 3$</td>
<td></td>
<td></td>
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<td>355 &lt; $f_y$</td>
<td>100</td>
<td>112</td>
<td>125</td>
</tr>
<tr>
<td>improved by hammer or needle peening, $m = 3$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>235 &lt; $f_y \leq 355$</td>
<td>112</td>
<td>125*</td>
<td>140*</td>
</tr>
<tr>
<td>355 &lt; $f_y \leq 550$</td>
<td>125</td>
<td>140</td>
<td>160</td>
</tr>
<tr>
<td>550 &lt; $f_y \leq 750$</td>
<td>140</td>
<td>160</td>
<td>180</td>
</tr>
<tr>
<td>750 &lt; $f_y \leq 950$</td>
<td>160</td>
<td>180*</td>
<td>-</td>
</tr>
<tr>
<td>950 &lt; $f_y$</td>
<td>180</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* no data available

From this study
Proposed Fatigue Strength Improvement using HFMI

Loading effects

• the guideline states that the techniques are not suitable for $R > 0.5$ or when $S_{\text{max}} > 0.8 \ f_y$

• **Stress ratio:**
  
  $k_R = 1.075 - 0.75 \cdot R$ for $0.1 \leq R \leq 0.5$
  
  $k_R = 1.0$ for $R < 0.1$

• Minimum reduction in the number of FAT classes in fatigue strength improvement for HFMI treated welded joints as presented in previous Figure based on $R$ ratio.

<table>
<thead>
<tr>
<th>$R$ ratio</th>
<th>Minimum FAT class reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R \leq 0.15$</td>
<td>No reduction due to stress ratio.</td>
</tr>
<tr>
<td>$0.15 &lt; R \leq 0.28$</td>
<td>One FAT class reduction</td>
</tr>
<tr>
<td>$0.28 &lt; R \leq 0.4$</td>
<td>Two FAT classes reduction</td>
</tr>
<tr>
<td>$0.4 &lt; R \leq 0.52$</td>
<td>Three FAT classes reduction</td>
</tr>
<tr>
<td>$0.52 &lt; R$</td>
<td>No data available. The degree of improvement must be confirmed by testing</td>
</tr>
</tbody>
</table>
Loading effects and variable amplitude loading

- the guideline states that the techniques are not suitable for $R > 0.5$ or when $S_{\text{max}} > 0.8 \ f_y$
- Limitation on maximum constant amplitude stress range, $\Delta \sigma$, that can be applied to a weld in order to claim benefit from HFMI treatment (in MPa)
The influence of steel strength:

- Computed cycle limit below which HFMI is not expected to result in fatigue strength improvement as a function of steel strength.

<table>
<thead>
<tr>
<th>$f_y$ (MPa)</th>
<th>$N$ (cycles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 355</td>
<td>72 000</td>
</tr>
<tr>
<td>355 – 550</td>
<td>30 000</td>
</tr>
<tr>
<td>550 – 750</td>
<td>12 500</td>
</tr>
<tr>
<td>&gt; 750</td>
<td>&lt; 10 000</td>
</tr>
</tbody>
</table>
Proposed Procedures and Quality Assurance Guidelines for HFMI

Procedures

**Operator Training:**
- 1-2 days of operator training
- identification of fatigue critical regions is also important to avoid extra costs and treatment

**Weld Preparation:**
- proper weld profile

**Safety Aspects:**
- less noise and vibration
- eight hour work shift
Quality control (Qualitative Measures):

Potential introduction of crack-like defect due to HFMI treatment of a weld with a steep angle or with too large of an indenter.

Resulting groove for a properly treated (left) and improperly treated weld toe (right).

Micrographs of the induced crack-like defects due to improper HFMI treatment.
Provision Procedures and Quality Assurance Guidelines for HFMI

Quality control (Qualitative Measures):

- No thin line representing original fusion line should be visible the groove, No individual strikes visible.

  thin crack-like defect which reduces or eliminates the effectiveness of the HFMI treatment

  defect-free groove but with individual indenter strike still visible indicating the need for additional passes
Industrial Applications

Fatigue hot-spots found in brackets supporting the TLP pontoons: HFMI successfully applied

Fatigue hot-spots found in six FPSO cargotanks, Bulkhead and bracket welds treated by HFMI rope access team
Conclusions

- The design proposal is considered to apply to *plate thickness 5 to 50 mm* and for *235 MPa ≤ f_y ≤ 960 MPa*.
- Fatigue resistance curves for HFMI improved welds are based on an assumed S-N slope of *m = 5* in the region *1 \cdot 10^4 ≤ N < 1 \cdot 10^7* cycles and, for variable amplitude loading, *m' = 9* for *1 \cdot 10^7 ≤ N*.
- Stress assessment may be based on *nominal stress, structural hot spot stress or effective notch stress* using stress analysis procedures as defined by the IIW.
- The design proposal includes proposals for the 1) effect of material strength, 2) special requirements for low stress concentration weld details, 3) high R-ratio loading conditions and 4) variable amplitude loading.
- A companion document concerning relevant equipment, proper procedures, material requirements, safety, training requirements for operators and inspectors, quality control measures and documentation has also been prepared and is published in this same issue.
- Successful validation have been shown on larger industrial welded structures.
Fatigue strength improvement of steel structures by high-frequency mechanical impact: proposed fatigue assessment guidelines

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Abstract In the past decade, high-frequency mechanical impact (HFMI) has significantly developed as a reliable, economic, and non-destructive method for post-weld fatigue strength improvement technique for welded structures. During this time, papers on HFMI technology or fatigue improvements have been presented within Commission XIII of the International Institute of Welding. This paper presents one possible approach to fatigue assessment for HFMI-treated joints. Stress analysis methods based on nominal stress, structural stress spectrum, and effective notch stress are all discussed. The document considers the observed benefits that have been experimentally observed for the HFMI-treated high-strength steels. Some observations and proposals on the effect of loading conditions on high-strength tensile fatigue, variable amplitude loading, and large amplitude cyclic fatigue cycles are given. Special considerations for hot stress concentration effects are also given. Several fatigue assessment examples are provided as an approach. A companion paper has also been prepared concerning HFMI equipment, proper procedures, criteria, testing, quality control measures, and documentation has also been prepared. It is hoped that these guidelines will provide a suitable foundation for conducting research in the area. In order to effectively utilize the proposed novel methods, the proposed novel method should be evaluated in a variety of expected environments.

Keywords: Fatigue impact; HFMI; fatigue damage; fatigue crack; hot stress concentration; high-strength steel; HFMI treated; fatigue life

1 Introduction

In 2007, Commission XIII of Welded Components and Structures approved the first general recommendations concerning post-weld improvement methods for steel and aluminium structures [1]. This recommendation covers four commonly applied post-weld treatment methods: bead grinding, tangential heat treating (TGT), electrospark remelting, hammer peening, and stirpe peening. These treatments are generally classified as post-weld improvement techniques for which the primary aim is to enhance weld toughness and to reduce local stress concentrations by achieving a smooth transition between the plate and the weld interface. However, grinding and peening procedures are classified as residual stress modification techniques which reference for high result residual stress in the weld zone and reduce compressive residual stress at the weld toe. These methods may be utilized in a reduced stress concentration at the weld toe. The guidelines also give practical information on how to implement these four improvement techniques, namely good work practices, testing, safety, and quality assurance.

The improvement techniques described in these recommendations are intended to be used both for increasing the fatigue strength of new structures and for the repair or upgrade of existing structures. It has consistently been emphasized that, especially with respect to new structures, weld improvement techniques should never be implemented to compensate for poor design or fabrication practice. Instead, improvement measures should be implemented as a means of providing additional strength after other measures have been taken.
Thank You for Your Kind Attention!

Questions?