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EXPERIMENTAL RESPONSES OF COMPRESSED I-SECTION SHORT COLUMNS WITH WEB OPENINGS

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Summary:

This paper reports the experimental study on compressed I-section short columns with web openings aimed at providing insight on the specific mechanical behaviour underlying the local buckling of the web panel around the opening. The I-section elements with web openings possess a minute flexural stiffness caused by lack of web contribution to the cross-section deformation capacity. In the case of compresses columns, this structural feature implies the high combined stresses around openings caused by compression force, global bending moment and shear force developed during buckling, and local bending moments due to Vierendeel action. The four stub column tests on IPE300-sections with widely spaced (isolated) and closely spaced circular and square web openings (S275 steel grade) was performed to determine their susceptibility to local buckling. The generated experimental data allowed the quantitative assessment of design procedure stated in draft version of new European code prEN 1993-1-13, revealing its good accuracy.

Key words: web openings, compression, local buckling, Vierendeel action

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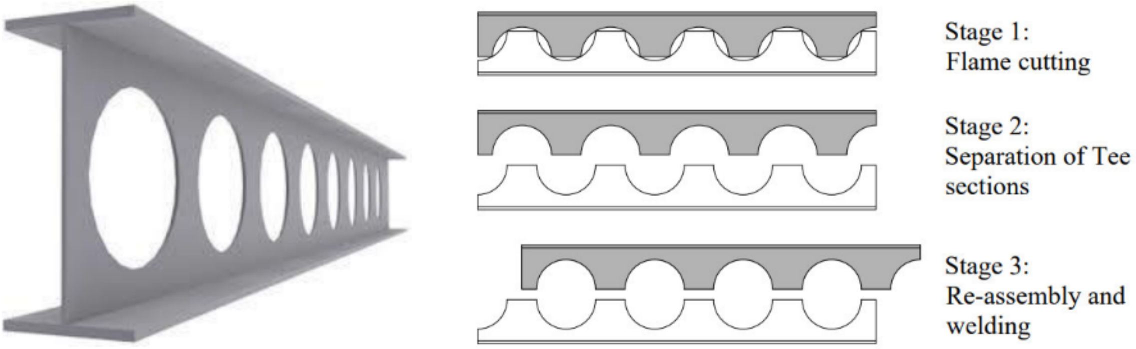
1. INTRODUCTION

Hot-rolled or welded steel beams with web openings combine function with flexibility. As alternative to trusses, these beams are lightweight and long-span structural elements that enable the passing of mechanical, electrical and plumbing pipes and ducts through the web openings reducing the floors depth and leading to an optimal use of space and steel material. They can be used in composite and non-composite structures, as simply supported members, cantilever elements or as part of moment or portal frames. The shape of the web openings depends on the purpose of the opening (the size of the installation route). Openings of regular shapes, such as circular, rectangular, hexagonal and sinusoidal are usually chosen.

Steel structural elements with web openings usually fabricated by flame cutting of hot-rolled profiles, following a specified path made in the web at the initial stage of the production process. After cutting, the two resulting Tee sections are reassembly (shear aligned) and then welded together (see Fig.1). The final element typically has a 40 to 50% higher cross-sectional height with a significant increase in flexural stiffness compared to the parent hot-rolled profile, all without increasing weight.



(a)final product [1] *(b) fabrication process*

Fig. 1 Fabrication process of steel beams with web openings

The web opening decreases both global and cross-section flexural stiffness of the beam resulting in larger deformations than the equivalent beam with solid webs. The failure modes are usually governed by the local yielding and plastic deformations of critical cross-section including opening. These structural features are caused by Vierendeel mechanism due to the local bending of web posts induced by the shear transfer around the openings. In the case of rectangular and hexagonal openings, the critical cross-section is located at the opening corners, considering that the Tee sections are uniform in upper- and lower-member's height along the opening length. However, for openings with perimeter variation along their length, the position of the critical cross-section is not straightforward and needs to be defined using a specific mathematical and numerical approach.

Nowadays, numerous experimentally-, numerically- and analytically-based scientific research have been performed to evaluate the structural responses and ultimate capacity of the beams with web openings [2-7].

The draft version of the new European code prEN1993-1-13 [8] gives supplementary design provisions and rules that extend the application of EN1993-1-1 [9] and EN1993-1-5 [10] to the design of rolled and welded steel I- or H-sections with various shapes of web openings. This pr-code accounts for the effect of the openings on the global behaviour of the beam, including lateral torsional buckling and covers the corresponding resistance verifications at the openings.

This paper presents an experimental investigation of short length IPE-section columns with circular and square web openings (also known as perforated webs), designed to experience at cross-section local and/or distortional buckling modes. The axial load-strain curve relationships were obtained by measuring the longitudinal and transverse strains at characteristic locations along the openings, and at the column ends. The failure modes can be linked to the Vierendeel mechanism due to the plastic local bending of flanges and/or web around the openings.

2. EXPERIMENTS

2.1. TEST DESIGN AND PREPARATION

The test matrix includes commercially available IPE300-sections made from conventional carbon steel with a nominal yield stress of 275 MPa. The tests were carried out on 4 specimens, each 600 mm length. The webs of specimens were perforated by circular and square openings, according to the following description:

- Specimen 1 – one circular opening with radius equal to 200 mm positioned in the specimen centre designed as “ICO1x200”, to account for influence of widely spaced openings;
- Specimen 2 – one square opening with dimension equal to 200 mm positioned in the centre designed as “ISO1x200”, to account for influence of widely spaced openings;
- Specimen 3 – two equidistant circular openings with radius equal to 120 mm named as “ICO2x120”, to account for influence of closely spaced openings;
- Specimen 4 – two equidistant square openings with dimension equal to 120 mm named as “ISO2x120”, to account for influence of closely spaced openings.

Webs of all specimens are unstiffened around the openings. The nominal length of 600 mm is chosen so that global buckling failure mode does not occur. The dimensions of the openings and the distance between them fulfill the geometric range of validity in accordance with prEN 1993-1-13 (see Table 1).

Tab. 1 Limiting dimensions for unstiffened openings; symbol designations are given in [8]

Shape of opening	Maximum opening height, h_o	Maximum opening length, a_o	Minimum edge to edge spacing, s_o	Minimum depth of Tee in compression, d_t
Circular	$0{,}8h$	-	$0{,}1h_o$	max ($t_f + r + 10$ mm; $t_f + 30$ mm)
Rectangular	$0{,}75h$	$2{,}5h_o$	max ($0{,}5a_o$; h_o)	max ($a_o/12$; $0{,}1h$)

The dimensions of the square openings were chosen as the maximum possible for the corresponding specimen length and the used number of openings. The dimensions and position of the circular openings were chosen so that they stand for the equivalent of square openings, and for the sake of sensitivity and a comparative study of the influence of the opening shape on the cross-section stress and deformation capacity. Position of the openings, as well as their dimensions, are shown in Figure 2.

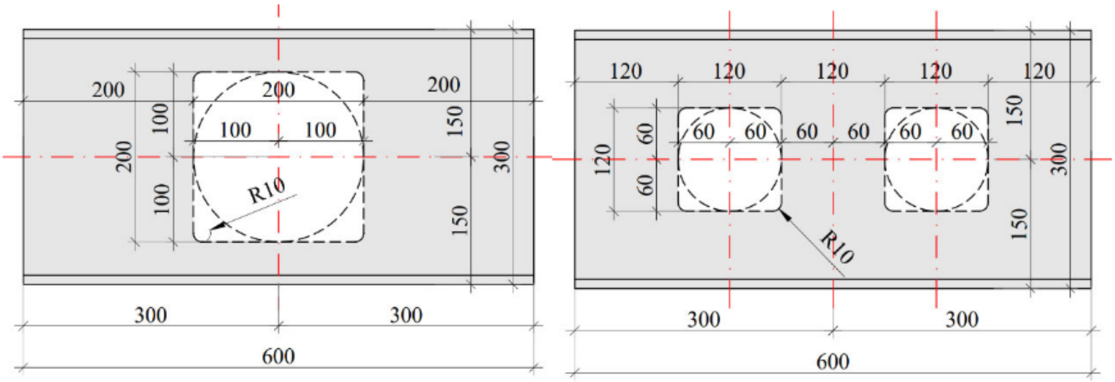


Fig. 2 Dimensions and positions of the openings at the specimens' webs

2.2. TEST SET-UP

The compressive load was applied using a strain-controlled Amsler hydraulic testing machine, with a capacity of 2500 kN. The parallel end plates were fixed against rotations and twist about any axis in order to achieve fixed boundary conditions.
End shortening of the stub columns was monitored by linear variable displacement transducers (LVDT) positioned at four points and placed on the upper plate of the testing machine. The stress-strain distribution fields in the specimen web, around openings, were measured using electrical strain gauges (SG). The test setup of stub column specimens with the position of the measuring equipment is shown in Fig. 3 and Fig. 4. A load cell was used to record the applied load. All experimental results: load, displacements and strains were recorded in one-second intervals on the data acquisition device.

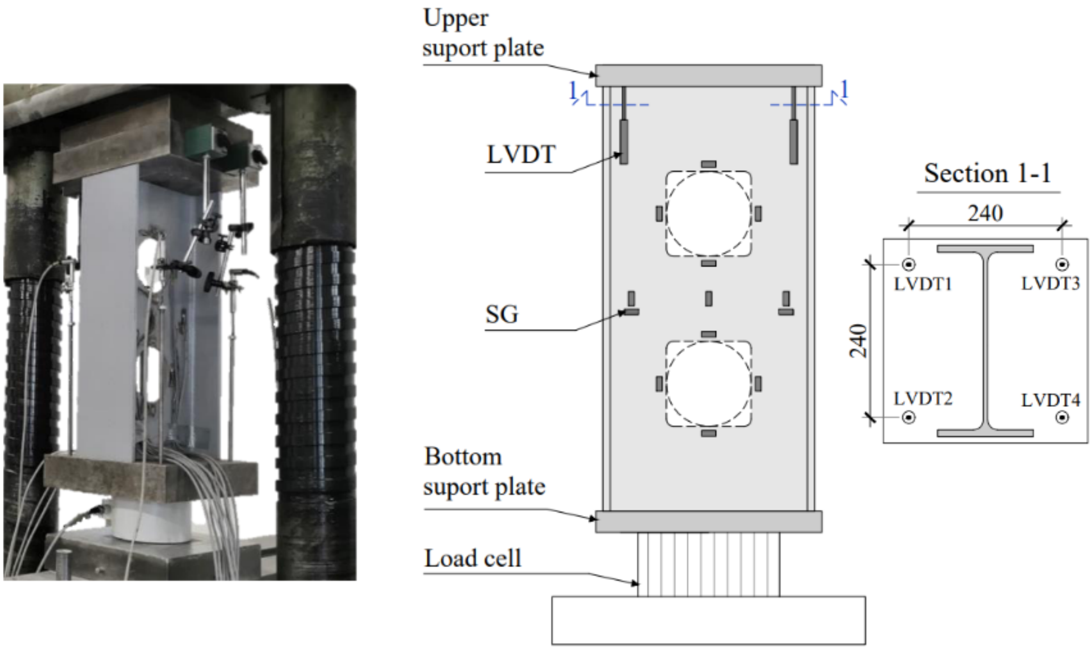


Fig. 3 Test set-up on the example of specimens with two openings

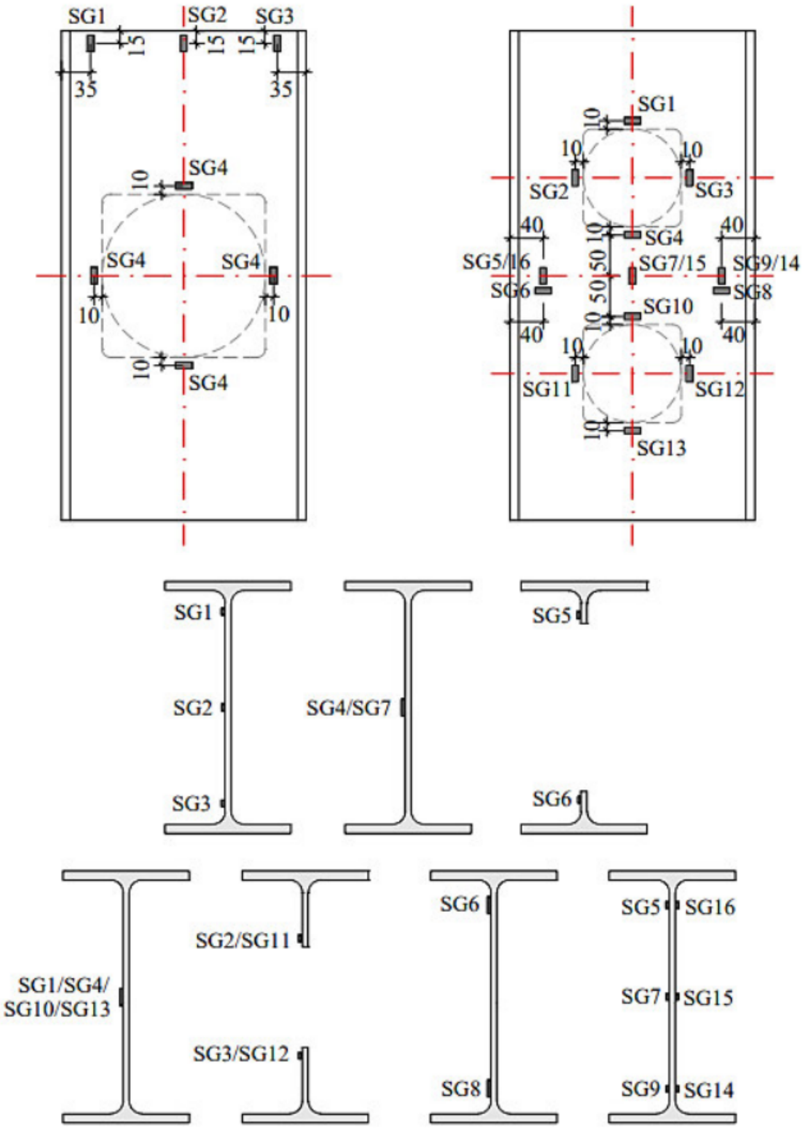
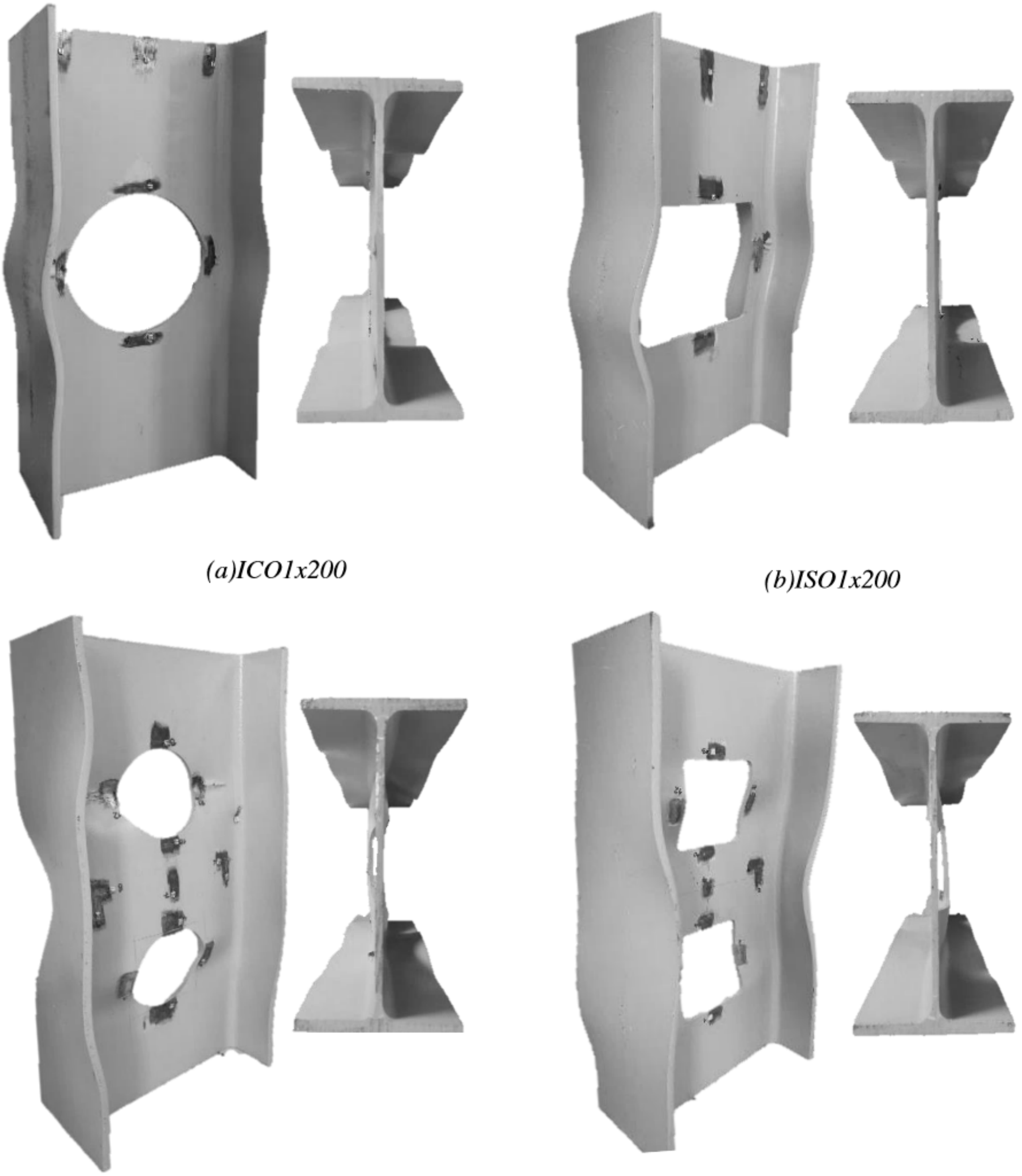


Fig. 4 Position of strain gauges

2.3. TEST RESULTS

The failure behaviours of the test specimens are shown in Fig. 5. All columns experienced local buckling occurred at the interface between the elastic and plastic stress regions. Local buckling of specimens with one opening was localised in the middle part of their height and characterised by the symmetric, one wave-shape deformations of the cross-section flanges in the opening area. The section web almost completely remained straight and angles between web and flanges did not change (see Fig.5a and Fig.5b). Local buckling of specimens with two closely spaced openings was also localised in the middle part of their height, however it was featured by the more wave-shape deformations of the cross-section flanges along the column length. The longitudinal deformation distributions at the ends of the same flange are of opposite signs, the convex deformation at one flange end corresponds to the concave deformation at the other flange end. The inflection planes are observed in the mid-length of both openings (see Fig.5c and Fig.5d).



(a)ICO1x200 *(b)ISO1x200*

(c)ICO2x120 *(d)ISO2x120*

Fig. 5 Post-buckling deformed shape of specimens with web openings

The key experimental results for specimens ICO1x200 and ICO2x120 are summarized in Table 2, in which $N_{c,u}$ is the ultimate failure load, σ_b is the ultimate buckling stress reached at the web post, σ_{bo} is the ultimate buckling stress reached at the opening, both calculated by dividing the corresponding ultimate load $N_{c,u}$ and measured bruto or neto (account for opening) cross-section area, respectively. It can be seen from Table 2 that the failure mode of the specimens is governed by elastic-plastic local buckling; the predicted (design) stress values around openings σ_{bo} are higher, whereas the predicted stress values at the web post σ_b are lower than the measured yield strength f_y = 328 MPa, respectively. It was also found that the ultimate resistances of specimens with circular openings are higher than those measured for the corresponding specimens with square openings. Thus, the ultimate resistances and deformation capacity of the tested specimens significantly depends on the shape, size and number of web openings (that is, distance between openings).

Tab. 2 Summary of stub column test results under pure compression

Specimen	$N_{c,u}$ [kN]	σ_b [MPa]	σ_{bo} [MPa]
ICO1x200	1327,7	256,6	346,6
ICO2x120	1474,2	284,9	337,5

The axial load-longitudinal strain curves for specimens ICO1x200 and ICO2x120 are shown below in Fig. 6 and 7. The results are presented for each strain gauge separately, without their averaging, in order to more easily notice the differences in the structural behaviour of the specimens at web post and at the opening. It can be seen from Fig. 6 and 7 that the measured axial strains around openings are higher than the strains at the web post, indicating the shear transfer around the openings.

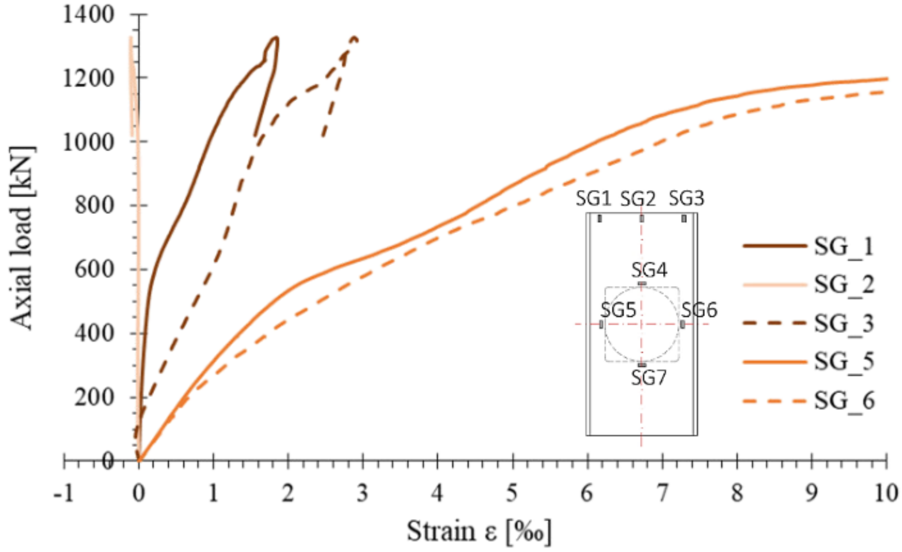


Fig. 6 Axial load-longitudinal strain curve for ICO1x200

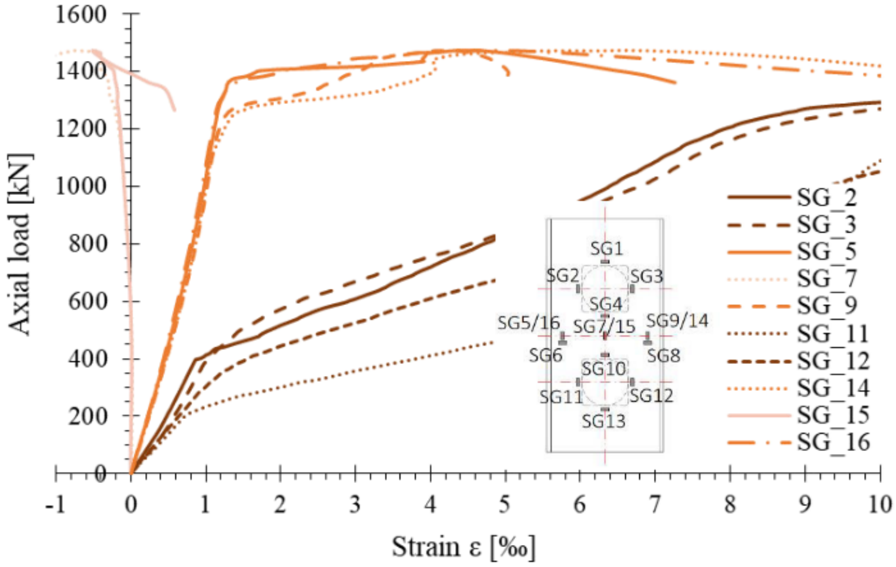


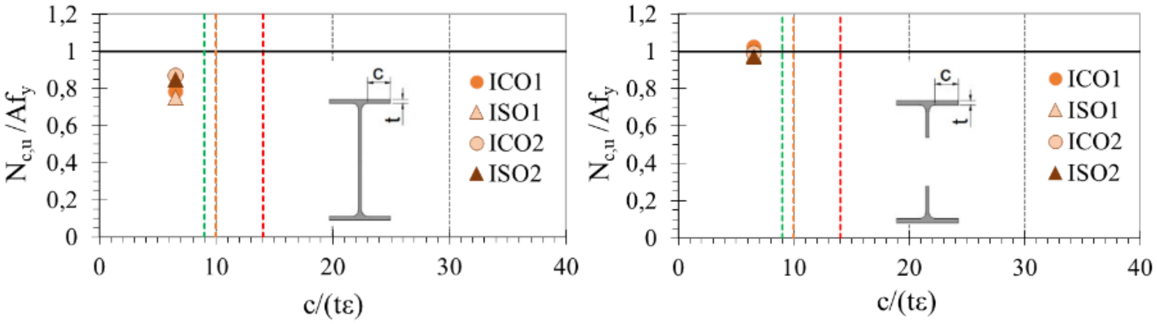
Fig. 7 Axial load-longitudinal strain curve for ICO2x120

3. EVALUATION OF prEN 1993-1-13 PREDICTIVE MODELS FOR CROSS-SECTION CLASIFIACTION

Based on the experimental results, an accuracy assessment of the cross-section deformation capacity, according to prEN 1993-1-13 was performed.

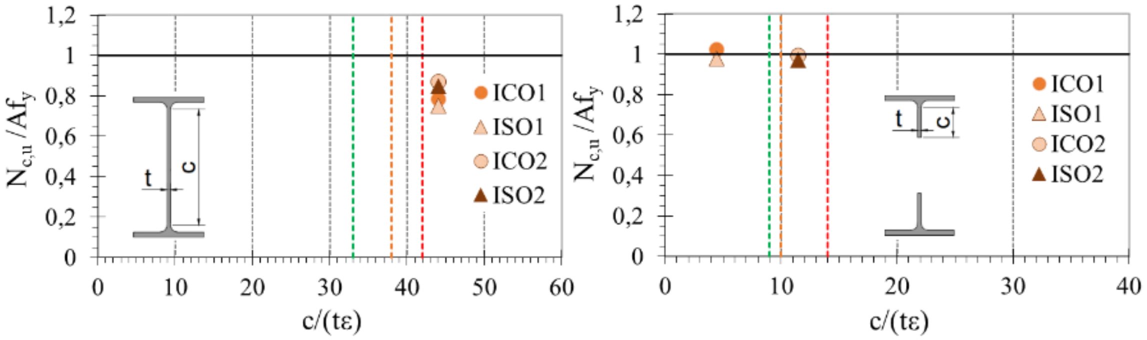
In accordance with prEN 1993-1-13, local buckling is accounted using the concept of cross-section classification and effective width based on an elastic-plastic material model, such as in the current code in use EN 1993-1-1. The cross-section class is determined by the classification of all cross-section elements, comparing their individual slenderness (width-to-thickness ratio) with the limit values prescribed in the code. In the case of perforated webs, cross-section should be classified at each web opening and web post. At the opening, both flanges and web are classified as outstand elements. The cross-section resistance is defined as buckling resistance of the compressed Tee sections, considering bending moments due to Vierendeel bending effects and axial force.

Fig. 8 shows a comparison of the slenderness of the outstand and internal parts of the cross-section with the limit values for classes 1 (green line), 2 (orange line) and 3 (red line) at pure compression (according to prEN 1993-1-13). The ultimate force obtained by tests is normalized by a value that represents the product of corresponding cross-section area and the measured yield strength. Diagrams are given separately for the cross-section at the opening and the cross-section outside the opening, for outstand (flanges) and internal (web) parts of the cross-section.



(a)flanges outside the opening

(b)flanges at the opening



(c) web outside the opening

(d) web at the opening

Fig. 8 Limit slenderness for pure pressure according to prEN 1993-1-13

It can be seen from Fig.8a and Fig.8b that the data points for flanges (outstand compressed element) are on left, safely side regarding to Class 1 slenderness limit. Similarly, Fig.8c shows that the Class 4 slenderness limit for web section (internal compressed element), outside the openings, corresponds to the experimental data points. However, considering the cross-section with web openings (Tee section web as outstand compressed element), the experimental data points for the specimens with one opening are on left, safely side regarding to Class 1 slenderness limit, while the experimental data for the specimens with two openings lie between the Class 2 slenderness limit and the Class 3 slenderness limit for outstand compressed elements (see Fig.8d). Thus, related to analysed specimens, prEN 1993-1-13 provides a considerably precise prediction of the cross-section deformation capacity and classification under pure compression load.

Finite element models will be calibrated and validated against the presented tests and used to perform a parametric assessment of the ultimate capacity of short length columns with web openings, considering the column length, cross-section dimension, opening shape and distances between openings, see Fig. 9. The experimental and numerical data related to failure loads (ultimate resistances) will be compared with resistance predictions obtained using the codified design methods in prEN 1993-1-13.

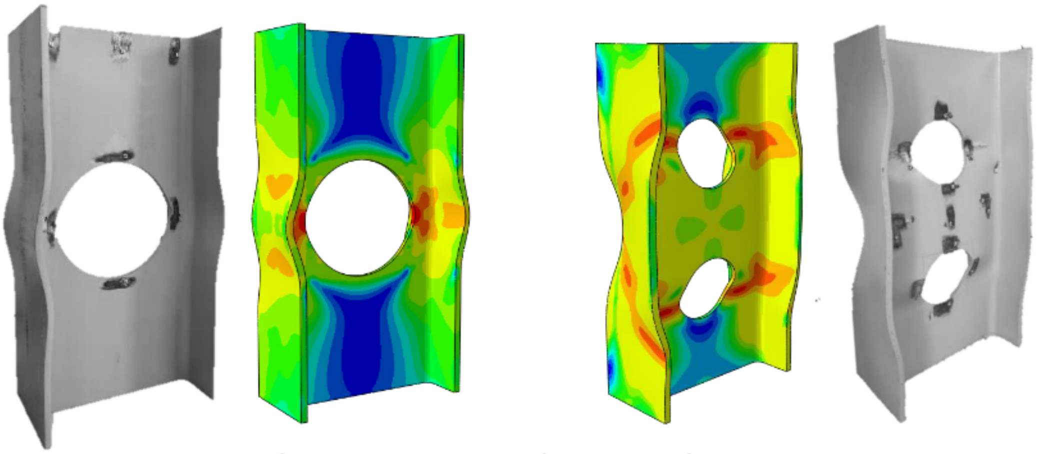


Fig. 9 Failure mode of FE models with circular web openings

4. CONCLUSIONS

An experimental investigation consisting of four IPE300-section columns with low slenderness was carried out under pure compression. The overall aim of the experiments was to investigate cross-section buckling modes and corresponding capacities and quantify the influence of shape and dimensions of the openings and their distances on the ultimate structural responses.

The failure mode of the tested specimens was local buckling triggered by the weakening of the section web by the openings and the consequent reduction of its flexural stiffness. The structural behaviour of specimens strongly depends on cross-section slenderness, opening shape and distance between openings.

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