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# LATERAL BUCKLING OF STEEL SIGMA-CROSS-SECTION BEAMS WITH WEB HOLES

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**Keywords**: Lateral beam buckling, Web holes, Sigma-cross-section, Experimental verification.

***Abstract.*** *In this paper the study on lateral flexural-torsional buckling of steel Sigma-cross-section beams with web holes will be presented. The analysis of corresponding stability problem is based on general approach derived for a group of beams including at least monosymmetric sections loaded transversally to their plane of symmetry. The effective flexural and torsional stiffness of steel beams with holes has been verified by tests. The results of theoretical analysis were compared with specification design procedure and also with actual behaviour of set of beams investigated by experiments. The study conclusions aim to become the background of the supplements to specified provisions for the design of steel structures.*

## 1 INTRODUCTION

In the field of advanced flooring and roofing systems the application of thin-walled steel beams with web openings represents the expedient and efficient structural concept. The profile perforation and web holes allow the fitting anchorage and also the facile installation for sprinkler pipes, electrical cables and other technical building equipment. In Fig. 1 the typical example of advanced storage structural system with perforated beams is being presented (Nedcon Groep N.V., NL).

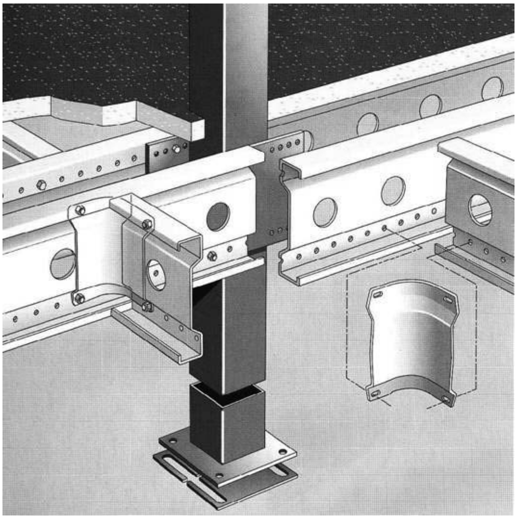

Figure 1: Example of storage flooring system composed of steel beams with web openings.

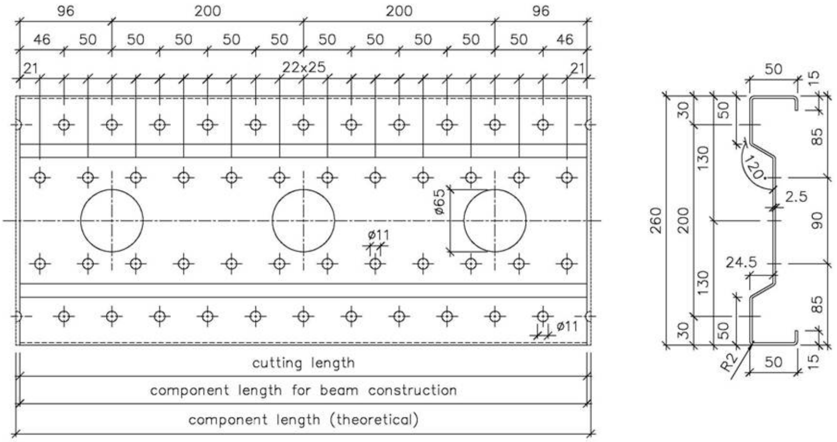

Figure 2: Arrangement of a segment of the steel Sigma-cross-section beam.

Fig. 2 indicates the arrangement of a segment of a steel Sigma-cross-section member analysed within hereinafter elaborated study, dealing with real cross-sectional characteristics and their influence on the beam buckling solutions.

## 2 STABILITY OF BEAMS WITH AT LEAST MONOSYMMETRIC SECTION LOADED TRANSVERSALLY TO ITS AXIS OF SYMMETRY

Fig. 3 shows a basic set of prevailing, at least monosymmetric steel beam sections, loaded transversally to their axis of symmetry. The Sigma cross-section pertains also to that profile group.

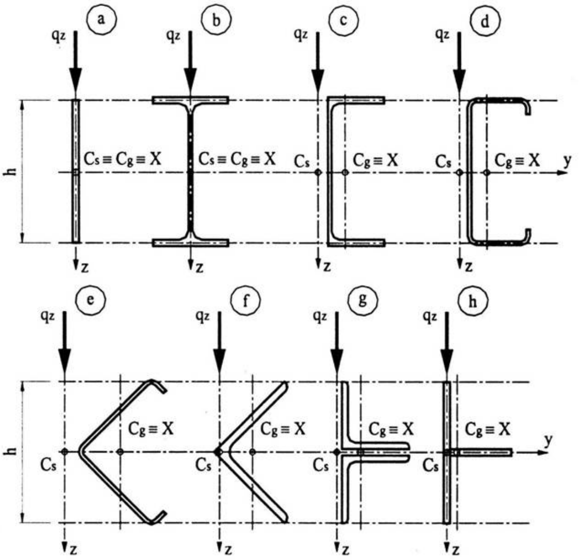

Figure 3: Prevailing monosymmetric steel beam sections.

Most of usually published studies on lateral beam buckling deals with the group of at least monosymmetric sections loaded in the plane of symmetry. Our first work on the at least monosymmetric steel beam sections, loaded transversally to their axis of symmetry, had been focused to channel section [1] and subsequently to generalized section group according to Fig. 3 - see [2] and [3], for example. Thus the stability problem of beams with Sigma-cross-section is being covered by accordant basis.

## 3 VERIFICATION OF ACTUAL BEAM CROSS-SECTIONAL CHARACTERISTICS

For the analysis and design of steel beams with regard to the flexural-torsional buckling the corresponding flexural and torsional member stiffness should be defined. At beams with the web holes the assessment of resulting substitute cross-sectional parameters could be disputable. Thus, in the frame of presented study, both the actual torsional and flexural effective stiffness were verified by tests. Herein just brief information on member pure torsional stiffness examination will be mentioned.

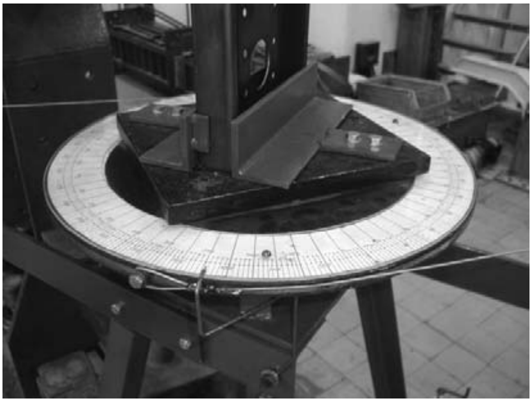

Figure 4: The specimen in the torsion test apparatus.

Figure 5: Torsion deformation.

Fig. 4 and Fig. 5 show the test arrangement. The specimens were tested vertically, on the upper end being suspended and simply supported regarding the torsion and on the lower free end being twisted by transverse couple forces $F_z$ with the lever arm of 600 mm. The angle of rotation $\Phi_z$ was measured by special horizontal disk. Together 10 specimens were tested, 4 pieces of 2.0 m length (T L2), 2 pieces of 3.0 m length (T L3) and 4 pieces of 4.0 m length (T L4). The base specimen segment corresponds to scheme in Fig. 2. The diagram in Fig. 6 shows the resulting relation of couple force $F_z$ to angle of rotation $\Phi_z$. In all cases the torsion loading both clockwise and counterclockwise has been applied.

## 4 TESTING OF LATERAL TORSIONAL BEAM BUCKLING

The study on lateral flexural-torsional buckling of steel Sigma-cross-section beams has been based on experimental investigation. Together 6 specimens were tested, by twos of 2.0 m (LB 2), 3.0 m (LB 3) and 4.0 m (LB 4) length. The specimens were simply supported and loaded by two concentrated loads placed in the thirds of the beam span. Fig. 7 shows the total test arrangements.

A particular attention has been paid to the setting of load implementation. Because of transparent and understandable tests evaluation, the selected reference theoretical model should correspond to free lateral buckling without any restraints in the beam span. The images in Fig. 8 and in Fig. 9 illustrate the deformation during beam buckling and adequate structural detailing. The load appliance placed in the thirds of the span allows the steady oriented load implementation to the compression beam flange without lateral restraint during loading process succeeded by large beam deformation.

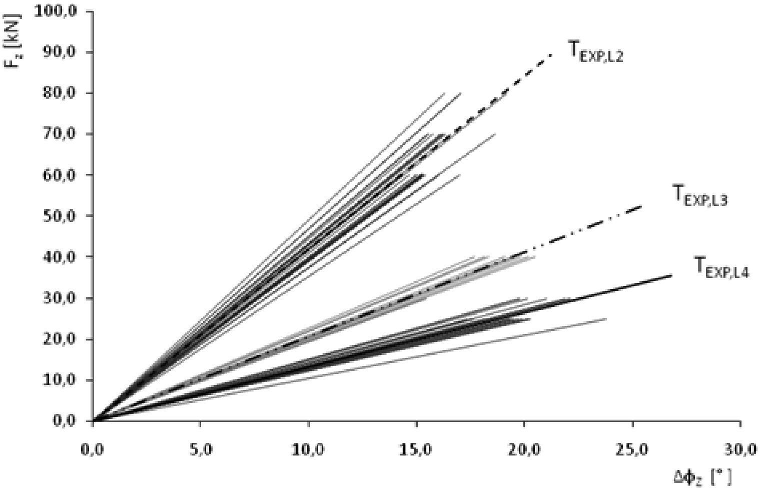

Figure 6: Relationship of couple force and angle of twist resulting from torsion tests.

During the loading progress the vertical and horizontal section displacements were observed up to the ultimate beam strength (see illustrative scheme in Fig. 12).

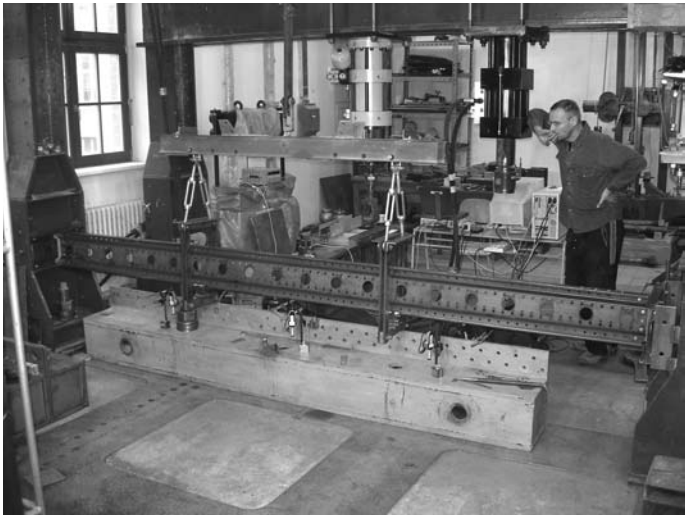

Figure 7: Arrangement of lateral beam buckling test.

## 5 INVERSE METHOD OF DESIGNING

In [4] we had pointed out that, in general, the problem of the load carrying capacity is not only the problem of ultimate strength but also the problem of final displacements, deformation or ductility parameters appropriate to the ultimate design state. The design limit state isn't any (science) fiction, but a reality which could occur during the structure operation.

Figure 8: Buckling deformation.

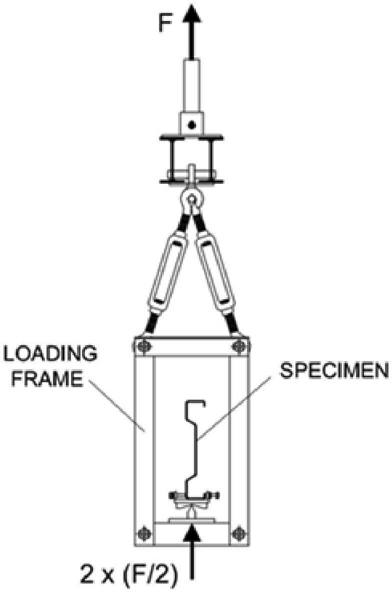

Figure 9: Scheme of loading implementation.

Thus especially in cases without code limitations for deflection or twisting (at torsion members, at lateral beam buckling, at compression members, for example) the ultimate displacements, deformations or ductility characteristics should be checked and verified.

Fig. 10 shows a scheme of three different load-displacement/strain relationships for a load bearing structural components with the identical ultimate (objective) strength but with quite diverse displacement or deformation advancement. So for the required or conventionally prescribed ultimate (max) deflection $\delta_u$ , permanent plastic strain $\varepsilon_p$ or other design parameters, the corresponding design (specified) strength could be less than the ultimate state capacity based on the ultimate strength.

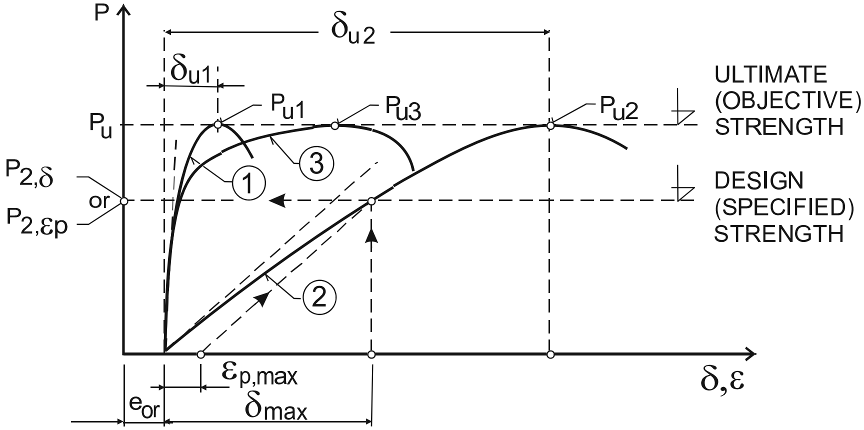

Figure 10: Principle of inverse method of designing.

That principle, called inverse method of designing, has been utilized also by evaluation of presented experiments, namely by derivation of design strength relevant to specific limitation of beam lateral deflection (Fig. 12).

## 6 EVALUATION OF BEAM BUCKLING EXPERIMENTS

Based on nominal geometry, the customary procedure of assessment of the static cross-sectional characteristics (second moments of area, St. Venant torsional constant and warping constant) for members with web holes (Fig. 11) proceeds from the smeared substitute values given by:

$$I_S = \frac{a \cdot I_{GS} + b \cdot I_{NS}}{a+b} \quad , \qquad (1)$$

where $I_{GS}$ is the section characteristic for the gross section between holes,
$I_{NS}$ is the section characteristic for the net section weakened by hole
and $I_s$ is the substitute calculation section characteristic.

In Tab. 1 the results of buckling tests are summarized. Together with ultimate strength buckling moments $M_{u,\,EXP}$ also the specified strength moments $M_{u\,(L/250),\,EXP}$ derived for conventionally defined limiting lateral deflection of L/250 (Fig. 12) are presented.

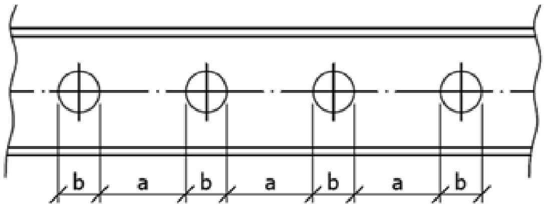

Figure 11: Scheme for substitute section characteristics.

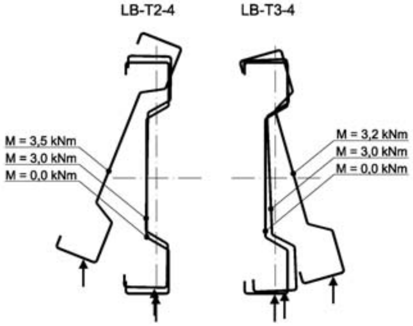

Figure 12: Section buckling displacements

Using the buckling curves and the procedure of beam buckling resistance according to EN 1993-1-1 [5] and EN 1993-1-3 [6], in Fig. 13 and Fig. 14 the results for both the experimentally verified cross-section characteristics and substitute characteristics are introduced.

Table 1: Results of beam buckling tests

| Specimen Indication | Beam Length $L$ [m] | $M_{u,EXP}$ [kNm] | $M_{u\,(L/250),\,EXP}$ [kNm] |
|---|---|---|---|
| LB-T3-2 | 2 | 7,081 | 6,590 |
| LB-T4-2 | | 7,303 | 5,723 |
| LB-T1-3 | 3 | 4,714 | 4,452 |
| LB-T2-3 | | 4,560 | 3,600 |
| LB-T2-4 | 4 | 3,483 | 3,437 |
| LB-T3-4 | | 3,227 | 3,170 |

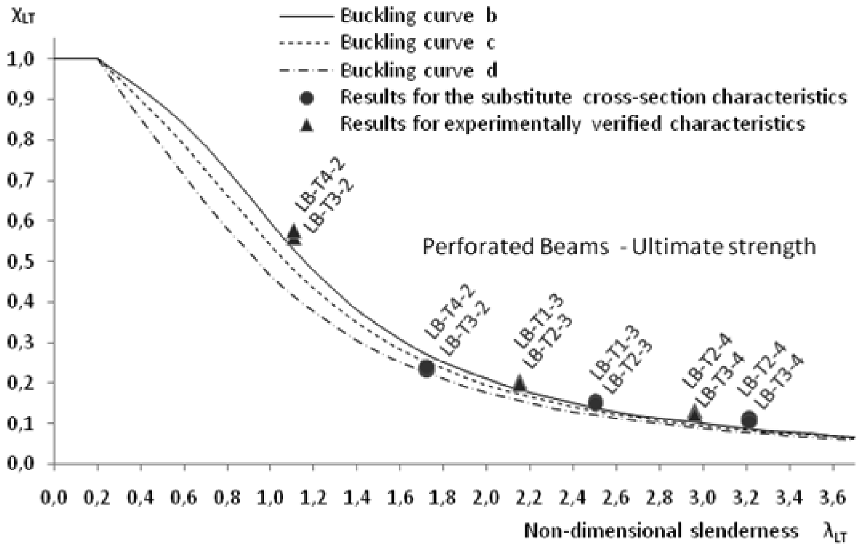

Figure 13: Resulting comparison for ultimate strength design concept.

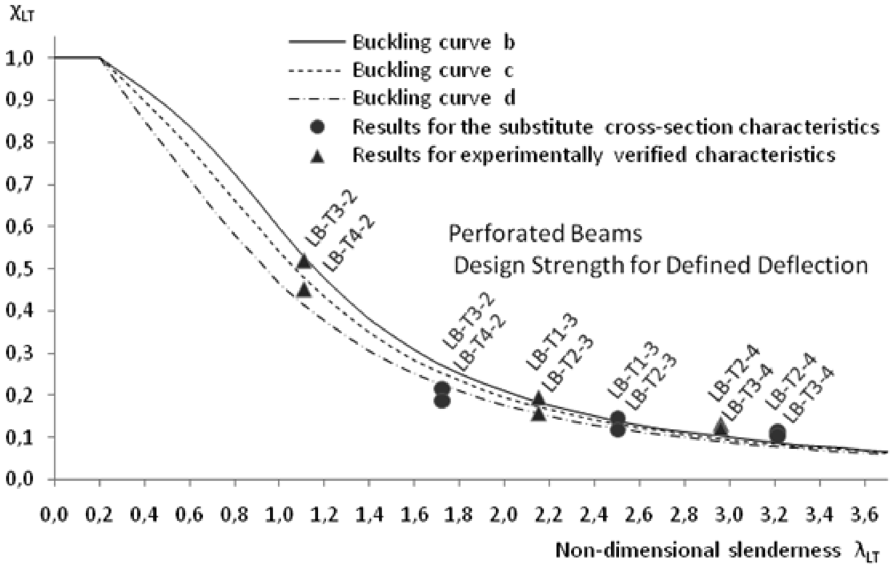

Figure 14: Resulting comparison for defined deflection design concept.

## 7 CONCLUSIONS

In this paper the inductive brief information dealing with study on lateral flexural-torsional buckling of steel Sigma-cross-section beams with web holes has been presented.

Summarizing the results of design analysis end realized experimental programme some concluding remarks can be mentioned:

- The customary used substitute cross-sectional characteristics of steel beams with web holes distinguish from actual values based on their experimental verification.
- The shorter is the beam length the larger is the difference in flexural or torsional section parameters (for an example: a pure torsional section constant $I_t$ for a member with web holes and length of L = 2.0 m is by about 70% higher than consonant value for a beam without web holes, while for a member with web holes and length of L = 4.0 m the consistent difference is just about 10%).
- The ultimate displacements, deformations or ductility characteristics related to design cases without code limitations for deflection or twisting (at torsion members, at lateral beam buckling, for example) should be checked and verified; presented results indicate the suitability of a less favourable buckling curve for respective design procedure.
- The generalization of the referenced topics postulates larger set of specimens for statistical evaluation of experiments, of course.

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