NEW PROPOSALS FOR EN 1993-1-5, ANNEX D: PLATE GIRDERS WITH CORRUGATED WEBS

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Keywords: Plate girder, sinusoidal corrugated web, stability

Abstract:
Especially for the main frames of single-storey steel buildings the use of corrugated web beams, mainly with sinusoidal corrugation, has been increased very much during the last years. Due to the thin web of 1,5 mm to 3 mm corrugated web beams afford a significant weight reduction compared with hot rolled profiles or welded I-sections. Buckling failure of the web is prevented by the corrugation. The buckling resistance of presently used sinusoidal corrugated webs is comparable with plane webs of 12 mm thickness or more.

Due to improvements of the automatic fabrication process corrugated webs up to 6 mm thickness became possible. Therefore the field of application of this beam type has been extended considerable. Even short span bridges are possible now.

The dimensioning of corrugated web beams is ruled by the EN 1993-1-5 Annex D - it covers only web thicknesses up to 3 mm. In the last years many tests and finite element simulations have been carried out.

Regarding this background, these EN rules will be discussed and extended. Furthermore, additional proposals for patch loading and lateral-torsional buckling of girders with sinussoidal webs will be given.

1. INTRODUCTION

Especially for the main frames of single-storey steel buildings the use of corrugated web beams, mainly with sinusoidal corrugation, has been increased very much during the last years (Fig.1).

Fig.1 Single-storey building

Due to the thin web of 2 or 3 mm, corrugated web beams afford a significant weight reduction compared with hot rolled profiles or welded I-sections. Buckling failure of the web is prevented by the corrugation. The buckling resistance of presently used sinusoidal corrugated webs is comparable with plane webs of 12 mm thickness or more.

When corrugated web beam have been developed during the 60ies of last century, especially the profiling of the web and the welding was hand work. Due to the progress of welding technology an automatic fabrication process became possible.

Since the end of the 80ies of last century corrugated web beams with sinusoidal corrugated webs are produced by an automated production process. In 1988 the first machine for the production SIN-beams were developed by ZEMAN, Austria. These semi-automatic machines of the first generation were able to produce SIN-beams with parallel flanges and a web thickness of 2.0 mm, 2.5 mm or 3.0 mm [1].

2. AUTOMATIC FABRICATION PROCESS

The machines of latest generation are able to produce SIN-beams by a fully automated process [2]. A more variable design of cross sections, a variety of web thickness, lower beam heights and smaller flange dimensions became possible. Furthermore tapered beams and machine-made web openings can be produced.
Actually there are around 10 production lines around the world. The automatic production of the following beam dimensions is possible:

- Web height 333, 500, 625, 750, 1000, 1250 and 1500 [mm]
- Web thickness 1.5, 2, 2.5, 3, 4, 5, 6 [mm]
- Flange thickness from 6 to 30 [mm]
- Flange width from 120 to 450 [mm]

The maximum beam length of 16 m corresponds to the maximum range of welding robots. Usually beam are shorter because of the limits for the transport, galvanizing etc. For tapered beams the maximum length is 12 m. Due to improvements corrugated webs up to 6 mm thickness became possible. Therefore the field of application of this beam type has been extended considerable. Even short span bridges are possible now.

The web material comes from a coil. It is unrolled and cut to length automatically by the machine. A so called "corrugator" forms the sheet to a corrugated web. The flanges has been already prepared and stored in special flange baskets. After the running-in of the web and flanges into the welding station all members are moved to the correct position, are pushed together and are welded by the welding robots.

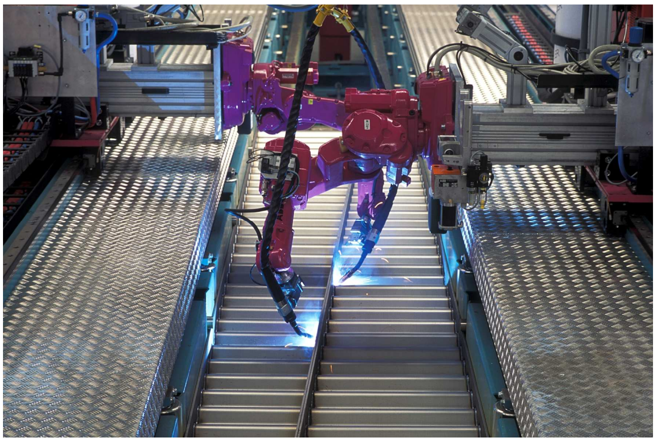

Figure 2: Automatic production process

3. PRESENT STATE OF CODES

2.1 General

Actually beams with corrugated webs are ruled by the Eurocode EN 1993-1-5, Annex D [3]. There used to be older standards as well, e.g. the German DASt-Ri 015 from 1990. But these standards deal about beams with trapezoidal corrugated webs only [4]. Only by consideration of additional papers [5] and expert opinions [6,7] it became possible to use this document for the calculation of sinusoidal corrugated webs.

The EN 1993-1-5 gives rules for both trapezoidal corrugation and sinusoidal corrugation. Whereas the dimensioning procedure for trapezoidal corrugated webs bases on the tests results for sinusoidal corrugated webs, the latest test results are not considered by the given rules. Therefore the calculation procedure according to EN is comparatively conservative.

The bearing behaviour of a beam with corrugated web is comparable with a lattice girder. Normal force and bending moment are carried by the flanges only. Due to the corrugation the web is not able to carry any normal stresses in the longitudinal direction of the beam. Therefore the web is loaded by shear force only.

2.2 Bending moment resistance of flanges

To verify the bending moment capacity of a beam, the resistance of flanges against yielding and global and local buckling for the compression flange has to be taken into account. Lateral-torsional buckling of beam is verified by global out-of-plane buckling of the compression flange . The verification is a conservative assumption because the torsional stiffness is neglected. Local buckling of the flange (cross section class 4) is considered by the determination of a reduced flange width.
A reduced yield strength $f_{yf.r}$ considers the influence of transverse bending moments. These moments are caused by the shear flow longitudinal to the joint of flange / corrugated web. It has to be taken into account for trapezoidal corrugated webs. Actually produced sinusoidal corrugated webs have a small corrugation height compared with the width of flanges. Therefore the influence of transverse bending moments is negligible.

2.3 Shear force resistance of web

The web loaded by shear force can fail due to yielding, local buckling and global buckling.

The EN 1993-1-5 defines the reduction factor for global web buckling as follows:

$$\chi_{c,g} = \frac{1{,}5}{0{,}5 + \bar{\lambda}_{c,g}^2} \leq 1 \qquad (1)$$

where:

$\chi_{c,g}$ is the reduction factor and

$\bar{\lambda}_{c,g}$ the reference slenderness for global web buckling.

For local buckling the following reduction factor is defined:

$$\chi_{c,l} = \frac{1{,}15}{0{,}9 + \bar{\lambda}_{c,l}} \leq 1 \qquad (2)$$

where:

$\chi_{c,l}$ is the reduction factor and

$\bar{\lambda}_{c,l}$ the reference slenderness for local web buckling.

4. GLOBAL AND LOCAL BUCKLING OF WEB

For global web buckling the given rule matches the test results very well.

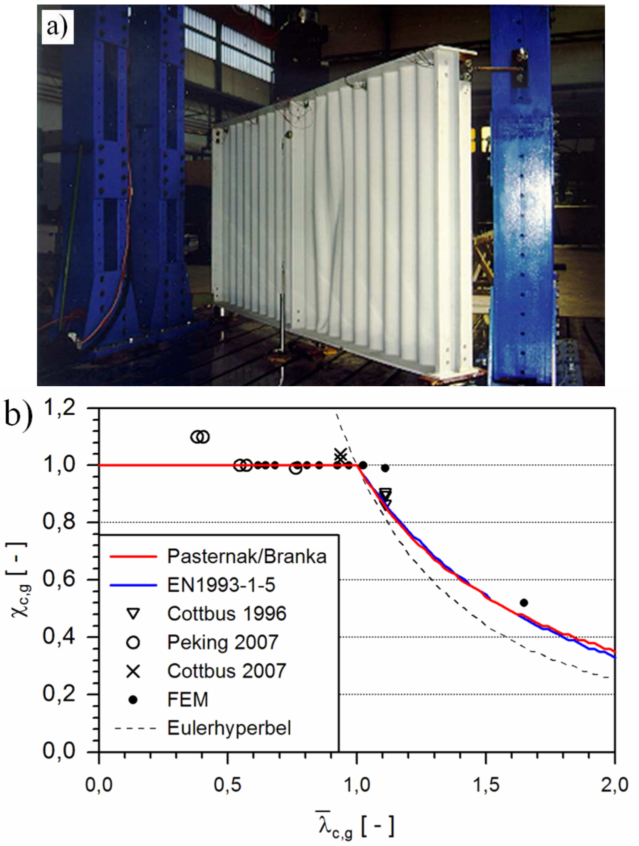

Fig.3 Global buckling curve a - test, b – curve and results according to [5],[6],[7],[8]

It was found by testing and FEM (e.g. [5]) that no local buckling occurs for all actually produced beams with sinusoidal corrugated webs. That means any reduction should be necessary for a reference slenderness smaller than 0,74 (area I of figure 4). A second reason for further research is the probably to large reduction factors for a reference slenderness greater than 1,5 (area II of figure 4). The reduction curve shows overcritical reserves of bearing capacity. This behaviour is typical for plate buckling and therefore understandable for trapezoidal corrugated webs that consist of plate elements. However, a sinusoidal corrugated web is mainly a shell structure. The overcritical reserve of the reduction curve of EN 1993-1-5 has to be proved.

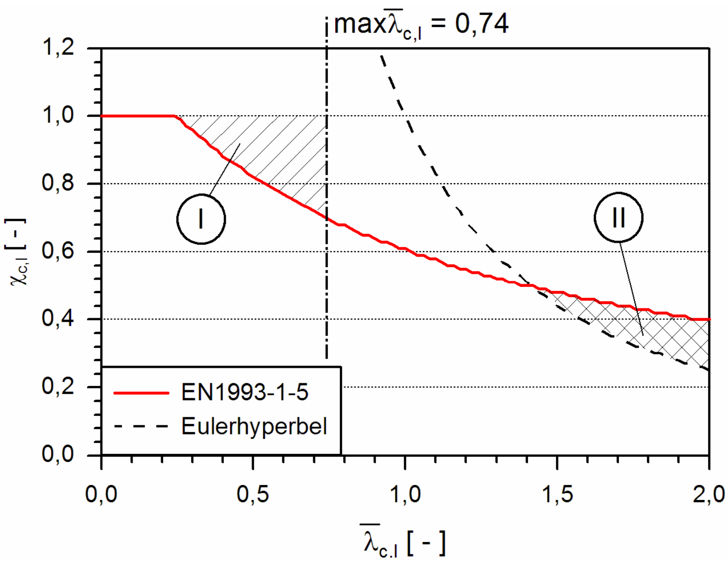

Figure 4: Reduction curve for local buckling EN 1993-1-5

5. LATERAL-TORSIONAL BUCKLING

Concerning lateral-torsional buckling four tests and a large amount of FE simualtions have been carried out [9]. Tests and FE results in comparison with European buckling curves are given in Fig.5.

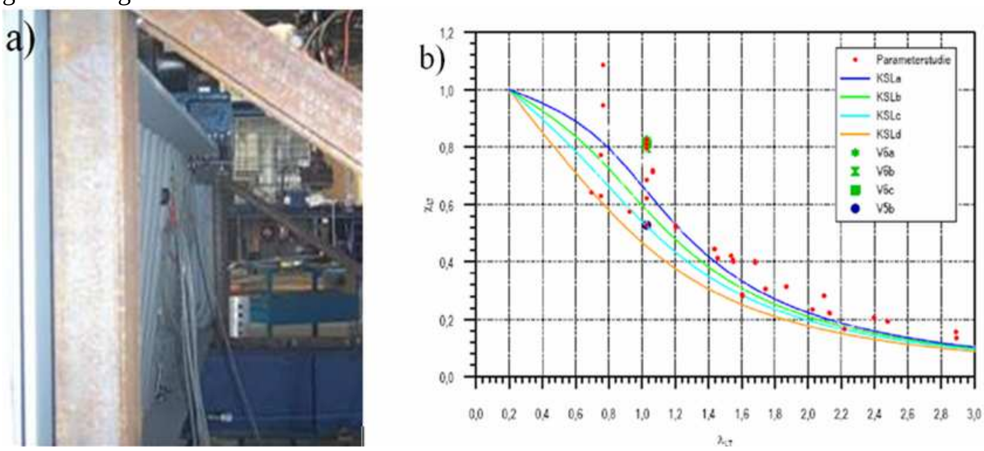

Figure 5.: Lateral-torsional buckling a - test girder V6c, b - test and FEM in comparison with European buckling curves

6. PATCH LOADING

In the parameter study girders with various forms of corrugation the patch load was investigated, the length and the amplitude of the wave were varied [4, 10].

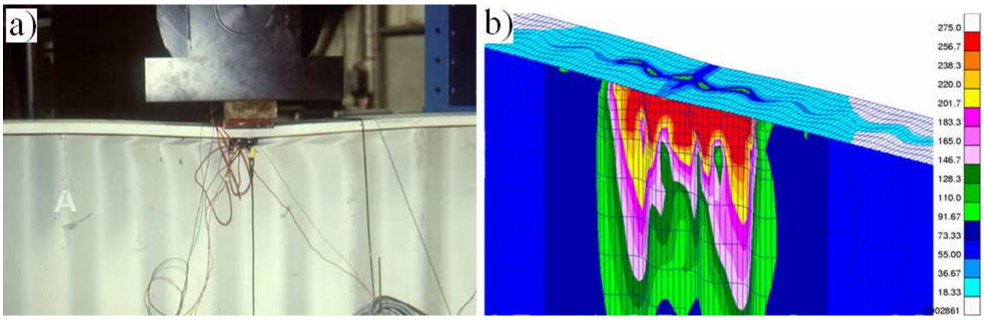

Figure 6.: Patch loading a - test, b - FEM

From many series of FE simulations a simple approach of the ultimate load was developed

$$F_{ult} = 10\left(\frac{W_{el}}{I/t}\right)^{0,4} \cdot 2 \cdot f \cdot t \cdot f_{y,d} \qquad (3)$$

where:

W_{el} - effective section modulus of the flange
I - moment of inertia of a full wave about the horizontal axis of symmetry
t - web thickness
2f, q - amplitude and length of the wave

$$I = 0{,}158 \cdot t \cdot q^{3} \left(\frac{2f}{q}\right)^{2,12}$$

The domain of definition is limited to 3 mm web thickness and 100 mm load distribution length. Analyzing a failure state [11], this formula gives reasonable ultimate loads. An extension of this formula to web thicknesses of 6 mm is necessary.

7. INTERACTION

First interaction diagrams between the bending moment and shear force resp. patch load are given in [4].

8. CONCLUSION

EN 1993-1-5 Annex D rules have been discussed for actually produced sinusiodal girders. For those girders do not appear local buckling effects before the web reaches its yielding shear capacity. The buckling curve should be improved. Furthermore, additional proposals for patch loading and lateral-torsional buckling of girders with sinussoidal webs were given.

Moreover tests showed nonlinear stress-strain relationship. This is a consequence of existence of thermal fields and initial stresses coming from welding of web to flanges and also from cold-forming process of web. These aspects are studied in a large national research project, carried out in Cottbus and Braunschweig [12].

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