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Theoretical Investigation of Steel Plated Girder Resistance

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Abstract**—** In the paper, the results of sensitivity analysis of the influence of initial imperfections on the web stress state of a thin-walled girder are presented. The results of the study corroborate a very good and effective agreement of experiments with theory. Most input random quantities were found experimentally. The change of sensitivity coefficients in dependence on working load value is analysed. The stress was analysed by means of a geometrically and materially non-linear solution by applying the program ANSYS. This research study offers important background for theoretical studies of stability problems, post-critical effects and limit states of thin-walled steel structures.

Keywords**—** Buckling, Fatigue, Imperfection, Steel, Sensitivity analysis.

I. INTRODUCTION

THE main contents of the experimental examination of the fatigue limit state of thin-walled steel girders is the analysis of "breathing" of a thin wall under multiple repeated loading. The research results presented in this paper corroborate a very good and effective cooperation of experiments with theory. Although only theoretical research is predominantly concerned, it was influenced, at the beginning, by the experiments which took place at the working place of the third author in past, and which have been going on until now. The present research work offers important background for theoretical studies of stability problems, post-critical effects and limit states of thin-walled steel systems. Taking into consideration a very complicated character of the mechanism of failure accumulation within the system with "breathing" plate elements, it is necessary to verify and calibrate a calculation model, based on experiments.

As the results of fatigue tests of thin-walled girders show a large variance, the causes must be searched for. Of course, this variance can be expected to be given, to a large extent, by the influence of inevitable initial imperfections of the system but this qualitative expectation is not satisfactory - it is necessary to quantify and to show in detail, to what extent is the girder fatigue effect sensitive to these imperfections. The sensitivity analysis is therefore an ideal instrument for researching into it.

II. EXPERIMENTAL RESEARCH OF FATIGUE BEHAVIOR OF THE WALL

It follows from the experimental research results that the major manifestation of failure accumulation in "breathing" walls is the fatigue crack initiation (see Fig. 1) which continues growing under permanent loading and becomes the main factor of the mechanism of the whole girder breakdown. Further on, experiments have shown that fatigue cracks initiate quite always in the close neighbourhood of fillet welds connecting the "breathing" wall with its peripheral elements (i.e., with flanges and stiffeners of the girder), namely in the points where the repeatedly buckling wall shows the stress peaks. Therefore it is purposeful to study the influence of imperfections on the stress state in those points of the wall where fatigue cracks initiate under repeated loading.

If reliable information on the influence of inevitable imperfections on the stress state intensity has to be obtained, it is appropriate to obtain reliable information on the shape of initial geometrical imperfections of slender walls of steel girders above all, fatigue behaviour of which is the topic of our study. And it was the first objective of the study described by the authors.

III. INPUT RANDOM QUANTITIES

The shape and size of initial curvature of the slender wall are among the imperfections measured. The girder initial curvature was approximated by double sine Fourier series with random amplitudes.

$$
\begin{aligned}
F(x,y) = {} & e_1 \sin\left(\frac{\pi x}{l}\right)\sin\left(\frac{\pi y}{l}\right) + e_2 \sin\left(\frac{\pi x}{l}\right)\sin\left(2\frac{\pi y}{l}\right) + e_3 \sin\left(\frac{\pi x}{l}\right)\sin\left(3\frac{\pi y}{l}\right) + \\
& e_4 \sin\left(2\frac{\pi x}{l}\right)\sin\left(\frac{\pi y}{l}\right) + e_5 \sin\left(2\frac{\pi x}{l}\right)\sin\left(2\frac{\pi y}{l}\right) + e_6 \sin\left(2\frac{\pi x}{l}\right)\sin\left(3\frac{\pi y}{l}\right) + \\
& e_7 \sin\left(3\frac{\pi x}{l}\right)\sin\left(\frac{\pi y}{l}\right) + e_8 \sin\left(3\frac{\pi x}{l}\right)\sin\left(2\frac{\pi y}{l}\right) + e_9 \sin\left(3\frac{\pi x}{l}\right)\sin\left(3\frac{\pi y}{l}\right).
\end{aligned}
$$

The statistical evaluation results of experiments are given in detail in [1]. It has been found that the shape of initial curvature e_1 (shape 1x1) has the dominant influence. The studies are elaborated analogously as in [2], where the random amplitude having the initial curvature form e1 was

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approximated by lognormal distribution. This assumption must be introduced into the sensitivity analysis so that a monotonous dependence was between the input and output. In case the value with negative sign was measured for coefficients e_1, the signs were changed for all coefficients e_1 to e_9 so that the coefficient e_1 were always positive. It means in practice that if the negative sign were obtained for a random amplitude, the measurement would be repeated but it were carried out from the "second" side of the wall (biaxially geometrical girder).

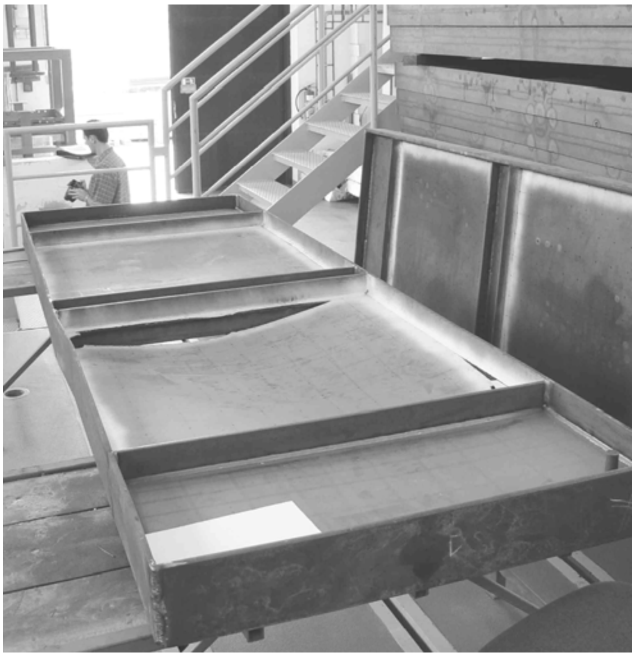

Fig. 1 Experimental research

Further on, the experimental research results were applied to theoretical analysis in which took part the Faculty of Civil Engineering of the Technical University in Brno together with the company VÚHŽ (Research Institute of Iron Metallurgy) in Dobrá, a.s. The aim of this research was to elaborate the statistic analysis of material and geometrical characteristics of steel plates and shaped members [3].

The not measured characteristics are based on the data given in special literature. The influence of deviations of physical mechanical characteristics (non-homogeneity above all) was substituted, in a simplified way, by the Young's modulus E variability. The Gaussian distribution with mean value m_E = 210 GPa and standard deviation S_E = 12.6 GPa were assumed; this is in agreement with experimental results [4] and [5]. In Tab. I, there are presented only the input random quantities for which it was confirmed according to the results of sensitivity analyses that their influence on bending stress along the wall circumference is not zero. In addition to these quantities, also the yield strength random variability was introduced for all plates by the histogram having mean value m_{fy} = 284.5 MPa, and standard deviation S_{fy} = 21.5 MPa, see [3].

TABLE I
INPUT RANDOM QUANTITIES

No.	Random quantity		Unit	Mean value	Standard deviation
1.	e_1	Amplitudes of the function (1) of initial curvature.	mm	3.574	3.335
2.	e_2		mm	1.544	2.315
3.	e_3		mm	-0.950	2.461
4.	e_4		mm	-0.106	0.937
5.	e_5		mm	-0.005	0.570
6.	e_6		mm	-0.117	0.298
7.	e_7		mm	0.040	0.650
8.	e_8		mm	0.182	0.577
9.	e_9		mm	-0.078	0.583
10.	Wall thickness t_w		mm	4	0.2
11.	Young's modulus of the wall		GPa	210	12.6
12.	Upper flange thickness		mm	10	0.7
13.	Young's modulus of upper flange		GPa	210	12.6
14.	Thickness of lower flange		mm	10	0.7
15.	Young's modulus of lower flange		GPa	210	12.6
16.	Thickness of left stiffener		mm	12	0.84
17.	Young's modulus of left stiffener		GPa	210	12.6
18.	Thickness of middle stiffener		mm	12	0.84
19.	Young's modulus of middle stiffene		GPa	210	12.6
20.	Thickness of right stiffener		mm	12	0.84
21.	Young's modulus of right stiffener		GPa	210	12.6

IV. SENSITIVITY ANALYSIS OF THE STRESS STATE

A. *Sensitivity analysis*

The sensitivity analysis was evaluated in the form of the Spearman rang-order coefficient [6], [7]. The work is based on the assumption of a study of the correlation between input quantities and output. The method described is based on the assumption that the correlation degree of the quantities to which the output is more sensitive will be higher, and it can be recommended for all the methods of the Monte Carlo type. Realizations of input random quantities were simulated by the LHS method for 1000 simulation runs.

B. *Computation model*

As the output quantity, bending stress perpendicular to the wall edge in points A, B, was considered, see Fig. 1, where fatigue crack initiation and propagation occur most frequently according to experimental tests. The girder stress state was analyzed by FEM, by means of geometrically and physically nonlinear solution. The girder was modeled in the very detail by the mesh of shell elements SHELL 181 in the program ANSYS LS Dyna. The appropriateness of calculation model was verified by comparison with results of experiments. At the works, both contemporary and earlier experiments realized at the UTAM AVCR (Institute of Theoretical and Applied Mechanics of the Academy of Sciences of the Czech Republic) were taken use of.

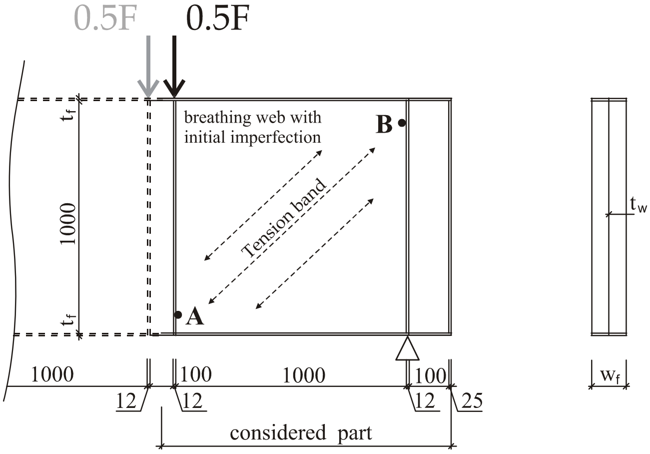

Fig. 2 Thin-walled steel girder

C. Sensitivity analysis results

The values of sensitivity coefficients (1) of influence of random imperfections on bending stress in the points A are plotted in Fig. 3. On the horizontal axis, there are plotted the l values of load action which was assumed deterministically in the interval 10 % to 60 % of the average static load-carrying capacity 695.62 kN; these are the values specifying the interval of the occurrence of working load approximately. The average value of static load-carrying capacity 695.62 kN was found applying the LHS method (by the program ANSYS), and it is in a very good agreement also with the result of the experiment. The sensitivity analysis results in the point B are shown in Fig. 4. Only the dominant imperfections of quantities 1 to 10 are represented graphically, see Tab. I (correlation coefficients of other quantities were found within the interval and have not been represented, being unimportant from the sensitivity point of view).

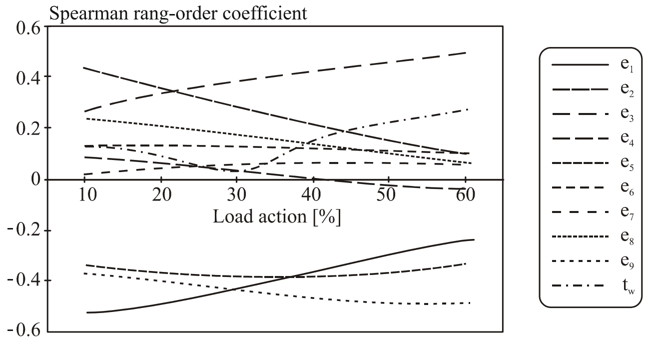

Fig. 3 Sensitivity analysis of bending stress in point A.

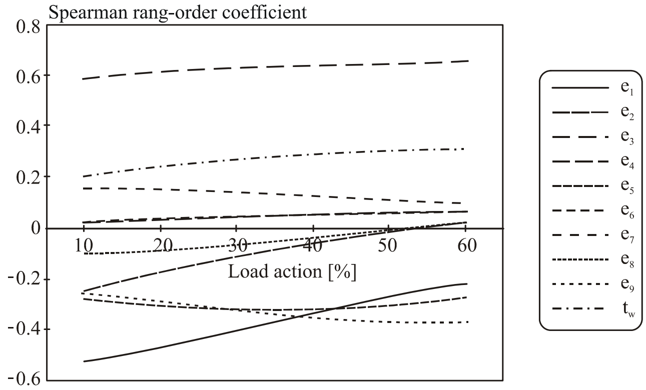

Fig. 4 Sensitivity analysis of bending stress in point B.

V. CONCLUSION

It is evident from Figs. 3 and 4 that the absolute value of correlation coefficients among bending stress and coefficients e_1, e_2 and e_8 decreases with increasing value of load action. On the contrary, the absolute value increases for coefficients e_3 and e_9, for coefficients e_4, e_5, e_6, e_7 and t_w it is not possible to observe an unambiguous trend. The positive or the negative sign of the known sensitivity coefficient suggests whether the input quantity influences the output quantity (bending stress) positively, or negatively. The variability of the wall initial curvature was modeled so that bending stress were a monotonous function of input quantities if possible. In case the bending area shape were assigned with opposite sign also the sign of bending stress, and by the same also that of correlation coefficient, were opposite. From the point of view of fatigue phenomena, it is relevant, in this case, to study absolute sizes of correlation coefficients. It must be noticed that the character of presented results is only partial because they relate only to bending stress in analyzed points A and B. The results complete purposefully the relative studies [8] of the sensitivity analysis of the stress state along the wall circumference [9].

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