Stability and Ductility of Steel Structures

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ANALYSIS OF THE EFFECT OF INITIAL CURVATURE ON THE STRESS STATE IN BREATHING WEBs

Z. Kala¹, J. Kala¹, M. Škaloud² and B. Teplý¹

¹Faculty of Civil Engineering, Brno University of Technology, Veveří 95, 662 37 Brno, CZECH REPUBLIC
²Institute of Theoretical and Applied Mechanics, Czech Academy of Sciences, Prosecká 76, Prague 9, CZECH REPUBLIC

ABSTRACT

The objective of the research is to support, via theoretical analysis, the extensive experimental investigation into the breathing phenomenon and the fatigue limit state of steel plate girders which has for several years been under way at the Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences in Prague. It was found out that the scatter of the experimental results obtained was mainly due to the effect of the initial imperfections of the test girders, particularly to the influence of the initial out-of-flatness of their webs. While the main objective of the striving of the authors of this paper is to carry out a sensitivity analysis of the problem based on probabilistic theories, this paper describes the main results of the first (preparatory) stage where the influence of the shape and magnitude of the initial curvature of the web is studied, on three characteristic cases, via a deterministic approach.

KEYWORDS

Web breathing, fatigue limit state, fatigue cracks, stresses in crack-prone areas.

INTRODUCTION

One of the most important tasks of current research on the stability problems of steel structures is research on the fatigue limit state of thin-walled plated systems subjected to many times repeated loading. The slender plate elements of such structural systems, exposed to many times repeated loading cycles, repeatedly buckle (“breathe”), thereby generating cumulative damage in them. Fatigue cracks then initiate in the system and propagate under further loading cycles so as eventually to influence, and very substantially so, the failure mechanism and the limit state of the structure. It is therefore understandable that no further progress in the design of steel bridges and similar systems subjected to many times repeated loading can be promoted unless the breathing problem is carefully studied. That is why extensive research, including also 140 experiments, on this problem has for
several years been under way at the Institute of Theoretical and Applied Mechanics of the Czech Academy of Sciences in Prague, during which valuable information in regard to the fatigue behaviour of steel plate girders has been obtained, see the general report for this session and the contribution Škaloud, Zörnerová (2002). It is hoped that the results obtained and conclusions drawn can contribute to the designer having soon at his disposal a reliable and economical method for the analysis of the breathing of the plate elements of thin-walled structural systems.

It is worth mentioning at this juncture that the results of the Prague breathing tests exhibited a large scatter. It was found out that this scatter was mainly due to the effect of the initial imperfections of the test girders, particularly to the influence of the initial out-of-flatness of the girder webs. That is why the authors decided to join their forces and to shed some light on this influence.

**DEFINITION OF THE PROBLEM TO BE STUDIED**

Let us study the sensitivity of the stress state in the webs of steel plate girders to the effect of the out-of-flatness of their webs.

The problem will be investigated on one of the girders tested in Prague, Figure 1.

![Diagram of the plate girder under investigation](image)

Figure 1: The plate girder under investigation.

The girder has two web panels and is loaded at its mid-span by a point load; hence, the web panels are subjected to combined shear and bending with shear predominating. Two cases of flange thickness are considered, thus giving the authors a possibility also to take account of the boundary conditions of the web.

As far as the state of stress in the web is concerned, our attention will be focused on those areas where fatigue cracks initiated during the Prague tests, i.e. at the toes of the fillet welds connecting the breathing web with its peripheral elements – flanges and transverse stiffeners. In so doing, the stress state will be measured by (i) the principal surface stress in the above crack-prone areas (which, in the light of fatigue analysis, is the geometric stress for so-called unclassified details) and (ii) the bending stress perpendicular to the web boundary (which, as was found out via theoretical and experimental analysis, is the main component of the state of stress in the crack-prone areas).
The effect of the initial curvature of the web is twofold, via:

(i) the effect of the shape of the initial curvature,
(ii) that of its magnitude.

Therefore, both of the two aspects will be subjected to analysis.

Of course, the main objective of the striving of the authors of this paper is to carry out a sensitivity analysis, based on probabilistic theories, of the shape and magnitude of the initial out-of-flatness of the girder web, in terms of the magnitude of the load to which the girder is subjected and taking account of the size of the girder flanges and thereby of the boundary conditions of the “breathing” web.

This sensitivity analysis has already started, but will take some time to be completed. The results obtained and the conclusions drawn will be published in due time.

This paper deals with the main results of a preparatory stage, during which the influence of the configuration of the web initial curvature is studied via a deterministic approach on three characteristic examples of the initial curvature (see Figures 2a, 3a and 4a).

**SOLUTION OF THE PROBLEM**

With the view to solve the problem by means of FEA, the program system ANSYS was used. With respect to the symmetry of the girder studied, and to the exacting character of the numerical calculation involved, only half of the plate girder length was considered. The symmetry plane was prescribed under the point of load application by preventing any displacement in the axis x and by the rotation around the axes y and z (UX, ROTY, ROTZ).

The arrangement of the structure geometry can be seen in Figure 1. The hinge support was modelled so as to prevent the displacements UY, UZ. The geometry of the thin-walled section studied was modelled by a four-node shell element provided in [ as SHELL 43, which makes it possible to solve physically and geometrically non-linear problems. The non-linear material behaviour was included in the analysis by means of a bi-linear kinematics model with stiffening. The density of the elements network was chosen as high as to enable the authors to describe the local buckling of the plate elements of the girder. The layout was then formed by 5344 finite elements with 5434 nodes. The solution of the problem leads to a system of 32 370 equations.

**DISCUSSION OF THE RESULTS OBTAINED**

Some of the main results are summarized in Figures 2, 3 and 4, each of them having parts (a), (b), (c), (d), (e) and (f).
Figure 2: The first case under study

(a) The shape of the initial curvature of the web
(b) The buckled pattern of the web
(c) The principal membrane stresses in the web
(d) The principal surface stresses in the crack-prone areas - the front side of the web
(e) The principle surface stresses in the crack-prone areas - the reverse side of the web
(f) The bending stresses in the crack-prone areas, perpendicular to the web edge
Figure 3: The second case under study

(a) The shape of the initial curvature of the web
(b) The buckled pattern of the web
(c) The principal membrane stresses in the web
(d) The principal surface stresses in the crack-prone areas - the front side of the web
(e) The principle surface stresses in the crack-prone areas - the reverse side of the web
(f) The bending stresses in the crack-prone areas, perpendicular to the web edge
Figure 4: The third case under study

(a) The shape of the initial curvature of the web

(b) The buckled pattern of the web

(c) The principal membrane stresses in the web

(d) The principal surface stresses in the crack-prone areas - the front side of the web

(e) The principle surface stresses in the crack-prone areas - the reverse side of the web

(f) The bending stresses in the crack-prone areas, perpendicular to the web edge
Figures denoted by (a) give the shape and magnitude of the initial out-of-flatness of the girder web. Figures (b) show the contour plots of the web buckled surface under load $F = 500 \text{ kN}$ (i.e. in a well advanced stage of the post-critical range, the critical load being $F_{cr} = 226 \text{ kN}$) and Figures (c) the principal membrane stresses in the buckled web under the same loading. Figures (d) and (e) exhibit the principal surface stresses, for both surfaces of the web sheet and the same load, in the crack-prone areas of the web, i.e. at the toes of the fillet welds connecting the web with its peripheral elements. Figures (f) then give, again for the same loading and in the same crack-prone areas, the values of the bending stresses in the buckled web sheet perpendicular to the corresponding web edge. It is usually assumed that it is these bending stresses which play the decisive role in the state of stress in the crack-prone areas of breathing webs. Similar calculations were also carried out for a lower load, $F = 300 \text{ kN}$.

An analysis of the results obtained shows that

- Even though the shapes of the initial curvature very significantly vary from one another, the shape of the buckled pattern of the web follows the initial curvature just for lower values of load. For higher loading, it tends to converge, frequently by way of snap-throughs, to the characteristic diagonal buckling mode (see Figures 2b, 3b and 4b), and the membrane stresses in the buckled web to the diagonal stress field, characteristic of the truss action in the post-buckled behaviour of slender webs in predominantly shear (see Figures 2c, 3c and 4c).

- A similar tendency can be observed for the stress state in the crack-prone areas of the web, even though here the effect of the shape of the initial out-of-flatness is more conspicuous (see Figures 2d, e, f; 3d, e, f; 4d, e, f), in particular for bending stresses. It can be expected that for lower loading (and the webs of ordinary steel bridges and of similar systems subjected to many times repeated loads do not operate in an advanced post-buckled range) this effect will be even more pronounced. And it is on these practically important loading cases that the sensitivity analysis will primarily be focused.

**FURTHER RESEARCH**

The next stage of the authors’ joint research will be concentrated on a sensitivity analysis proper of factors influencing the state of stress in breathing webs, special attention being paid to a sensitivity analysis of the effect of initial imperfections, with due regard to the magnitude of the load to which the girder is subjected and to the boundary conditions of the “breathing web.”

**ACKNOWLEDGMENT**

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Škaloud M. and Zörnerová M. (2002). The fatigue limit state of the webs of thin-walled steel girders “breathing“ under repeated loading. Ibid.


This book presents the general reports and the presentations of the International Colloquium on Stability and Ductility of Steel Structures, held in Budapest, Hungary on September 26-28, 2002.

On hundred papers have been contributed by European, American, Japanese and Australian engineers and researchers concerned with a wide range of applications of stability and ductility problems.

The aim of the Colloquium was to bring together specialist in the stability and ductility of steel structures, as well as to provide a forum for the exchange of information regarding the theoretical foundations and experimental investigations and methods, and to promote further development.

Highlights of the volume:

- Design theories and the present phase of creating new standards and codes.
- Theoretical and experimental problems of buckling of columns, lateral buckling of beams, and lateral-torsional buckling of beam-columns.
- The stability of steel frames and the effects of semi-rigid connections.
- Numerous new results achieved in the field of plate and box girders, including those of experimental and theoretical studies on fatigue induced web breathing.
- Experimental tests and theories of cold-formed and thin-walled steel structures.
- New methodology to analyse the problem of seismic stability of steel frames.

This edition providing an international approach to the stability and ductility of steel structures, will be a useful addition to research conducted in this field. It is very important to emphasise that this Colloquium was devoted to the memory of the late professor Ottó Halász.

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