EAN 2020
58th conference on experimental stress analysis

Verification of Multiaxial Stress Methods in the Field of Lifetimes Fatigue of Specimens From Steel ČSN 41 1523

FOJTÍK F.[1,a], PAPUGA J.[2,b], PAŠKA Z.[1,c], FUSEK M.[1,d], HALAMA R.[1,e]

[1]Deparment of Applied Mechanics, Faculty of Mechanical Engineering, VŠB – Technical University of Ostrava; 17. listopadu 2172/15, 708 00 Ostrava, Czech Republic

[2]FME Czech Technical University in Prague, Technická 4, 166 07 Prague 6, Czech Republic

[a]frantisek.fojtik@vsb.cz, [b]jan.papuga@fs.cvut.cz, [c]zbynek.paska@vsb.cz, [d]martin.fusek@vsb.cz, [e]radim.halama@vsb.cz

Keywords: high-cycle fatigue, multiaxial fatigue, experiments

Abstract. The contribution describes predictions of fatigue criteria in the area of high cycle fatigue and analysis of fatigue limit. The influence of multiaxial loading is taken into account. The study is performed on the pipe specimens, which were made from steel ČSN 41 1523. The specimens were subjected to different types of combined loading: tension-compression, bending, torsion and inner-outer pressure. Methods for prediction are rated in the interval from 100 000 cycles to 1 000 000 cycles. No significant deviation in prediction abilities of these methods was observed. The three methods - PCRN, QCP and Liu-Zenner (LZ) give the best predictions. Despite the slightly less accurate results of the MMP method, it remains also at stake due to its fastness.

Introduction

The contribution extents results presented by authors in [1,2]. In publications mentioned, authors informed about extensive fatigue research on hollow specimens made of construction steel ČSN 41 1523 (often used for welded constructions). The new method suitable for multiaxial fatigue solution denoted as MMP is also presented in publication [1]. It is extension of Manson–McKnight (MMK) method. The advantage of this method is its simplicity whereas any tabular processor (MS Excel for example) is suitable for the calculation. Here, the method uses Bergman´s approximation is used and therefore it is marked as MMPB. This improved method leads to better prediction of fatigue in comparison with MMK method. Results of undertaken analyses show that results obtained by MMP method can reach the similar quality as results produced by more complex criterions of multiaxial fatigue.

The analysis of fatigue strength stated in [1] was carried out for the lifetime of 750 000 cycles and for all 24 S–N curves acquired from experiments. In publication [2] are presented results of prediction of chosen criterions, each for set of four cross sections in the area of oblique branch of S–N curves acquired from Kohout–Věchet approximation in the range from 100 000 to 750 000 cycles. The aim of this publication is to extend the area tested by the data deducted from S–N curves at the value of 1 000 000 cycles using the new approximation and further to compare the prediction quality using different multiaxial calculation methods and then to compare mutual results of individual methods

Experiments

Three types of specimens were used for experiments. The specimens´ dimensions are given in [1]. Three different types of hollow specimens with following diameters (measured in critical cross section) were used: *D*=20 mm a *d*=18 mm or *D*=11 mm a *d*=8 mm. Specimens were made of construction steel ČSN 41 1523 melt T31052. The static material properties are summarized in Table 1.

Table 1: Static material parameters of the material investigated

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

Description and the realization of experiments can be found in [1]. Ways of specimens loading denoted as FFXX are schematically depicted in Fig. 1.. Each experiment of 24 different loading cases was performed in the force control mode.

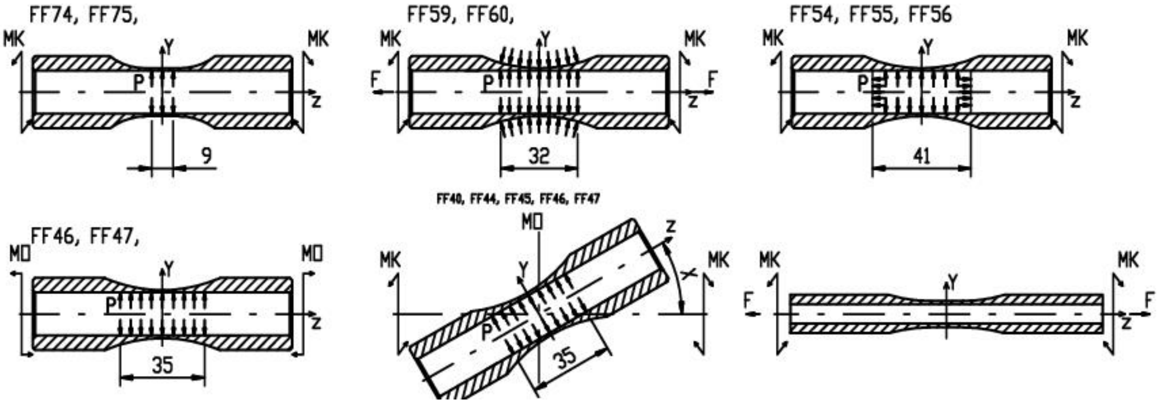

Fig. 1: Overview of various setups of experiments. F – push-pull, M0 - bending moment, MK – torque and P – pressure [1]

Each S–N curve in [1] was acquired from at least 5 experiments by linear regression (Basquine model) or by nonlinear regression (Kohout–Věchet model, see [3]). In some experimental sets (over 750 000 cycles of lifetime), the insufficient agreement between data calculated and experimental results was observed. Therefore, the new regression method (first mentioned in [4]) was used and also the regression of the influence of the mean stress. The regression function proposed is of the form:

$$\sigma = \sigma_0 - (\sigma_0 - \sigma_C) \cdot \sin\left\{\frac{\pi}{2} \cdot [log(4 \cdot N)/log(4 \cdot N_C)]^{a_2}\right\}. \quad (1)$$

This regression can be used as one parametric, where a_2 is a parameter of regression determined by the regression, σ_0 is a static strength and σ_C is a fatigue limit corresponding to the number of cycles N_C. Further, this method can be used as multi parametric where the fatigue limit or static strength can be determined by the regression. The third possible way of use is to estimate the corresponding value of the stress for chosen number of cycles (in the range of 0.25 cycles and the first crack on the specimen). In order to obtain desired loading combination, it was necessary to use different experimental machines and appropriate gripping jigs – reconstructed machine Schenck PWXN, biaxial servo hydraulics machine LABCONTROL 10kN/1000Nm and servo hydraulics machine INSTRON 8802.

Due to unusual load combinations, in some cases, it is not immediately obvious which surface of the hollow specimen is loaded more. For this reason, it was necessary to analyse the critical points on both surfaces during the fatigue prediction phase. The stress components for all load cases on individual specimens were obtained by FE analyses.

Calculations

A total of 21 computational methods were analyzed in the framework of the predictive evaluation. With the exception of the MMP method (see [1]) and the adjusted PCRN method [6], all prediction methods are described in [5]. Stress states in each loading channel corresponding to number of cycles *Nx* were calculated from regression curves. These regression curves were derived using the new regression method. In this contribution, the evaluation for five lifetime levels is carried out: 100 000, 200 000, 500 000, 750 000 and 1 000 000 cycles acquired from regression curves using the new regression.

The relative error between the damage parameter DP calculated (equivalent stress amplitude) and e.g. the fully reversed fatigue tensile strength p_{-1} (tensile loading) or b_{-1} (bending) is determined using fatigue index error ΔFI:

$$\Delta FI = \left(\frac{D_P - p_{-1}}{p_{-1}}\right) \cdot 100\% \,. \tag{2}$$

The contribution evaluates the quality of the prediction based on this parameter. The calculations were performed in the software PragTic (www.pragtic.com). Results obtained for 24 different load cases and for five different lifetimes (read from curves using the new regression) were processed statistically here. Here, the mean value ΔFI and the sum of ΔFI squares are evaluated.

Discussion of results

The results obtained for all prediction methods are statistically processed and are depicted in Table 2.

Table 2: Results of the ΔFI statistics for 21 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	1 000 000
PCRN	46%	2.67%	2.45%	3.54%	2.93%	2.46%	1.95%
DV	121%	2.64%	2.95%	2.82%	2.73%	2.49%	2.21%
SINES	451%	7.88%	9.18%	8.71%	7.89%	7.09%	6.56%
CROSSLAND	135%	-3.23%	-2.84%	-2.92%	-3.15%	-3.46%	-3.76%
PDS	46%	-0.25%	0.97%	0.51%	-0.28%	-0.73%	-1.69%
KK	161%	5.45%	6.84%	6.36%	5.45%	4.62%	3.99%
MMPB	59%	0.28%	1.33%	0.96%	0.32%	-0.29%	-0.92%
MCDMD	175%	1.06%	3.07%	2.07%	0.76%	0.18%	-0.76%
ROGERT	87%	9.44%	11.00%	10.44%	9.44%	8.54%	7.78%
PAPADO	142%	-2.15%	-1.89%	-1.91%	-2.05%	-2.31%	-2.58%
FINDLEY	418%	11.63%	11.22%	11.61%	11.95%	11.78%	11.57%
LZ	57%	0.62%	1.75%	1.38%	0.64%	-0.02%	-0.67%
PIR	87%	1.84%	2.38%	2.25%	1.88%	1.46%	1.22%
PCR	50%	1.64%	2.08%	1.96%	1.69%	1.40%	1.05%
MATAKE	435%	10.59%	10.17%	10.54%	10.89%	10.76%	10.58%
GAM	149%	2.60%	2.54%	2.72%	2.81%	2.57%	2.37%
CS_MD	61%	1.50%	2.22%	1.95%	1.53%	1.22%	0.56%

LM	61%	-2.77%	-2.01%	-2.17%	-2.58%	-3.21%	-3.86%
QCP	40%	-1.06%	-0.04%	-0.40%	-1.06%	-1.57%	-2.24%
SUSMEL	139%	3.30%	4.99%	3.89%	2.99%	2.53%	2.10%
PAPADO_CPA	105%	3.88%	3.96%	4.04%	4.03%	3.83%	3.55%

Table 2 summarizes the sum of squares *ΔFI*, which describe well the remoteness of the general trend from the correct one. To distinguish the general shift of all results to a conservative or non–conservative prediction from the variance around the mean value, Table 2 also contains mean relative error values for individual lifetimes and for all lifetimes. The best results show QCP, PCRN and PDS methods, the worst results then SINES, MATAKE and FINDLEY methods.

An important question in the overall assessment is whether individual methods will show a substantial difference in different lifetimes. Table 2 shows that the mean values of the fatigue index error change slightly. The most methods show the difference of mean value up to 2%.

Conclusions

The analysis presented in this contribution is focused on comparison 21 different damage prediction methods, which were tested on the set of 24 S–N curves for different loading cases. S–N curves were determined by new regression. The experimental results described earlier [1] were obtained on hollow specimens made of structural steel ČSN 41 1523 of melting T31052.

There are presented and compared results of calculations of 21 selected multiaxial methods and the statistical processing of results in the form of an mean value *ΔFI* and the sum of their squares is performed. It can be stated that the QCP and PCRN methods lead to the results with the lower variance unlike the Dang Van method (DV), which is the most commonly used method in the industry. In the range of 100 000 to 1 000 000 cycles, the quality of prediction of individual methods remains relatively stable and, for example, the change in the average error index value is negligible compared to the overall variance of the prediction results.

Acknowledgement

The paper has been done in connection with project: National Competence Centre of Mechatronics and Smart Technologies for Mechanical Engineering, reg. no. TN01000071. This work was also supported by Grant Agency of the Czech Republic (GACR) project No. 19-03282S, and by the specific research SP2020/23 project, supported by the Ministry of Education, Youth and Sports of the Czech Republic.

References

[1] J. Papuga, F. Fojtík, Multiaxial fatigue strength of common structural steel and the response of some estimation methods, International Journal of Fatigue 104 (2017) 27-42.

[2] J. Papuga, F. Fojtík, M. Fusek, Efficient Lifetime Estimation Techniques for General Multiaxial Loading, in: Proceedings of the 56th International Scientific Conference on Experimental Stress Analysis 2018, 2018 pp. 96-101.

[3] J. Kohout, S. Věchet, A new function for fatigue curves characterization and its multiple merits, International Journal of Fatigue 23 (2001) 175-183.

[4] F. Fojtík, J. Fuxa, New modification of conjugated strength criterion, Transactions of the VŠB - Technical University of Ostrava – Mechanical Series, Vol. LVI, No. 1, (2010), 53–60.

[5] J. Papuga, A survey on evaluating the fatigue limit under multiaxial loading, International Journal of Fatigue 33 (2011) 153-165.

[6] J. Papuga, R. Halama, Mean stress effect in multiaxial fatigue limit criteria, Archive of Applied Mechanics, (2018), 1–12.