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Validation of Multiaxial Stress-based Analysis on Specimens from ČSN 41 1523

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Abstract. The paper describes the study on fatigue strength prediction criteria within the scope of a common high-cycle fatigue strength analysis including the effect of multiaxial loading. The study is based on own experiments performed on tubular specimens from ČSN 41 1523 structural steel in a combination of various load channels: push-pull, torsion, pressurizing, bending. The prediction methods are assessed in various fatigue lifetimes ranging from 100 000 cycles to 750 000 cycles. No substantial deviation of the methods behaviour in various lifetimes is observed, likely due to the stresses being low enough not to induce substantial plasticity effects. The PCRN method and the Liu-Zenner methods result in best predictions. Results of the recently proposed MMP method allowing the users to evaluate quickly multiaxial load states remain promising and only slightly worse than these two best methods.

Introduction

The paper extends the topic presented by authors in [1]. They reported on extensive experimental fatigue program on hollow specimens manufactured from ČSN 41 1523 structural steel, and they introduced a new MMP calculation method. This extension of the Manson-McKnight (MMK) method preserves its simplicity of the calculation, for which any simple spreadsheet program as e.g. MS Excel is sufficient. On the other hand, thanks to the substantial modification of the formula, MMP resulted in much better fatigue prediction compared with MMK. It was stated that the MMP method can reach quality of results comparable with much more complex multiaxial fatigue criteria.

The fatigue strength analysis provided in [1] was prepared at 750,000 cycles for all 24 S-N curves involved in the experimental campaign. The extension in the current paper concerns evaluating the same set in section cuts in the range from 100,000 to 750,000 cycles. The goal is to analyse, whether the quality of prediction by various evaluated calculation methods is in any way modified, if lower lifetimes are treated.

Experiments

The specimens tested in the experimental campaign are described in [1]. Three different types of hollow specimens were used with the major and minor diameters in the critical cross-section either D=20 mm and d=18 mm or D=11 mm and d=8 mm. They were manufactured from ČSN 41 1523 structural steel, properties of which are provided in Table 1.

Tab.1 Static material parameters and chemical composition of the studied material

Designation	Ultimate tensile strength [MPa]	Tensile yield stress [MPa]	Elongation at fracture [%]	Reduction of area at fracture [%]	True fracture strength in torsion [MPa]
ČSN 41 1523	560	400	31.1	74.0	516.6
Chemical composition:					
C [%]	Mn [%]	Si [%]	P [%]	S [%]	Cu [%]
0.18	1.38	0.4	0.018	0.006	0.05

The setup of experiments was extensively described in [1]. Here the schematic drawings in Fig. 1 show the setup of individual experiments. 24 different load cases were tested in the stress-controlled regime. Each final S-N curve was obtained by the linear (Basquin model) or non-linear (Kohout-Věchet model, see [4]) regression from at least 5 finished experiments. Various experimental machines had to be used to result in described load combinations (see also the setup of tests in Fig. 2 and Fig. 3) – the reconstructed Schenck PWXN machine, the INOVA ZUZ servo-hydraulic pulsator equipped with combined hydraulic cylinder for push-pull and torsion loading and the INSTRON 8802 biaxial servo-hydraulic pulsator.

Due to unusual load combinations, it is not immediately obvious in some cases, which surface of the hollow specimens is the more loaded one. Because of that, potential hot-spots on both surfaces had to be analysed during the fatigue prediction phase.

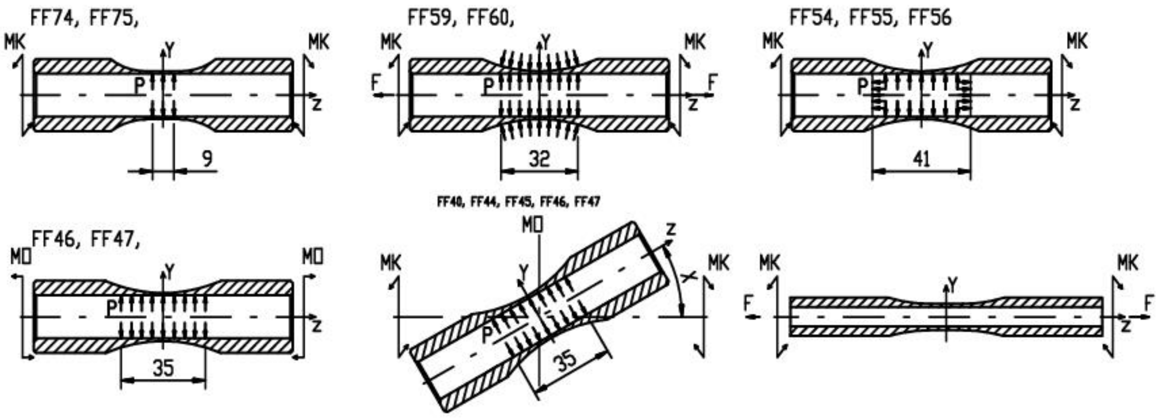

Fig.1 Overview of various setups of experiments. M0 ~ bending moment, MK ~ torque, P ~ pressure and F ~ push-pull

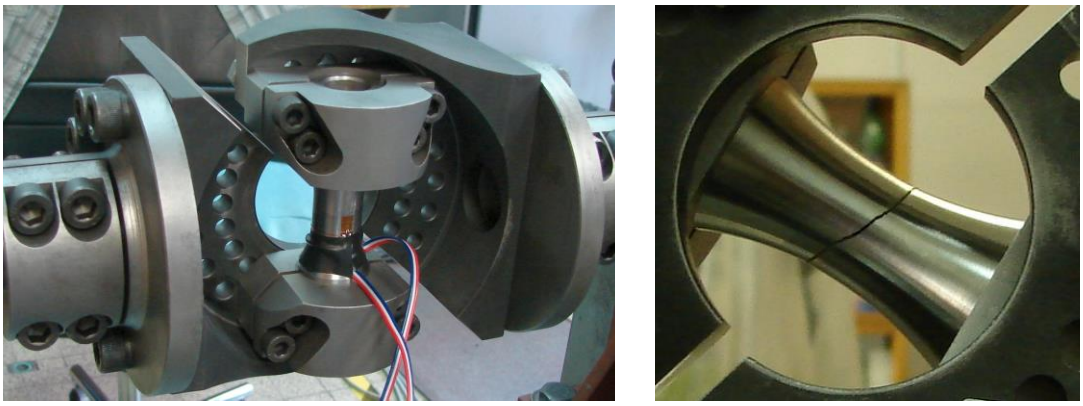

Fig.2 Setup of the experiments for load cases of torsion and bending on the torque controlled Schenck PWXN machine (bending load case FF040 left, combined load case FF044 right).

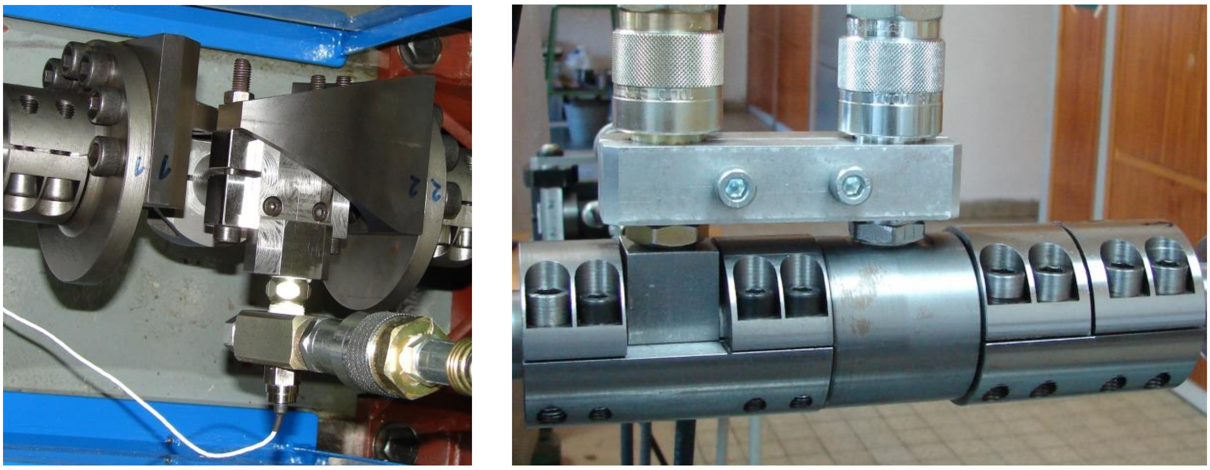

Fig.3 The load case of bending and pressurizing, with the pressure chamber and the pressure sensor visible – FF046 load case (left). The setup of the test case with the pressure chamber inducing inner and outer pressure – FF059 load case (right)

Calculations

Within the prediction evaluation, 27 calculation methods were analysed in total. Most of them are described in [2]. The stress states on individual load channels relevant to the durability at a given number of cycles N_x were calculated from the regression curves derived from the experimental data. The fatigue strength analysis was performed, i.e. the damage parameter D_P in the form of an equivalent axial stress amplitude was computed for various load combinations presented here and relevant to the evaluated number of cycles N_x. This equivalent stress amplitude was compared with the fully reversed axial fatigue strength p_{-1} (push-pull loading) or b_{-1} (bending) at the same N_x.

The analysis of the prediction quality was not evaluated on raw experimental data, but on fatigue strengths derived from the regression curves. The analyses were performed only on fatigue strengths that can be obtained within the interpolation regions of the individual S-N curves. The paper [1] referred to the fatigue strengths relevant to 750 000 cycles. Three more lifetimes are evaluated here: 100 000, 200 000 and 500 000 cycles.

The paper [1] comments the way of selecting the appropriate axial load mode for various load cases. At last, the bending fatigue strength was used only for cases loaded explicitly also in the bending load mode. The relative error between computed damage parameter D_P (equivalent stress amplitude) and e.g. the fully reversed push-pull fatigue strength p_{-1} defines the fatigue index error ΔFI:

$$\Delta FI = \left(\frac{D_P - p_{-1}}{p_{-1}}\right) \cdot 100\% \qquad (1)$$

The paper evaluates prediction quality based on this parameter. To enable the analysis for 24 different load cases at four different lifetimes, it must be processed statistically – here the mean value, standard deviation and the sum of its squares are evaluated.

Discussion of results

From results obtained for all tested prediction methods, only some are presented statistically in Table 2, Table 3 and in Fig. 4. Except of the MMP method (see [1]) and the updated PCRN method [3] derived from PCR [2], all prediction methods are described in [2]. The selection to highlight these particular methods was driven by the intention to show results of methods, which are used in available fatigue solvers (methods by Dang Van, McDiarmid, Findley, Sines and Matake), which present substantially better results than these methods (Liu-Zenner, MMP, PCR, PCRN), or which are often used in comparisons of prediction methods (Crossland and Papadopoulos).

Table 2 presents the summary in the sum of ΔFI squares, which describes well the remoteness of the general trend from the correct one. To distinguish the general shift of all results to either conservative or non-conservative prediction from the scatter around this mean value, Table 2 contains also the values of the mean relative error for individual lifetimes and for all of them. Table 3 then summarizes the information about the standard deviation of the same parameter, thus effectively showing the induced scatter of the prediction quality.

The most important question in the overall evaluation was, whether the individual methods will show a substantial difference at different lifetimes, i.e. if their results are stable within the high-cycle fatigue domain tested here. Table 2 and Table 3 show that the mean values of the fatigue index error change a bit. For most of the methods, the difference in the mean value is within 2%. The biggest differences can be observed for the McDiarmid, Findley and Matake methods. Compared with the overall scatter of the results, such shift in the mean value is not excessive.

Tab.2 Results of the ΔFI statistics for selected eleven methods at different N_x – sum of squares and mean values

Computational method	Sum of ΔFI squares	Mean value of ΔFI for N_x				
		All	100 000	200 000	500 000	750 000
Crossland	75%	-0.9%	-1.8%	-1.0%	-0.5%	-0.4%
Dang Van	84%	6.1%	4.8%	6.0%	6.6%	6.7%
Findley	351%	13.3%	11.1%	12.8%	14.2%	14.8%
Liu-Zenner	26%	1.8%	2.6%	2.2%	1.5%	1.1%
Matake	363%	12.4%	10.3%	12.0%	13.4%	13.9%
McDiarmid, MD var.	115%	4.1%	6.8%	5.1%	3.0%	1.9%
MMP	41%	2.5%	3.4%	3.1%	2.1%	1.4%
Papadopoulos	87%	0.2%	-0.7%	0.1%	0.7%	0.7%
PCR	43%	3.3%	3.2%	3.3%	3.4%	3.3%
PCRN	32%	3.9%	4.7%	4.1%	3.5%	3.3%
Sines	346%	10.1%	10.3%	11.0%	9.8%	9.2%

The change in the standard deviation is the most pronounced in the evaluation of the Findley and Matake methods, where it decreases with the decreasing lifetime. Because the mean value decreases in the same way, it can be stated that both these methods are more suitable for use at the lifetime 100 000 cycles than at higher lifetimes. Their results stay too scattered and too conservative anyway (see the histogram for the Findley method in Fig. 4).

If the overall prediction quality of individual methods is compared in all evaluated lifetimes, the methods by Liu-Zenner, PCRN, PCR and MMP provide better results than other methods evaluated here. If the standard deviation of the PCRN method is compared with the Dang Van method, which is the most important solution used in industrial practice, it can be noted that the standard deviation of the PCRN is 60% of the Dang Van solution. This means that the prediction results are less scattered, and they can be accepted with a better certitude (see again the comparison of histograms in Fig. 4).

The newer PCRN method [3] results in better prediction if compared with the original PCR [2]. It leads to a lower scatter of results, as can be documented by the lowest value of the overall standard deviation of ΔFI. Anyhow, its mean value is more distant from perfect prediction ($\Delta FI = 0$) than the mean value of the Liu-Zenner method (This larger deviation is at least in the conservative direction). Because of that, the sum of ΔFI squares of the Liu-Zenner method is the lowest one of all methods.

Tab.3 Results of the ΔFI statistics for selected eleven methods at different N_x – standard deviations

Computational method	Standard deviation of ΔFI for Nx				
	All	100000	200000	500000	750000
Crossland	8.9%	10.5%	9.0%	8.3%	8.3%
Dang Van	7.3%	8.2%	7.1%	7.0%	7.3%
Findley	14.1%	13.7%	13.5%	14.6%	15.2%
Liu-Zenner	5.0%	4.9%	4.5%	5.1%	5.6%
Matake	15.3%	14.6%	14.5%	15.9%	16.8%
McDiarmid, MD var.	10.3%	10.6%	10.0%	10.2%	10.4%
MMP	6.1%	6.8%	6.1%	5.8%	5.9%
Papadopoulos	9.7%	11.2%	9.7%	9.2%	9.2%
PCR	6.0%	6.6%	6.0%	5.8%	5.8%
PCRN	4.4%	4.3%	4.2%	4.6%	4.8%
Sines	16.4%	16.0%	16.3%	16.9%	17.4%

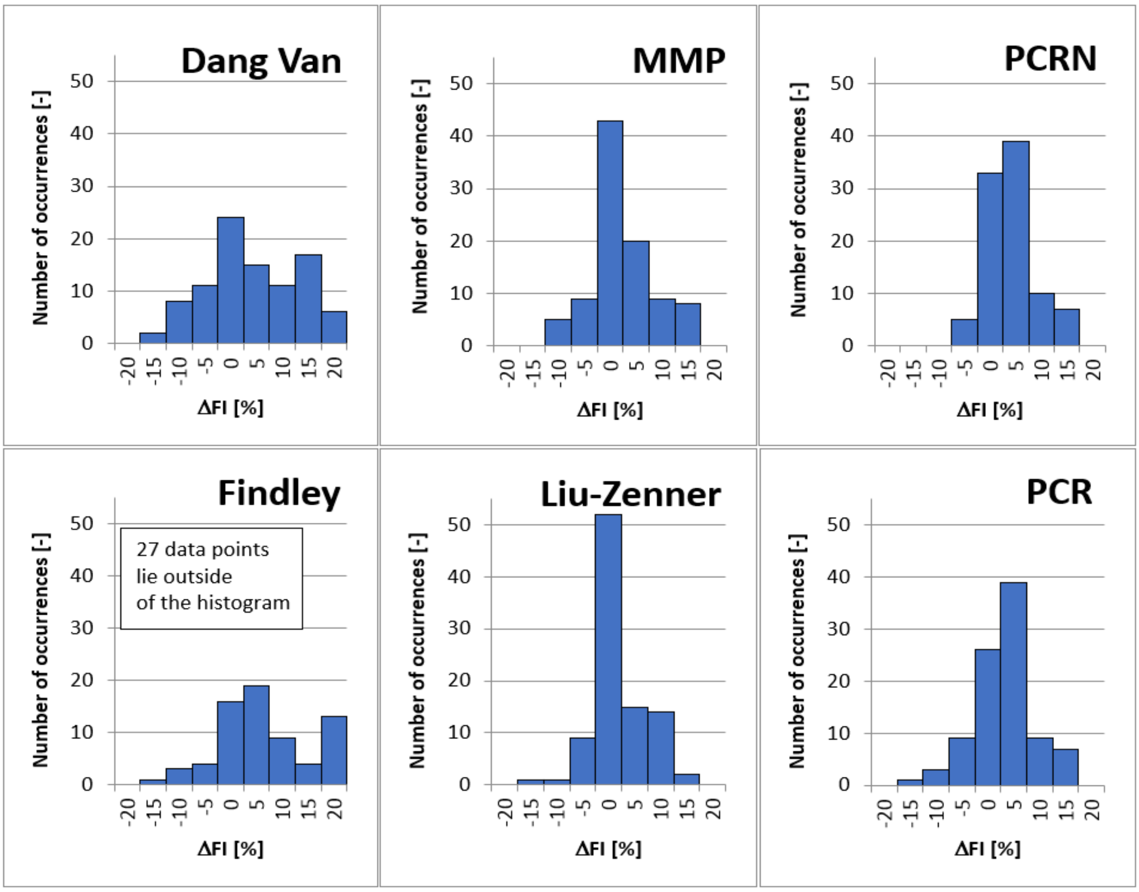

Fig.4 Examples of histograms of the fatigue index error over all experiments and all evaluated section cuts (100,000; 200,000; 500,000 and 750,000 cycles)

If the new MMP method [1] is compared with these two methods, it quite well resembles prediction quality of the original PCR. It has to be noted, that the simplicity of its computation is such, that the MMP can be solved within the MS Excel spreadsheet, while PCR(N) or Liu-Zenner methods require a dedicated software program.

Conclusions

The analysis presented in this paper concerned 27 different calculation methods of various types, which were tested on a test set of 24 S-N curves of different load cases. The experimental results described previously [1] were obtained on hollow specimens manufactured from ČSN 41 1523 structural steel.

Results of 11 selected calculation methods are provided here for comparison. It can be concluded that Liu-Zenner and PCRN methods lead to results with the lowest scatter, their standard deviation being close to one half of the standard deviation relevant to the industrially most often used Dang Van method. Within the range between 100 000 and 750 000 cycles, the prediction quality of individual methods stays relatively stable, and the observed trends (e.g. the change of the mean fatigue index error) is insignificant if compared to the total scatter of prediction results. The relatively narrow scope of the test set does not allow the researchers to generalize more detailed conclusions.

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