

Parametric study of the potential of application of high-strength steels to increasing the service fatigue life of vehicle structures

M Kepka Jr.¹ and M Kepka¹ and J Tittel¹

University of West Bohemia, Univerzitni 8, 306 14 Pilsen, Czech Republic

kepkam@rti.zcu.cz

Abstract. The paper highlights the main impacts of HFMI technology on increasing the fatigue resistance and extending the fatigue life of joints and components welded from both conventional and high strength steels. Parametric calculations of the permissible stresses of a selected structural detail are performed, assuming its application in the bus construction, which is subjected to random loading in real operation.

1 Introduction

Steel welds are still being used in vehicle constructions. For some welded nodes, increased fatigue strength can be achieved if one of the HFMI (High Frequency Mechanical Impact) technology is applied. This is especially important for details made of high-strength steels. Of course, vehicle manufacturers are interested in whether the application of the new technology will be beneficial for real vehicle operation. Therefore, this parametric study was carried out which used the knowledge about stress spectra in the bus constructions and the recommendations of the International Institute of Welding for improving the fatigue strength of welded joints with HFMI treatment.

2 HFMI treatment for improving the fatigue strength of welded joints

Various names have been used in literature for HFMI technology: ultrasonic impact treatment, ultrasonic peening, ultrasonic peening treatment, high frequency impact treatment, etc. The working principal is identical: cylindrical indenters are accelerated against a component or structure with high frequency. The impacted material is highly plastically deformed causing changes in the material microstructure and the local geometry as well as the residual stress state in the region of impact. Weld geometry is improved and compressive residual stresses are induced. Initiations and development of fatigue cracks are prevented. Everything about the improving the fatigue strength and durability by the HFMI application is best summed up in the publication [1]. This guideline is applicable to steel structures of plate thicknesses of 5–50 mm and for yield strength ranging from 235 to 960 MPa. The publication is linked to the recommendations for fatigue design of welded joints and components [2].

The fatigue assessment of classified structural details and welded joints is based on the nominal stress range. Each fatigue strength S-N curve is identified by the characteristic fatigue strength of the detail in MPa at 2 million cycles. This value is the fatigue class (FAT). The slope of the fatigue strength S-N curves for details assessed on the basis of normal stresses is $m = 3$, if not stated expressly otherwise. The constant amplitude knee point is assumed to correspond to $N = 10^7$ cycles.



New experimental data indicate that a fatigue limit does not exist and the S-N curve should continue on the basis of a further decline in stress range of about 10 % per decade in terms of cycles, which corresponds to a slope of $m_d = 22$. For variable amplitude loading (for application of Palmgren-Miner summation) is recommended slope $m_d = 2 \cdot m - 1 = 5$. An example of a set of the resistance S-N curves is shown in figure 1.

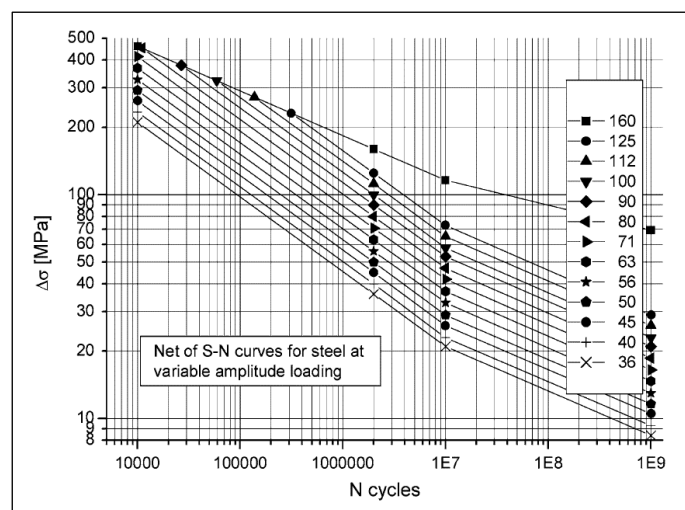


Figure 1. Resistance S-N curves at variable amplitude loading (steel, nominal stress) [2].

The most of the fatigue design methods for HFMI improved welds are based on an assumed S-N slope of $m = 5$, and fatigue strength improvement factor are defined at $N = 2 \cdot 10^6$. For steel with a yield strength of less than 355 MPa, HFMI processing improves to up to 4 FAT classes. For steels with a yield strength above 355 MPa, the HFMI processing is reflected by an improvement in one additional FAT class for each increase in the yield strength by 200 MPa, see figure 2.

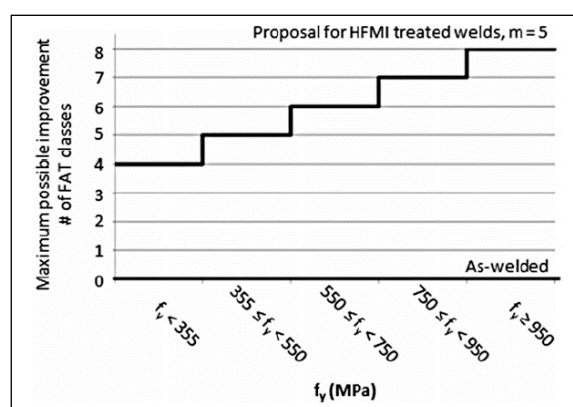


Figure 2. Maximum increase in the number of FAT classes as a function of yield strength f_y [1].

HFMI treated welds can have up to 8 FAT classes of improvement (!) depending on the material strength, welded joint geometry, etc. However, some factors limit and modify this optimistic situation. The detailed explanation is given in [1], here is just a rough summary of three important factors that are later taken into account in parametric calculations. The HFMI improvement is applied to the weld toe and is intended to increase the fatigue live of the weld threatened from the view point of potential fatigue failure from the weld toe. The benefit of HFMI treatment can be claimed only for details in design Class FAT 50 to FAT 90 in the IIW notation for S-N curves. The positive effect of

the technology reduces the high tension pre-stress. The stress ratio influence is expressed as a penalty with respect to the maximum increase in the number of FAT classes. In the interval ($0.15 < R \leq 0.52$) this reduction is 1 to 3 FAT classes. With the increasing stress ratio R , significant reduction is applied.

3 Parametric study

3.1 Procedure

In this study, we followed the procedure as shown in the diagram in figure 3.

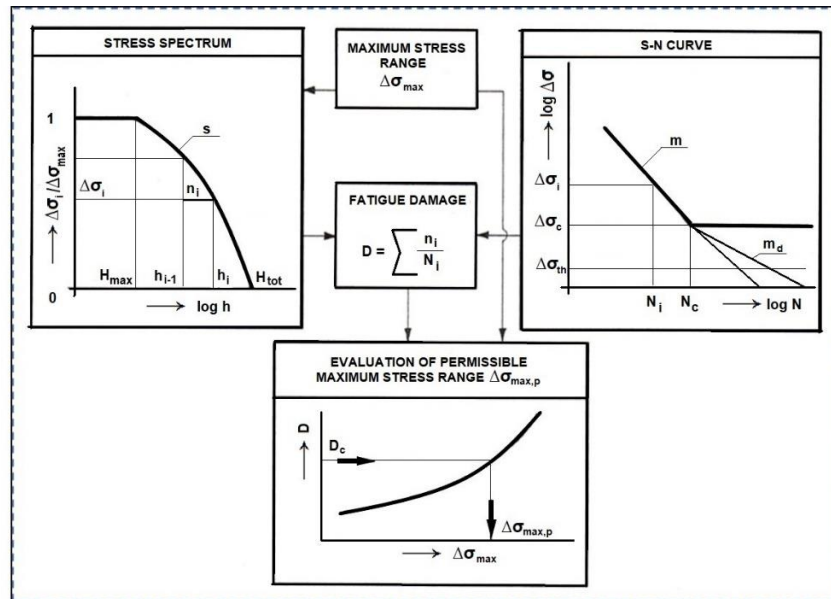


Figure 3. Evaluation of permissible maximum stress range $\Delta\sigma_{\max,p}$ of design stress spectrum [5].

3.2 Structural detail and materials

For our parametric study (asked by a bus producer), we chose the structural detail that can occur in a bus construction. The selected detail is shown in figure 4 and has the FAT 71 category.

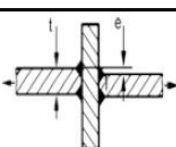
Structural Detail	Description	FAT
	Cruciform joint or T-joint, K-butt welds, full penetration, potential failure from weld toe Misalignment < 15 % of primary plate thickness in cruciform joints	71

Figure 4. Structural detail used for parametric study [2].

We considered the following material alternatives:

- $f_y < 355$: conventional structural steel, e.g. S355J0;
- $355 \leq f_y < 550$: high-strength structural steel, e.g. WEATHERING 550W;
- $550 \leq f_y < 750$: high-strength structural steel, e.g. STRENGTH 700 MC.

3.3 S-N curves

We considered: maximum FAT classes improvement and 3 FAT classes reduction with respect to cycles with positive stress ratio R that may occur in random load process. The resulted S-N curves are plotted in figure 5.

- Weldable structural steel, as welded / no HFMI (+0 FAT, $m = 3$, $m_d = 5$);
- S355J0 + HFMI (+1 FAT, $m = 5$, $m_d = 9$);
- WEATHERING 550W + HFMI (+2 FAT, $m = 5$, $m_d = 9$);
- STRENGTH 700 MC + HFMI (+3 FAT, $m = 5$, $m_d = 9$).

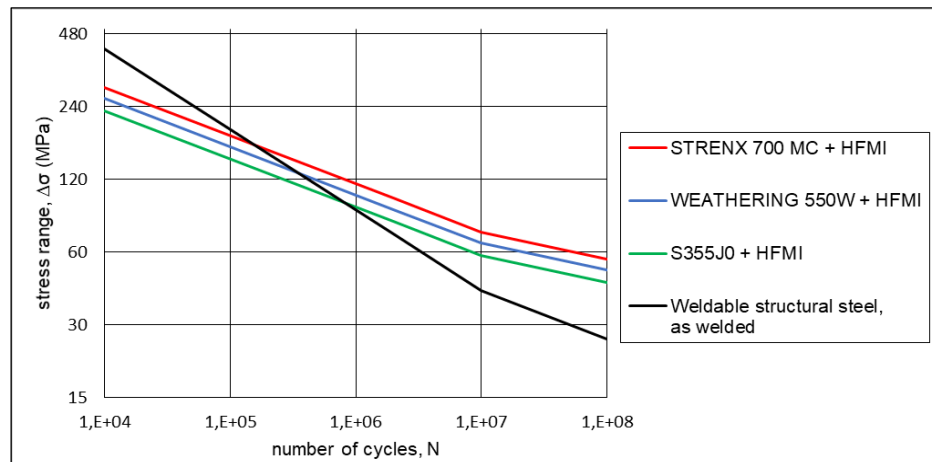


Figure 5. Considered resistance S-N curves.

From figure 5, it can be easily estimated (using exact parameters of the S-N curves precisely calculated) what extension of the fatigue life can potentially be achieved at a harmonic loading, what maximum stress range can be allowed for the required number of harmonic load cycles.

3.4 Stress spectra

At the design stage of a bus structure, no accurate data on its service loading is available. Therefore, design load (stress) spectra are employed in this parametric study. The design stress spectra were generated using the relative coordinates $\Delta\sigma_i / \Delta\sigma_{\max}$ and the equation proposed in [3]:

$$h_i = H_{\text{tot}} \cdot \left(\frac{H_{\max}}{H_{\text{tot}}} \right) \left(\frac{\Delta\sigma_i}{\Delta\sigma_{\max}} \right)^s \quad (1)$$

$\Delta\sigma_{\max}$ - maximum stress amplitude in the spectrum;

H_{\max} - number of cycles with $\Delta\sigma_{\max}$ amplitude in the spectrum;

H_{tot} - total number of cycles in the spectrum;

s - shape parameter of the spectrum;

h_i - cumulative frequency of cycles with an amplitude of $\Delta\sigma_i$.

Long-term monitoring of run on irregular road surfaces lead to linear distribution stress spectra with shape parameter $s \rightarrow 1$, manoeuvres (curve riding, braking, etc.) lead to stress spectra with normal distributions and $s \rightarrow 2$ [4]. Both types of stress spectra can occur on a bus construction.

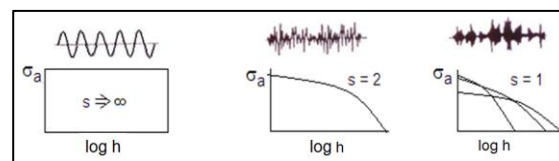


Figure 6. Characteristic shapes of design stress spectra [4].

In our parametric calculations, we considered both values $s = 1$ and $s = 2$. Further parameters of the design spectra were taken from the literature [5]. The design life was set as $L_d = 10^6$ km with the estimation of $H_{tot} = 7.2 \cdot 10^8$ cycles. The occurrence of the load cycle with the maximum stress range $\Delta\sigma_{max}$ was considered once per 100 km of run, so $H_{max} = 10^4$ cycles during the design life.

3.5 Calculation of fatigue damage

Fatigue damage D was calculated using the Haibach-modified version of the Palmgren-Miner rule. According to this rule, the fatigue limit state is reached when the following condition is met:

$$D = \sum_i \frac{n_i}{N_i} = D_c \quad (2)$$

- D - fatigue damage caused by the stress spectrum imposed;
- n_i - number of cycles applied at the i -th level of stress with the range $\Delta\sigma_i$;
- N_i - limit life under identical loading (the number of cycles derived from the S-N curve at the stress range $\Delta\sigma_i$);
- D_c - critical (limit) value of fatigue damage.

3.6 Maximum permissible stress ranges

At a constant width of the classification interval $d\Delta\sigma$, one can derive the discrete stress spectrum ($\Delta\sigma_i - n_i$). An absolute class frequency is calculated $n_i = h_{i-1} - h_i$ and this number of cycles is assigned to the mid-point of the class (or, safely, to its upper limit) $\Delta\sigma_i$. Then, considering the S-N curve and the fatigue life accumulation hypothesis, the procedure shown in figure 3 can be applied.

The $D = f(\Delta\sigma_{max})$ functions were evaluated for 2 types of design stress spectra (with shape parameter $s=1$ and $s=2$) and for 4 considered resistance S-N curves (see figure 5). The maximum permissible stress ranges $\Delta\sigma_{max,p}$ can be deduced from the functions plotted in figures 7 and 8. The maximum stress range $\Delta\sigma_{max,p}$ can be derived for the critical damage D_c . If these value $\Delta\sigma_{max,p}$ is not exceeded, the design life L_d should be guaranteed.

Estimates of permissible stress ranges $\Delta\sigma_{max,p}$ are influenced by the choice of the critical value of fatigue damage D_c . According to the original version of the Palmgren-Miner rule $D_c = 1$, but D_c can be within the wide range and non-conservative. This problem can be partially solved by recommending a value of $D_c = 0.5$. The most correct solution is to calibrate this value D_c based on a properly designed and correctly implemented experimental program (relative Palmgren-Miner).

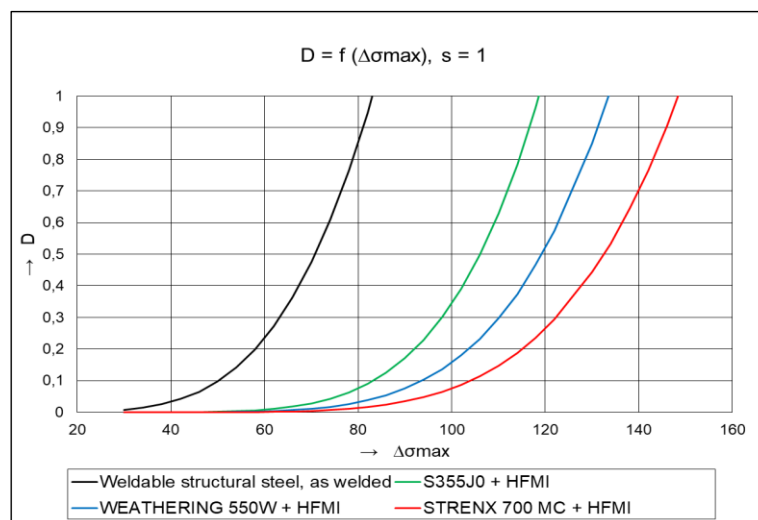


Figure 7. Functions for evaluation of maximum permissible stress range $\Delta\sigma_{max,p}$.

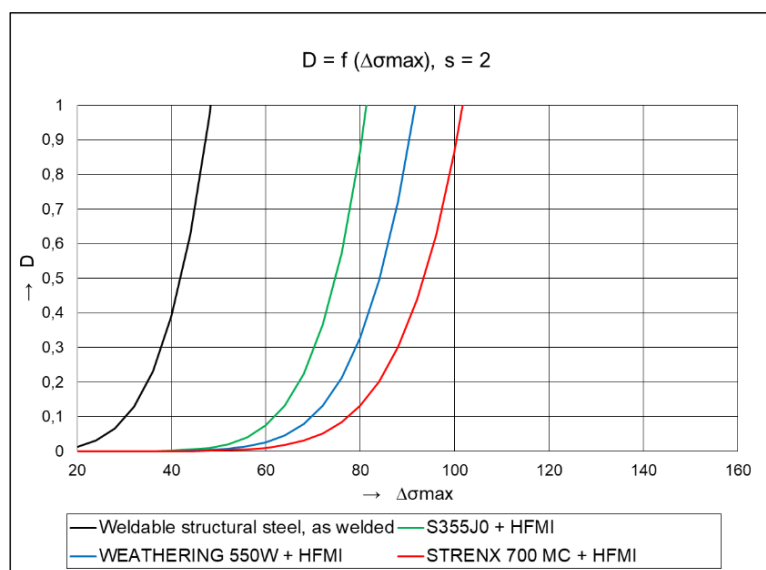


Figure 8. Functions for evaluation of maximum permissible stress range $\Delta\sigma_{\max,p}$.

4 Conclusions

The study confirmed the potential of production of vehicle structures welded from high-strength steels. Taking into account HFMI process during development and production, on same load level and same lifetime, the construction can be slimmed down specifically. Considering the additional benefit of the weight advantage e.g. the achievable payload in vehicles can be increased. Using the parametric calculations with the structural detail suitable for HFMI application and theoretically made of steels with different strengths we have also proposed the procedure for determining the maximum permissible stresses at which the design lifetime can be guaranteed in case of random loading of the vehicle structure in real operation. In real practice it's of course necessary to take into account the question of the stability of the increase the fatigue strength achieved by HFMI under the effect from real operation (for example due to the sudden overload, etc.).

Acknowledgment

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References

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