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THE FATIGUE AND SERVICEABILITY LIMIT STATES OF THE WEBS OF STEEL GIRDERS SUBJECTED TO REPEATED LOADING

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Abstract. *As a great part of steel structures are subjected to many times repeated loads (bridges, crane-supporting girders and the like), it is demonstrated, by means of the results of numerous experiments carried out by the authors in Prague, how the post-critical reserve of strength, the failure mechanism and the limit states of the webs of steel girders are affected by the cumulative damage process generated by the many times repeated character of loading, and how this phenomenon influences the design of such girders.*

1 THIN-WALLED CONSTRUCTION AND POST-BUCKLED BEHAVIOUR IN IT

One of the most promising trends in our striving to save steel is to use thin-walled structures, i.e. structural systems made of slender (usually plate) elements. Of course, here it can be argued that such elements are liable to buckle so that then the limit state of the system is substantially reduced by stability phenomena. The situation is however remedied by the miracle of post-buckled behaviour, in the light of which a thin-walled plated system subjected to quasi-constant loading behaves like a (so called) super-smart structure, i.e. like one which is able not only to diagnose its own situation, but also to generate a means of powerful self-defence, thanks to which the ultimate strength of the system is usually very significantly higher than the linear-buckling-theory critical load.

That is why a great attention has been internationally paid to research on the post-buckled behaviour and ultimate strength of slender webs, flanges and other plate elements, the Czech research always striving to play a useful role in these activities.

For example, the authors of this paper and their co-workers spent about three decades in investigating the post-critical reserve of strength and ultimate load behaviour of steel plate girders, box girders, thin-walled columns etc.

2 PARTIAL "EROSION" OF THE POST-BUCKLED BEHAVIOUR IN THIN-WALLED CONSTRUCTION SUBJECTED TO MANY TIMES REPEATED LOADING

Although a great part of steel plated structures used in building construction can be listed among structures under the action of quasi-constant loading, this cannot be said about steel bridgework, crane supporting girders and similar systems. Such structures are exposed to many times repeated loading. Then, if their webs are slender, they repeatedly buckle out of their plane. This phenomenon, being now usually termed web breathing, induces significant cumulative damage process in the breathing webs and we can ask the obvious question of whether the breathing phenomenon leads to a significant „erosion" of the post-critical reserve of strength described above.

And to research on this problem the authors turned their attention several years ago.

Given the complex character of the cumulative damage process in breathing webs, it was crystal clear that a very important role should be played by experiments. The tests, their number already exceeding two hundred, were conducted in three laboratories, viz. at (i) the Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences, (ii) Klokner Institute of the Czech Technical University, and (iii) the Research Institute of Materials.

The large number of tests proved to be indispensable in view of the large scatter which is characteristic of all breathing experiments.

But as this juncture it is useful to say a few words about the character of the test girders used.

Like most girders tested now by the writers at the Institute of Theoretical and Applied Mechanics in Prague, they are fairly large, having a web 1000mm deep, so that their character is not far from that of ordinary girders.

All the girders were fabricated in the steel fabricator of Division 7 of the Company METROSTAV plc., using the same technological procedures as are applied there in the fabrication of ordinary steel bridges. It is important to note that, in the fabrication of the test girders, no attempt was made to diminish (by heat treatment) the initial curvature of the web generated during the process of girder fabrication.

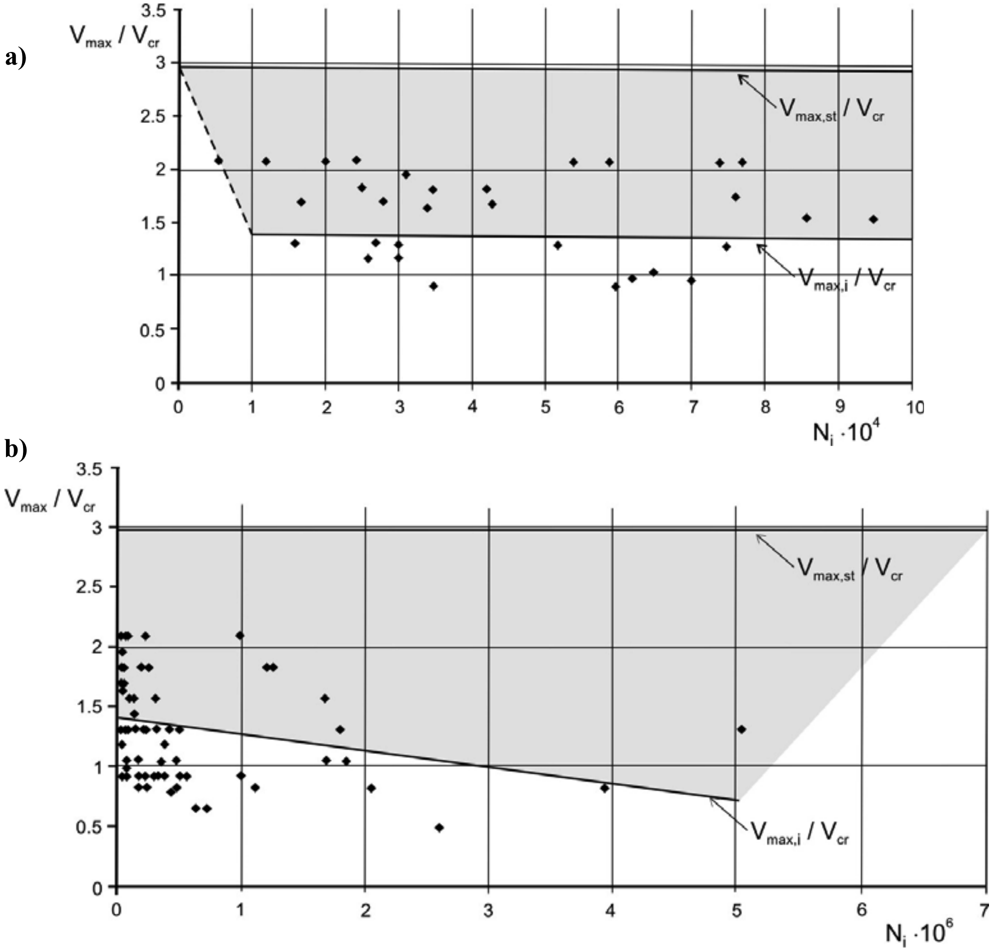

Figure 1: The cumulative-damage induced "erosion" of the maximum load – with respect to the initiation of the first fatigue crack.

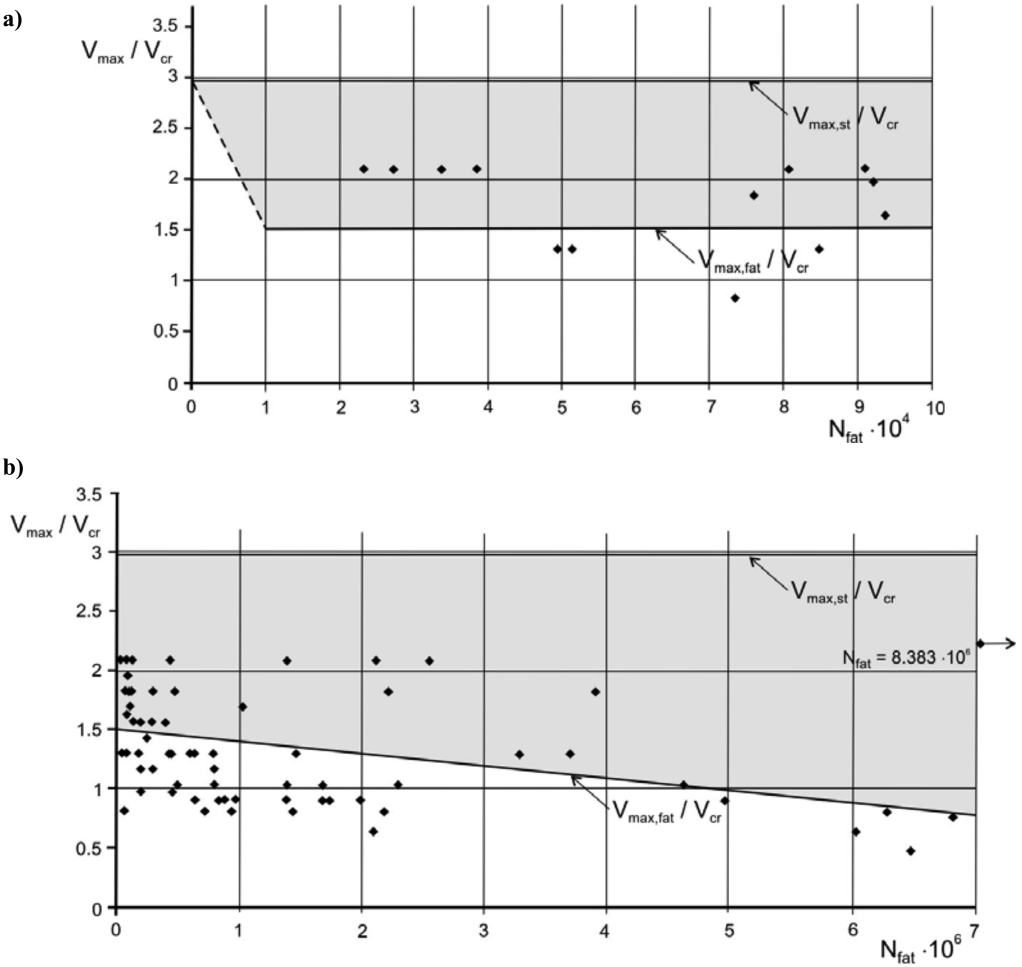

Figure 2: The cumulative-damage induced “erosion” of the maximum load – with respect to the fatigue failure of the girder.

Here only some of the conclusions drawn during the experimental investigation can briefly be mentioned. Other results and conclusions can be found for example in [1].

For the purpose of practical design it is important to know what portion of the post-buckled strength , i.e. of the maximum load that a girder is able to sustain, is “eroded” when the girder is exposed to many times repeated loads.

The authors were able to shed some light on this interesting question because for each series of their fatigue tests, they also carried out a few static experiments on girders having the same dimensions. Given the character of the Prague test girders, their webs were subjected to combined shear and bending, with the effect of shear predominating. Let us therefore measure the loading of each web panel by shear force V, its intensity being determined by ratio V/V_{cr} , when V_{cr} is the critical shear force (given by the linear buckling theory), calculated for a web panel clamped into the flanges and hinged on the transverse stiffeners. The ratio V/V_{cr} then also determines the post-buckled reserve of strength.

The results of the writers´ experiments are shown in Figures 1 and 2. The corresponding ratios V_{max}/V_{cr} are plotted on the vertical axis, the related numbers N of loading cycles on the horizontal axis.

As all of the Prague breathing tests are conducted to failure, the authors are able to study the whole history of the development of each fatigue crack from its initiation to the collapse of the whole girder. Figure 1 is then related to the initiation of the first crack and Figure 2 to the fatigue failure of the whole girder.

Each of the two figures is divided into two parts: that denoted by a concerns $0 < N \leq 10^5$ (i.e. the interval of N where the gradient of the test results is greatest), the part b then holds for $N > 10^5$.

A very significant impact of the cumulative damage process on the fatigue tests can easily be seen in the figures. As the Prague breathing experiments exhibited, like most fatigue tests of all kinds, a large scatter, an average line of the breathing tests is also given in the figures. The area above it, $(V_{max,st}/V_{cr} - V_{max,fat}/V_{cr})_{average}$, gives an average value of the cumulative-damage induced "erosion" of the maximum sustainable load.

3 IMPACT ON FAILURE MECHANISM

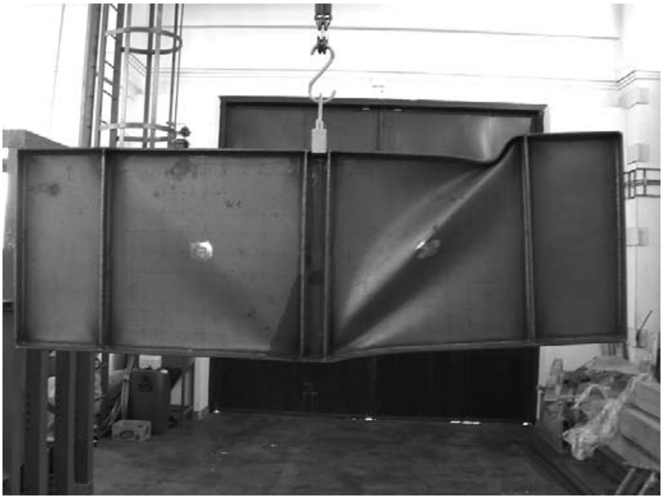

Figure 3: The failure mechanism of one of the test girders subjected to constant loading

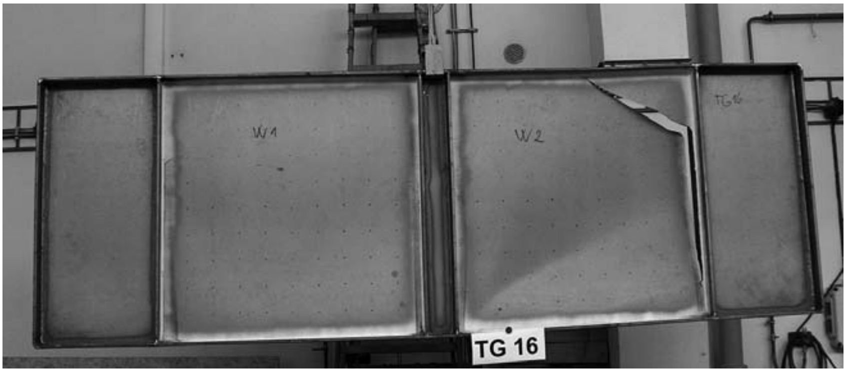

Figure 4: The failure mechanism of one of the test girder subjected to repeated loading

The process of the initiation and propagation of fatigue cracks in the breathing web substantially alters the failure mechanism of the whole girder.

When the girder is under the action of quasi-constant loading, the performance and limit state mechanism of the web is well-known: a redistribution of membrane stresses in webs subjected to compression or in-plane loading, which can easily be taken into account by way of defining an effective depth of the web, and a kind of tension field, or tension band, action in webs in shear, for which also user-friendly methods exist. In the case of constant predominantly shear loading, this mechanism consists (as was in detail described by K. C. Rockey and one of the authors more than four decades ago) of a plastic diagonal tension band in the web and a system of partial plastic hinges (see Figure 3).

But in the case of many times repeated loads, the web - so to speak - does not have enough time to develop the aforementioned classical mechanism, since its behaviour is over-shadowed by the initiation and propagation of fatigue cracks, and the failure mechanism of the girder is more complex. And the cumulative damage process is not here parallel to, but instead of classical buckling failure, which it entirely replaces and therefore determines the maximum sustainable load.

Then, in the case of repeated predominantly shear loading, this mechanism is significantly affected by the presence of a large opening in the web (which is a well developed main fatigue crack) usually “cutting” the plastic diagonal band in the web (see Figure 4).

4 IMPACT ON DESIGN

It follows from the above analysis that the problem of web breathing can play a very important role and therefore cannot be disregarded; on the contrary, it can significantly affect the design of steel bridges, crane-supporting girders and other structural systems under the action of many times repeated loads.

And to establish a reliable method for the analysis of the breathing webs of thin-walled girders was the main objective of the authors´ research.

First it should be mentioned here that during the first stage of our research, we deliberately postponed any attempt to establish a design procedure, desiring first to “map” in detail all aspects of the breathing phenomenon (the initiation and propagation of fatigue cracks and their role in the failure mechanism of the girders, and a suitable definition of the limit state of the whole system) and the part of all factors influencing it.

It is also worth mentioning that, unlike some tests carried out by other authors, in which the experiments were stopped when the first observable crack was detected, all of the Prague tests were conducted to failure. Thus we were able to “map” the whole history of all fatigue cracks – from their initiation to the failure of the girder. Thereby we avoided being “fascinated” by the very phenomenon of crack appearance, but were able to study the further development of each crack, to see whether it propagated or stopped, and to find out how far away was the initiation of the first fatigue crack from the fatigue failure of the whole girder.

Based on an analysis of the experimental results obtained and thanks to having thus “mapped” for all test girders the whole regime of fatigue crack growth from the initiation of the first fatigue fissure to the failure of the whole girder, the authors were able to establish a design procedure based on S-N curves.

5 S-N CURVES ESTABLISHED BY THE WRITERS ON THE BASIS OF THEIR BREATHING TESTS

The authors follow the general features of the design philosophy proposed by Maquoi and Škaloud [2], according to which two limit states are introduced in the analysis, viz. (i) the fatigue limit state, (ii) that of serviceability.

While the fatigue limit state can be related to the failure of the girder (i.e. to unrepairable damage – which is acceptable in view of the fact that the fatigue limit state can never be attained during the planned life of the girder), the limit state of serviceability should be related to a much more limited, easily repairable degree of damage. In the case of steel girders with breathing webs, this means that, in the course of the useful fatigue life of the girder, either no or very small fatigue cracks can develop, such as to be easily kept under control, or easily retrofitted in case of need.

The two limit states can be ascertained directly on the basis of the authors´ breathing tests, following the statistic procedure recommended in Appendix Z of EUROCODE 3. In so doing, the range of the stress state in the breathing web can be measured simply by the range $\Delta\tau$ of the average shear stress τ_0 (= shear force V/web area A_w) in the web. Only those of the writers´ experiments were considered in which the girder went through all stages of fatigue crack growth until the very failure of the girder.

Before proceeding to the derivation of the S-N curves, let us define the range of their application.

The breathing phenomenon is usually linked with high-cycle fatigue. The frontier, measured by the number N of breathing cycles, between high-cycle and low-cycle fatigue is between 10^4 and 10^5 cycles. As the authors also obtained enough results in this domain, the S-N curves can be regarded as applicable for $N > 10^4$. As regards the other boundary, i.e. for high values of N, the S-N curves established herebelow hold for all $N < 10^m$ cycles. For the fatigue limit state m = 6.75, for the serviceability limit one m = 6.25. However, for these very high values of N, the S-N curves shall yet be completed by determining their threshold values.

As far as web slenderness λ and aspect ratio α are concerned, let us mention that the authors´ experiments were carried out for λ = 117, 175, 250 and α = 1, 1.43, 2, which are the parameters of the webs of most steel plated girders subjected to breathing. The influence of these parameters is reflected in the S-N curves by the role of the quantity τ_{cr}, the (linear-buckling-theory) critical load of the web. Given the fact that the writers´ tests were conducted on girders with various flange dimensions, τ_{cr} can also take account of the boundary conditions of the web.

A similar statement can be made in regard to web loading. The webs of the writers´ test girders were under the action of combined shear τ and bending σ, with shear predominating, i.e. their σ/τ ratios < 1.0. This means that the S-N curves are applicable to webs subjected to shear or to combined shear τ and bending σ provided $\sigma/\tau \leq 1.0$. For larger σ/τ ratios the S-N curves shall be the objective of further research.

Let us now establish, via the statistic procedure recommended in Appendix Z EUROCODE 3, the S-N curves for both limit states.

148 test results, i.e. the data resulting from all of those authors´ experiments in which the authors were able to study the whole cumulative damage process in the breathing webs from the initiation of the first fatigue crack to the complete fatigue failure of the whole girders, were used in the analysis.

All test results related to the fatigue failure of the test girders, i.e. to their fatigue limit state, are plotted in Figure 5a. Also two straight lines are given there: one of them shows average values of the experimental results obtained (their scatter being large) and the other one is the fatigue limit state S-N curve proposed by the authors.

Mathematically it can be expressed as follows:

$$\log(\Delta\tau/\tau_{cr} + 1) = -0.1027\log N + 0.7537 \tag{1a}$$

where $\Delta\tau$ is the shear stress range, τ_{cr} the critical load of the web given by linear buckling theory, and N is the number of loading cycles to which the web is subjected.

All test results related to the initiation of the first fatigue crack, i.e. to the serviceability limit state, are plotted in Figure 5b, the two straight lines having the same meaning as above in Figure 5a.

Mathematically the S-N curve for the limit state of serviceability is given by this relationship:

$$\log(\Delta\tau/\tau_{cr} + 1) = -0.0756\log N + 0.5265 \tag{1b}$$

all symbols having the same meaning as in the formula for the fatigue limit state.

The above formulae for the S-N curves need completing by determining their threshold values. In their analysis, let us concentrate merely on experimental results for high N-values, and let us determine the threshold value, $\log(\Delta\tau/\tau_{cr} + 1)_{th}$,by the requirement that only 5% (this high percentage is acceptable in the view of the scatter of test results being very large) of the experimental data obtained can be under the threshold value.

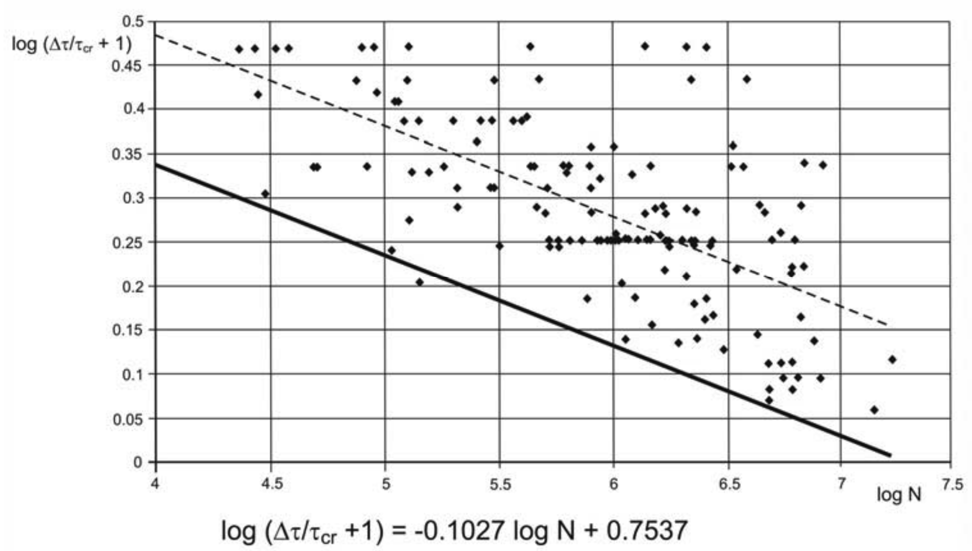

Figure 5a: S-N curve for the fatigue limit state.

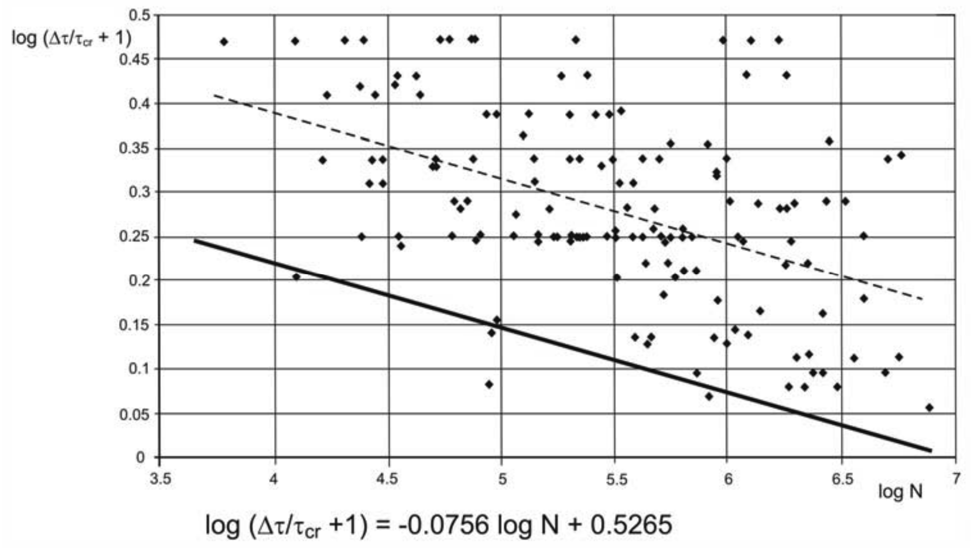

Figure 5b: S-N curve for the serviceability limit state

Thereby we arrive, for both of the two limit states, at the threshold value

$$\log(\Delta\tau/\tau_{cr} + 1)_{th} = 0{,}08 \qquad (2)$$

For lower values of log $(\Delta\tau/\tau_{cr} + 1)_{th}$ and for all larger values of N, the S-N curves are assumed to be horizontal.

And what about the effect of various stress ranges?

If, during its lifetime, the web is subjected to various stress ranges $\Delta\tau_i$ Palmgren-Miner´s criterion can be used:

$$\sum \frac{n_i}{N_i} \leq 1 \tag{3}$$

where n_i is the actual number of loading cycles for the stress level $\Delta\tau_i$ and N_i is the life, determined from the above S-N curves, of the web determined on the assumption that $\Delta\tau_i$ is the only loading to which the breathing web is subjected during its whole lifetime.

6 FATIGUE ASSESSMENT OF BREATHING WEBS IN THE LIGHT OF THE S-N CURVES ESTABLISHED BY THE AUTHORS

The fatigue assessment of breathing webs should then proceed as follows:

- The first limit state, connected with fatigue failure, shall not be reached before the whole planned life of the structure has been exploited.
- The other limit state, related to the (experimentally observable) initiation of the first-fatigue-through-crack, governs the maximum time before which the first inspection of the girder for potential fatigue cracks needs to be carried out.

If no fatigue fissures are found during the inspection, the useful life of the girder can be extended until another inspection is conducted after one half of the time period to the first inspection (this reflecting the fact that the degree of cumulative damage in the breathing web is then larger than during the first period). Failing to detect any fatigue cracks even then, the system of inspections can be extended in the same way. If, and when, a fatigue crack is detected, it shall be carefully measured – via frequent enough inspections – with the view to find out whether it (i) propagates or (ii) has stabilised.

The results of the two checks mentioned above will decide whether some retrofitting of the girder is necessary.

7 CONCLUSIONS

Based on their experimental results, the authors established S-N curves which can serve as a basis for the design of plate girder webs breathing under many times repeated combined shear and bending.

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REFERENCES

[1] Škaloud, M. and Zornerová, M., “The post-buckled behaviour in thin-walled steel construction and its partial "erosion" under repeated loading”, invited lecture at *Mini-Symposium Stability and Non-Linear Behaviour of Steel Structures,* Lisbon, 2009. To be published in a Special Issue of the Int. Journal of Struct. Stability and Dynamics.

[2] Maquoi, R. and Škaloud, M., “Some remarks in regard to the fatigue analysis of steel plate girders with breathing webs”, *Proc. of the 20th Czech-Slovak Conference Steel structures and bridges 2003,* J. Studnička, Czech Technical University in Prague, Prague, 397-402, 2003.