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An alternative HFMI master S/N-curve approach

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Abstract

High frequency mechanical impact (HFMI) treatment has significantly developed as a reliable and effective method for post-weld fatigue strength enhancement especially for high-strength steel structures. A proposal for HFMI fatigue assessment guidelines by increasing the structural detail dependent fatigue class by a specified number of steps is given in the IIW document XIII-2452-13.

This paper deals with a subsidiary notch stress approach for HFMI-treated structures. As the effective notch stress approach is widely used for the fatigue assessment of welded structures in industrial applications, this alternative HFMI master S/N-curve approach is based on the stress concentration factor for an effective radius of $r_{eff} = 1\ mm$, the material strength and the applied stress ratio at dynamic loading.

The contribution is split into two parts. First, the development of this complementary HFMI notch stress approach is depicted in an abbreviated manner. The developed method bases on about three-hundred fifty constant amplitude specimen fatigue results including butt joints, non-load carrying transversal joints, cruciform joints and longitudinal stiffeners. Second, both the models applicability and its limitations are discussed by additional examples.

Keywords: high frequency mechanical impact (HFMI), weld toe improvement, fatigue improvement, high strength steel, effective notch stress.

1. INTRODUCTION

The fatigue behaviour of welded structures is reliably defined in the IIW recommendations for fatigue design of welded joints and components [1]. A design guide to the structural hot-spot stress is given in [2], whereas [3] summarizes modelling guidelines for the notch stress approach.
A best practice guideline concerning post-weld treatment methods for steel and aluminium joints is documented in [4], but this guideline covers only the four most common applied post treatment methods; burr-grinding, TIG re-melting, hammer and needle peening.

By high frequency mechanical impact treatment (HFMI) additional benefits in fatigue strength can be achieved. Proposed HFMI procedures and quality guidelines are summarized in [5]. Proposed fatigue assessment guidelines covering the nominal, the structural and the notch stress approach are given in [6]. It has to be mentioned that the increase in fatigue strength by HFMI treatment at the weld toe is within reach only if the failure origin is not merely shifted from the weld toe to the root [4]. It is recommended for improved welds to use full penetration welds or extra-large throats [4].

2.1 HFMI master S/N-curve approach

The concept of unifying HFMI-treated constant amplitude fatigue results into a master S/N-curve is first introduced in [7]. A brief summary of the key steps during the development of the HFMI master S/N-curve approach is given.

2.1.1 Influence of steel strength

The evaluated fatigue tests [8-18] comprise steel strengths from $f_y = 355\ MPa$ up to $f_y = 960\ MPa$. A strength magnification adjustment k_Y, based on the definitions given in [19], is capable to unify the influence of different steel grades. The strength magnification adjustment k_Y, defined in equation 1, is equal to one for *S355* and greater than one for high strength steels. Based on own test results, a value of $\alpha = 0.277$ is applicable for the yield strength correction after the HFMI-treatment [7]. The evaluated strength correction is equal to the proposed increase of one fatigue class for every *200 MPa* increase in static yield strength [20].

$$k_Y = 1 + k_y = 1 + \alpha \left(\frac{f_y - 355MPa}{355MPa} \right) \qquad (1)\ [19]$$

2.1.2 Influence of stress ratio

The investigated specimen test results are within a tumescent stress ratio from $R = 0.1$ up to $R = 0.5$. As the beneficial influence of HFMI-treated joints decreases with higher mean stresses, an influence factor for higher stress ratios is applied [19]. It has to be mentioned that seventy-five percent of the evaluated records are tested at a stress ratio of $R = 0.1$.

$$\begin{aligned} k_R &= 1.075 - 0.75\,R & \quad 0.1 \le R \le 0.5 \\ k_R &= 1.0 & \quad 0.1 < R \end{aligned} \qquad (2)\ [19]$$

2.1.3 Influence of structural detail

To assess the fatigue life enhancement by HFMI-treatment of different specimen geometries, especially for the nominal stress approach, an expression in terms of increase of fatigue classes is advisable [6]. But this HFMI master S/N-curve approach offers a different method as the structural detail is reflected by the notch stress concentration factor applying an effective radius of $r_{eff} = 1\ mm$.

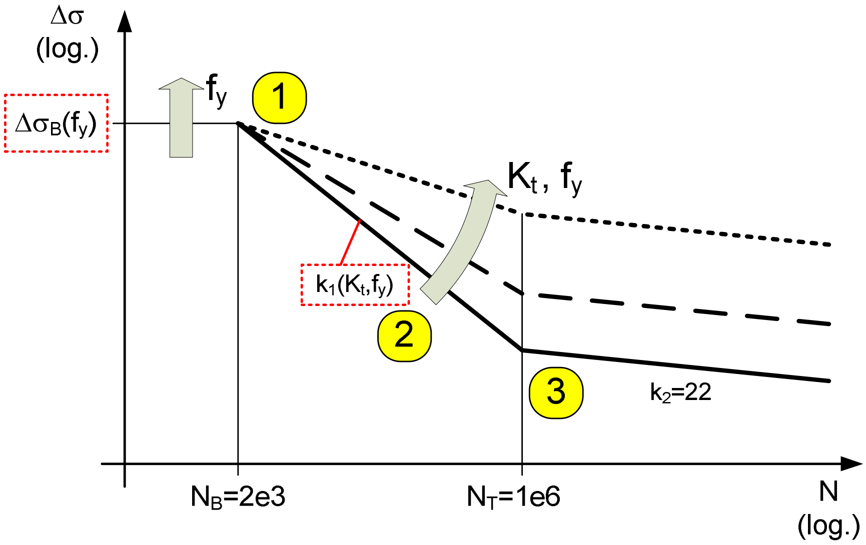

Figure 1: Model for local notch stress S/N-curve considering HFMI treatment [21]

The three steps to determine the local S/N-curve for HFMI-treated joints, see Figure 1, are:

a) A base point at $N_B = 2{,}000$ cycles is defined. This low-cycle fatigue base point is influenced by the base material yield strength f_y only.

b) The examined test database refers to a minimum yield strength of $f_y = 355\ MPa$ and to a (maximum principle) stress concentration factor of $K_{t,r=1mm} = 1.6$. By minimization of the scatter band it was deduced that the slope in the finite life region shifts linearly with the yield strength f_y and along with a power law to the stress concentration factor $K_{t,r=1mm}$. Figure 2 displays the surface plot of the derived slope magnification factor k_k.

c) As only constant amplitude tests are examined in the database, a shallower slope of $k_2 = 22$ can be used in the high-cycle fatigue section. A non-conservative shift of the transition knee-point down to one million cycles, instead of the recommended transition knee point at ten millions, is used for the model setup. This can be reasoned by the occurrence of geometric mild notches and compressive residual strains by HFMI treatment and their subsequent effect on the transition knee point [22].

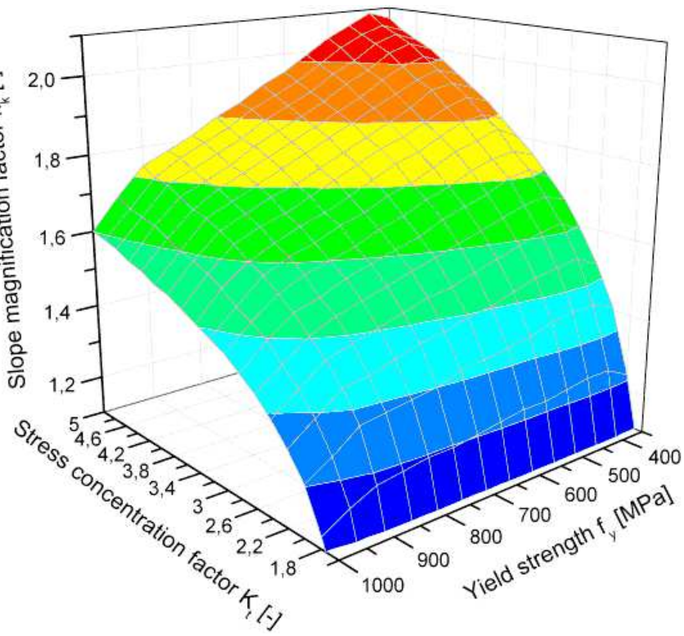

Figure 2: Evaluated slope magnification factor in the finite life region [21]

To unify the data into a notch stress HFMI master S/N-curve, the transformation procedure must be performed on the whole fatigue test database in dependency of steel strength, stress ratio and evaluated notch stress concentration factor. Figure 3 shows the statistically minimized HFMI master S/N-curve for a stress ratio of $R = 0.1$.

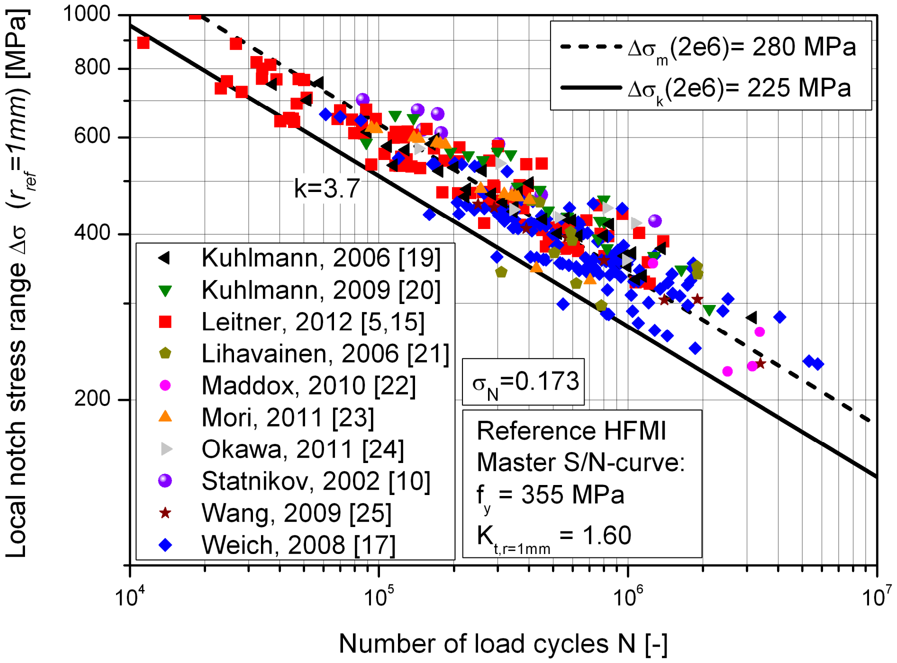

Figure 3: Notch stress master S/N-curve for HFMI-treated joints [21]

The derived standard deviation of $\sigma_N = 0.173$ is below the typical value of $\sigma_N = 0.206$ [23]. The assessed HFMI master S/N-curve exhibits a notch stress range of *225 MPa* with *97 %* probability of survival at two million cycles and a slope of $k = 3.7$. It has to be noted that this evaluated slope in the finite life region depends both on the steel strength and the notch stress concentration factor for each specific joint.

As an example, assuming a notch stress concentration factor of about $K_{t,r = 1\,mm} = 2.7$ for a cruciform joint made of *S700* high-strength steel, the introduced slope magnification factor in Figure 2 leads to a value of $k_k = 1.59$ and subsequently the slope of the HFMI-treated cruciform joint is calculated as $k_1 = k_k\, k_{ref} = 1.59\; 3.7 = 5.88$. This value is close to the recommended value of $k = 5$ for HFMI-treated joints [6].
To determine the FAT notch stress range for this example of a high-strength cruciform joint, first the base point value $\Delta\sigma_B(N_B{=}2e3)$ has to be calculated from the notch stress master S/N-curve as depicted in Figure 3. This leads to a notch stress range at two thousand cycles of $\Delta\sigma_B = 1455\ MPa$. This value is influenced by the material strength, in this case high-strength steel with a static yield strength of about $f_y = 700\ MPa$. The derived strength magnification adjustment, see equation 1, is calculated as $k_Y = 1.27$. The stress ratio should be $R = 0.1$, therefore no adjustment k_R is taken into account. The final base point is therefore determined as $\Delta\sigma_B\, k_Y\, k_R = 1455\ MPa\ 1.27\ 1.0 = 1847\ MPa$. By means of the evaluated slope of $k_1 = 5.88$, a notch stress range of *FAT570* is calculated for this joint.

The determined value is slightly above the proposed fatigue assessment guidelines given for the notch stress approach in [6], but this is expected because the introduced HFMI master S/N-curve approach takes both the steel strength and the stress concentration into account, whereas in the proposal according to [6] the HFMI improved effective notch stress range must be conservatively valid for a wide range of weld geometries, e.g. from butt joints up to longitudinal stiffeners.

2. DISCUSSION OF HFMI MASTER S/N-CURVE APPROACH

The presented method is an extension of the notch stress concept to determine the local notch stress range of HFMI-treated joints. Based on the presented master S/N-curve for HFMI-treated joints in Figure 3, it is possible to assess the fatigue life of HFMI-treated joints in dependency of the steel strength, the stress ratio and the notch stress concentration applying a reference radius of $r_{ref} = 1\ mm$.

The depicted method defines the finite life region from a material strength and stress ratio influenced base point at two thousand cycles, see equation 3. The exemplified HFMI notch stress range is valid for a stress ratio of $R = 0.1$, a test at a high stress ratio of $R = 0.5$ leads to a decrease of the fatigue limit by a factor of $k_R(R=0.5) = 0.7$.

$$\Delta\sigma_B(k_Y, k_R) = 225MPa\left(\frac{2e6}{2e3}\right)^{3.7} k_Y\, k_R = 1455MPa\, k_Y\, k_R \qquad (3)$$

As HFMI introduces effectively residual stresses at the critical weld toe, HFMI-treated joints can be considered as welded joints with low tensile residual stresses. Figure 4 compares the change in surface residual stress and residual stress into plate depth for HFMI-treated joints after the treatment and after fifty million load cycles. Although the compressive residual stress is reduced near the surface layer, it can be expected that only minor tensile or even slight compressive residual stresses remain within the treated region.

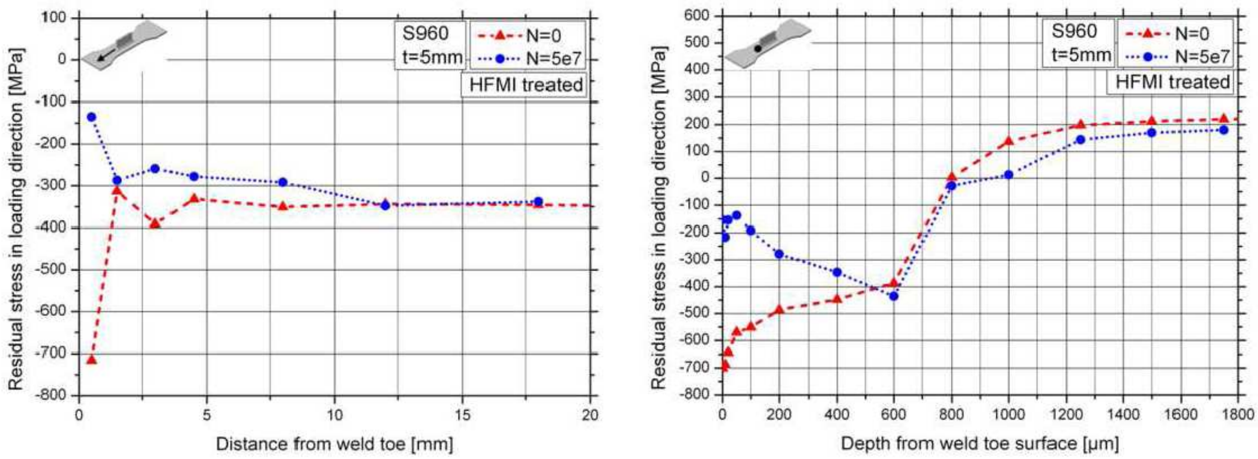

Figure 4: Residual stress measurements of HFMI-treated, longitudinal high-strength steel stiffeners at different load cycles [24]

Therefore, for stress ratios between $R = -1$ and $R = 0.1$, a linearly increasing enhancement factor incorporating mild tensile stresses might be applicable for HFMI-treated joints [6]. Equation 4 summarizes the suggested course of the stress ratio, whereby the stress ratio $R = 0.1$ defines the reference point of $k_R = 1.0$.

$$\begin{aligned} k_R &= 1.075 - 0.75\,R & 0.1 \le R \le 0.5 \\ k_R &= 1.0345 - 0.345\,R & -1 \le R < 0.1 \end{aligned} \qquad (4)$$

Although the model was developed with a non-conservative transition knee point of one million cycles, for unification purposes it is suggested to use a transition knee point of $N_T = 10^7$ cycles. Furthermore, this ensures a more conservative design.

The value of the slope k_1 in the finite life region is evaluated by multiplication of the reference slope value of $k = 3.7$ and the two-parametric, yield strength and notch stress concentration factor dependent, slope magnification factor k_k. If the stress concentration is below a value of $K_{t,r=1mm} = 1.65$, the slope keeps unchanged and the evaluated reference value of $k = 3.7$ has to be used.
In regard to the slope k_2 above the transition knee point of ten million cycles, a shallower slope of $k_2 = 22$ can be applied for constant amplitude tests. For variable amplitude tests, Haibach´s principle [25] in combination with the suggested constant slope of $m = 5$ for HMFI treated joints [6] leads to a more conservative slope value of $k_2 = 9$.

Finally, to assess the fatigue life of variable amplitude tests, an equivalent constant amplitude value can be gained by equation 5 for HFMI-treated joints [26]. As documented in [6], $\Delta\sigma_k$ is the stress range associated with the knee point computed at ten million cycles; N_i is the number of load cycles of stresses $\Delta\sigma_i$ where $\Delta\sigma_i \geq \Delta\sigma_k$ applies; N_j is the number of load cycles of stresses $\Delta\sigma_j$ where $\Delta\sigma_j < \Delta\sigma_k$; m is the slope above the knee point, $m' = 9$ is the slope beyond the transition knee point and $D = 0.5$ is the damage sum.

$$\Delta\sigma_{eq} = \left(\frac{1}{D} \frac{\sum \Delta\sigma_i^m N_i + \Delta\sigma_k^{(m-m')} \sum \Delta\sigma_j^{m'} N_J}{\sum N_i + \sum N_j} \right) \qquad (5)\ [26]$$

2.1. APPLICATION OF THE HFMI MASTER S/N-CURVE APPROACH

Beside the tumescent fatigue dataset used for built-up of the model, the application of this notch stress master S/N-curve for HFMI-treated joints is exemplified for further constant amplitude tests as well as some variable test data as follows.

2.1.1 Butt joints

Three additional fatigue data records [17, 28] of HFMI-treated joints were evaluated both by the presented HFMI master S/N-curve approach and the proposed notch stress fatigue classes [6, 27]. In addition, the maximum constant stress range was checked in regard to the proposed upper limit, compare to Figure 10 in [6]. The proposed maximum stress range of HFMI-treated joints depends on the yield strength and the applied stress ratio [6].
For each evaluated record, the material strength, the stress ratio as well as the notch stress concentration factor for a reference radius of one millimetre is indicated in the corresponding legend of the diagram.

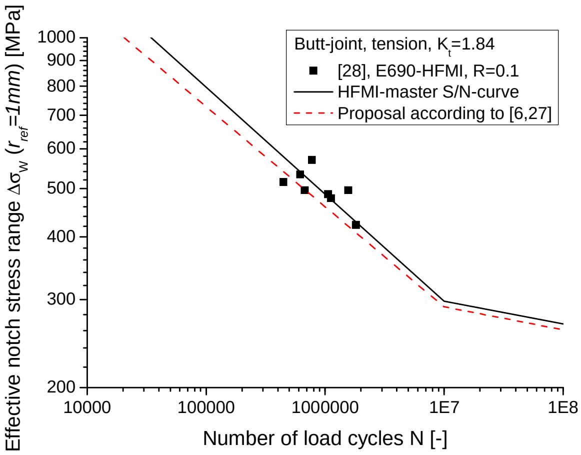

Figure 5: Evaluated notch stress fatigue life of HFMI-treated joints, data from [28]

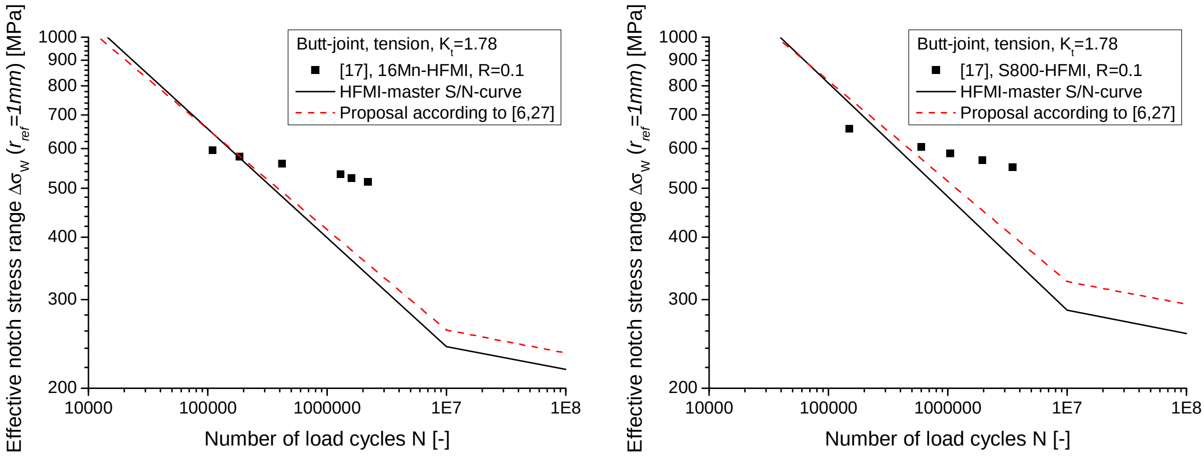

Figure 6: Evaluated notch stress fatigue life of HFMI-treated joints, data from [17]

All data records in Figure 5 and Figure 6 are within the proposed limits [6] of the maximum stress range for HFMI-treated joints.

2.1.2 Cruciform joints

Two additional fatigue data records [29, 15] of HFMI-treated joints were evaluated both by the presented HFMI master S/N-curve approach and the proposed notch stress fatigue classes [6, 27].

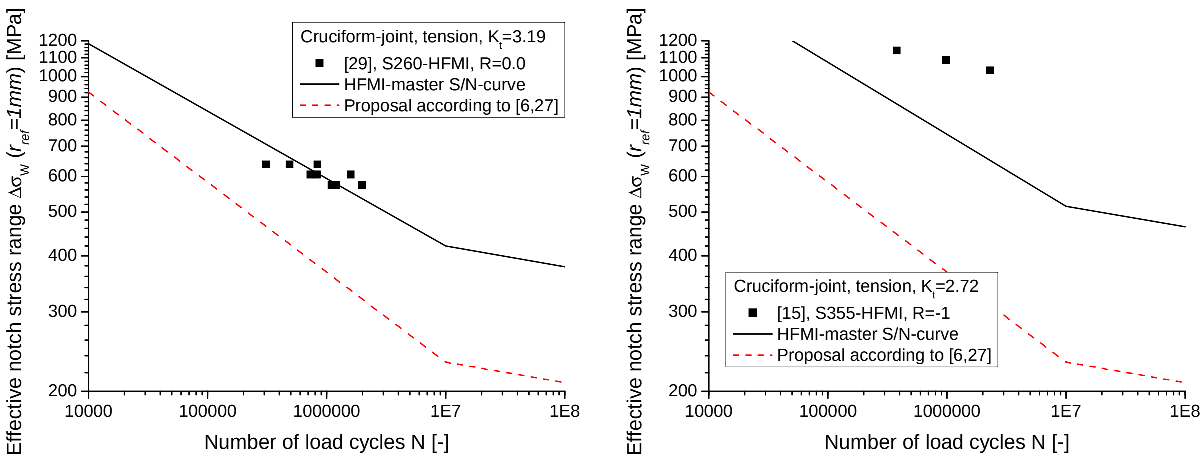

Figure 7: Evaluated notch stress fatigue life of HFMI-treated joints, data from [29, 15]

The data record [15] in the right subfigure of Figure 7 exceeds the proposed maximum stress range by about twenty-five percent.

2.1.3 Longitudinal stiffeners

As the majority of the experimental work focuses on this kind of specimen, five additional data records comprising different stress ratios and material strengths were evaluated.

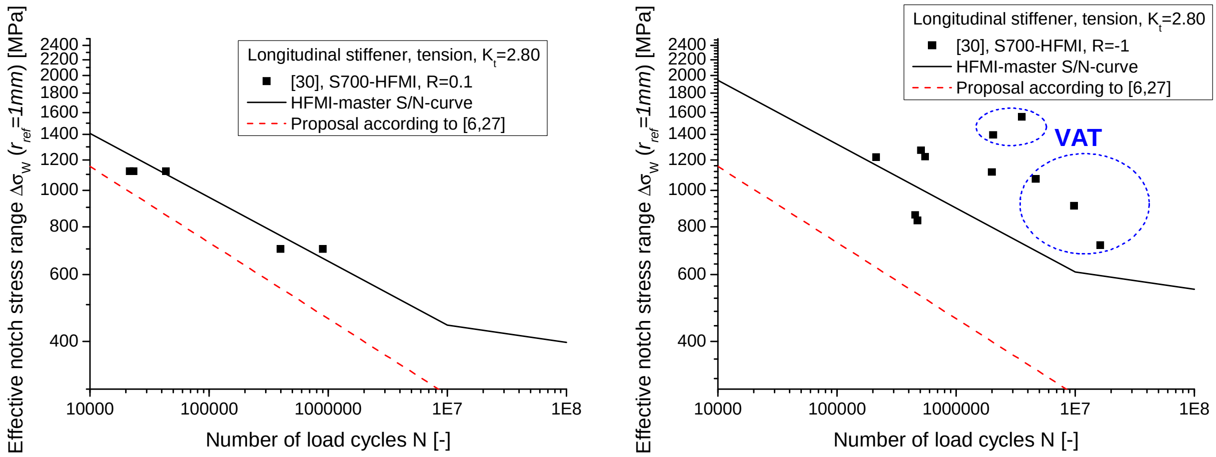

Figure 8: Evaluated notch stress fatigue life of HFMI-treated joints, data from [30]

In the right subfigure of Figure 8 and the left subfigure of Figure 9 data points covering variable amplitude testing are marked with a blue, short-dashed circle. To calculate the equivalent stress, equation 5 with a damage sum of *D = 0.5* is applied. All data points are within the maximum stress range; in case of variable test data the maximum stress range has been additionally checked.

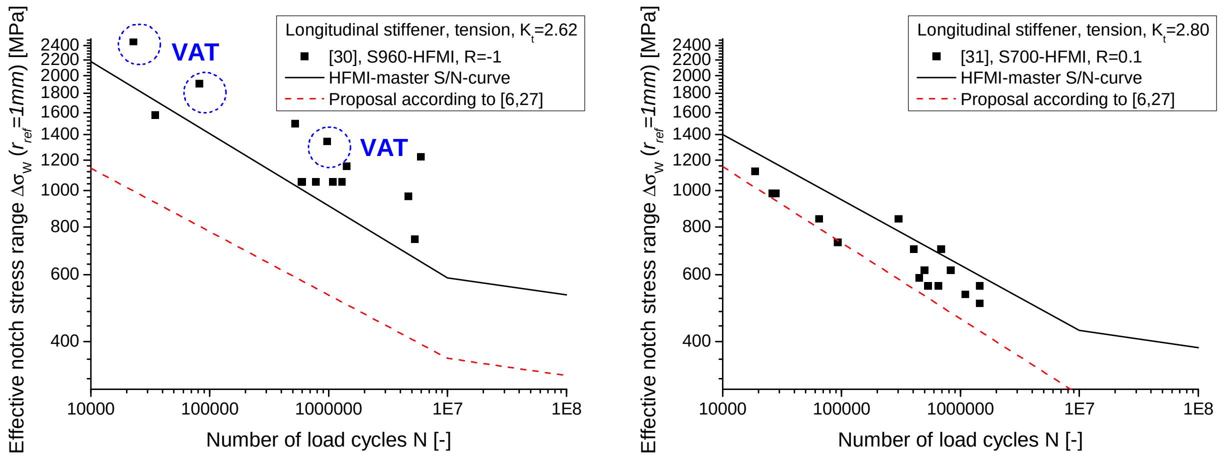

Figure 9: Evaluated notch stress fatigue life of HFMI-treated joints, data from [30, 31]

The data from the Round-Robin-Test [31] is within the proposal according to [6], but the HFMI master S/N-curve approach exhibits a non-conservative assessment for this dataset.

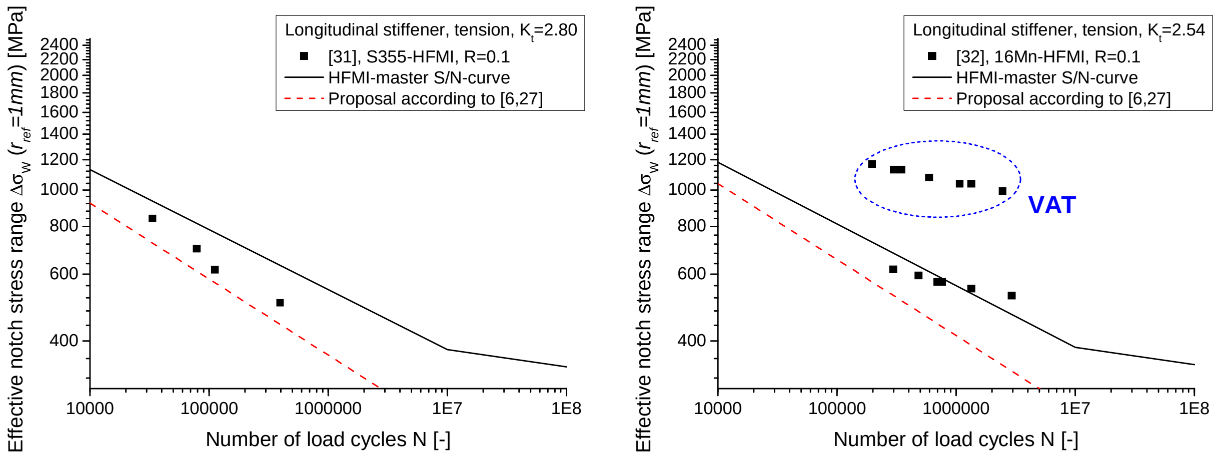

Figure 10: Evaluated notch stress fatigue life of HFMI-treated joints, data from [31, 32]

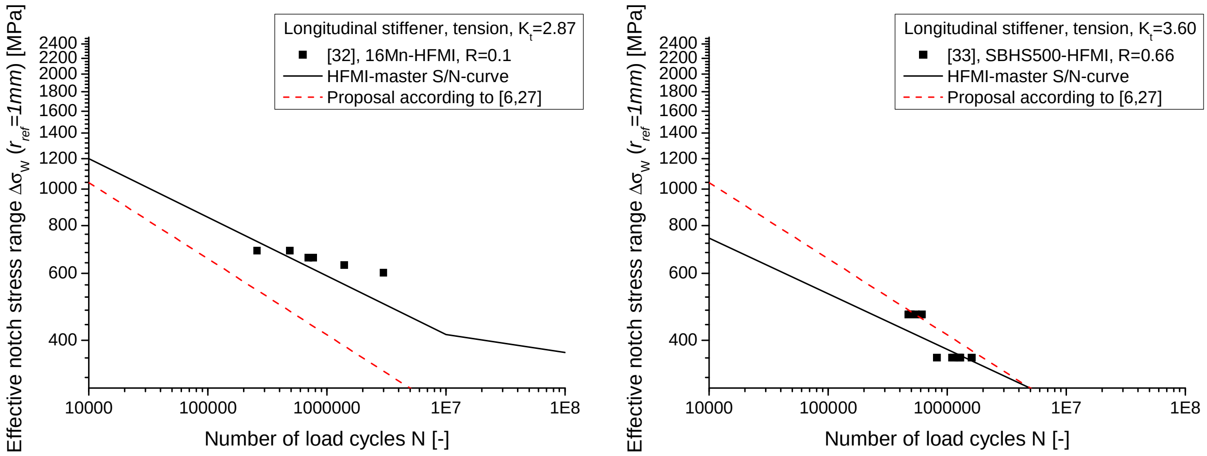

Figure 11: Evaluated notch stress fatigue life of HFMI-treated joints, data from [32, 33]

2.1.4 Non-load carrying transversal attachments

Four additional data records were evaluated for T-joint specimens. The examined tests comprise only bending test results, this leads to an increased fatigue life because of the comparable small most stress volume within in the HFMI-treated region. The applied bending loads exceed the proposed maximum stress range [6] by about thirty percent.

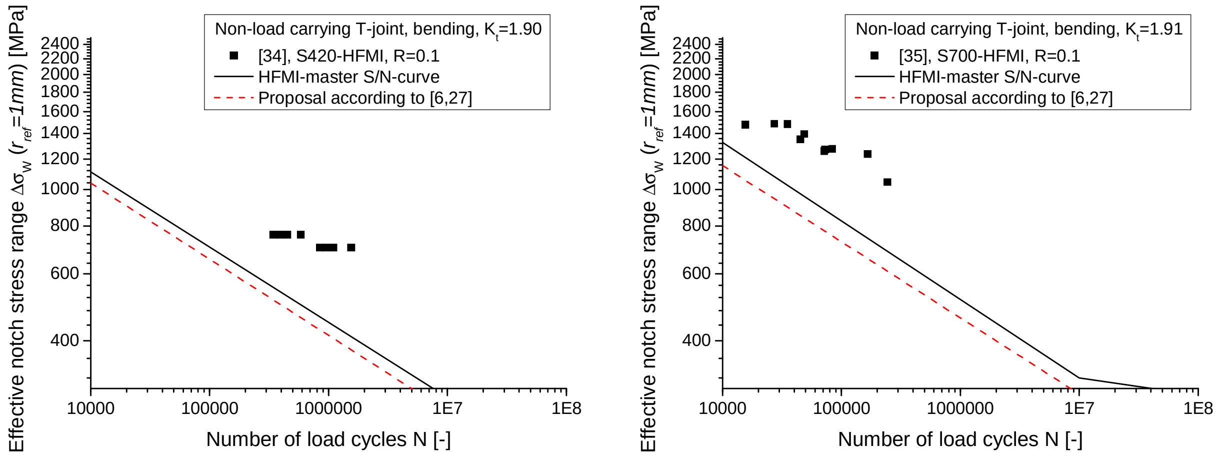

Figure 12: Evaluated notch stress fatigue life of HFMI-treated joints, data from [34, 35]

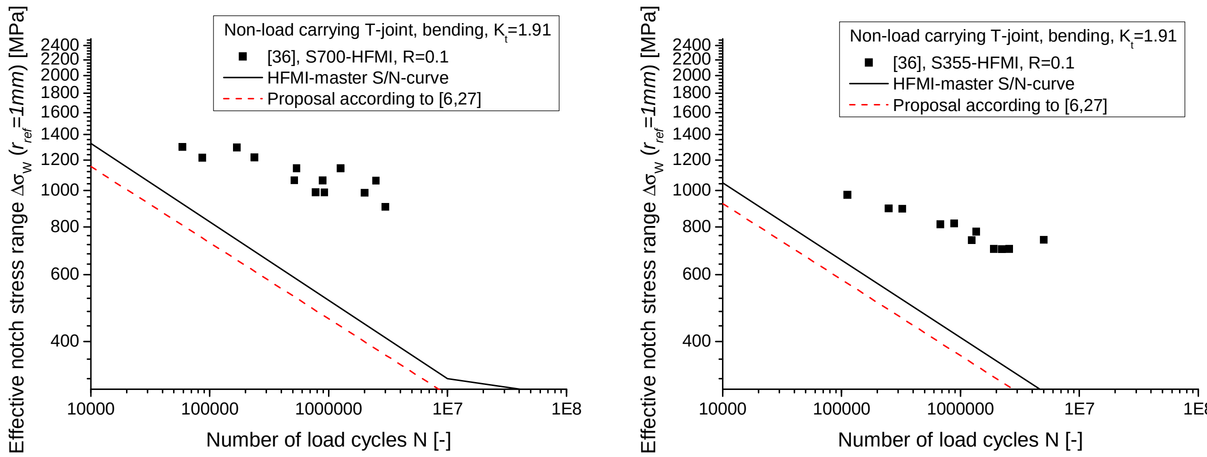

Figure 13: Evaluated notch stress fatigue life of HFMI-treated joints, data from [36]

3. CONCLUSION

The introduced master HFMI S/N-curve method offers a complementary method to asses the fatigue life of HFMI-treated joints by means of the notch stress approach. The assessment procedure can be easily automated as a script and supports therefore the fatigue evaluation of complex structures possessing different material strengths and varying joint geometries.

Beside the extensive dataset used to generate the method, seventeen additional data records were examined. This complementary master S/N-curve approach facilitates the fatigue assessment of HFMI-treated joints in an accurate manner; only in case of data record [31] a non-conservative result was achieved. It is therefore recommended to reduce the proposed HFMI master S/N-curve value of *FAT225* in Figure 3 down to *FAT200*. This assures a conservative fatigue life calculation for all processed HFMI data records.

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