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EXPERIMENTAL AND NUMERICAL STUDY OF FLANGE CLASS 3 CROSS-SECTION MEMBERS

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Abstract. *This paper deals with the behaviour of structural steel members with Class 3 cross-sections. According to the Eurocode 3 classification system, the resistance of such members cannot be higher than the elastic one. In reality, they may exhibit a higher load carrying capacity than predicted by the code, as Class 3 sections possesses an intermediate resistance between the elastic and full plastic ones. In order to improve the design recommendations of Eurocode 3, a research project has been initiated in which both Class 3 sections and members with Class 3 sections are considered. Experimental as well as numerical investigations on HEAA profiles have been performed. In this paper, it is shown that adequate FEM models can predict the carrying capacity of members with Class 3 cross-sections with a good accuracy. These models will be further used in extensive parametric studies in view of the further development and validation of new design proposals for members with semi-compact cross-sections.*

1 INTRODUCTION. SCOPE OF RESEARCH PROJECT

Four different classes are defined in Eurocode 3 for cross-sections in bending (Figure 1). Class 1 "plastic" and 2 "compact" cross-sections may exhibit a plastic resistance $M_{pl.Rd}$, while Class 3 "semi-compact" sections may only develop an elastic resistance $M_{el.Rd}$. Class 4 cross-sections are slender ones in which local plate buckling in the constitutive walls prevents the section from reaching the elastic moment resistance $M_{el.Rd}$.

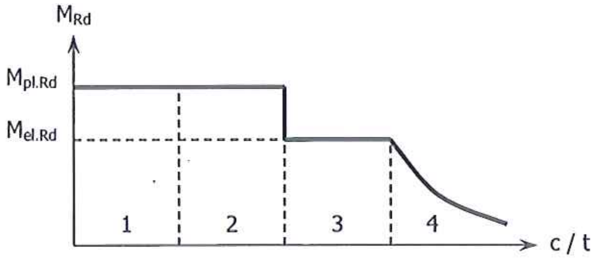

Figure 1: Eurocode 3 cross-section classification system.

Present paper deals with the behaviour of structural steel members with semi-compact cross-sections. According to Eurocode 3 [1], members with "Class 3" cross-sections may only exhibit an elastic resistance because of the risk of early occurrence of local plate buckling in the member cross-section. The Eurocode 3 procedure for cross-section classification consists in (i) determining the class of each cross-section wall in compression and in (ii) defining the cross-section class as the one of the weakest cross-section wall. The class of each wall depends on the applied stresses and on its slenderness parameter c / t, where c represents the compressed part of the studied wall and t its thickness (Figure 1).

According to this classification system, the cross-section resistance is therefore associated to the one of the weakest constitutive wall, even if the other walls are far from being sensitive to local plate buckling phenomena.

As seen in Figure 1, a jump of resistance from $M_{pl.Rd}$ to $M_{el.Rd}$ is observed at the limit between Class 2 and Class 3, which has no real physical meaning. This discontinuity is not necessarily negligible; for an I-shaped cross-section bent about minor axis, for instance, $M_{pl.z}$ is 50% higher than $M_{el.z}$. In reality, the actual bending resistance of a Class 3 section is intermediate between $M_{pl.Rd}$ and $M_{el.Rd}$ and a smooth transition from Class 2 to Class 4 cross-sections may be physically expected, as illustrated in Figure 2.

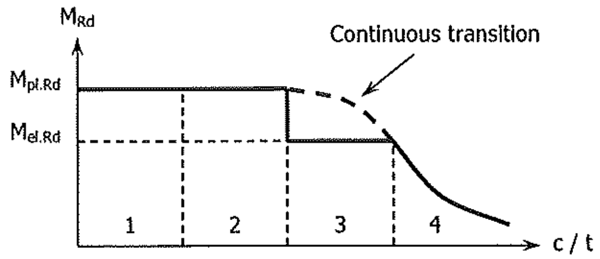

Figure 2: Continuous transition along Class 3.

As a consequence the "actual" resistance of a Class 3 cross-section might be significantly higher than the pure elastic resistance, what Eurocode 3 systematically ignores. By considering the actual level of resistance, a less conservative design of the cross-sections, but also of the members with Class 3 sections, may be reached.

In order to profit from this actual extra resistance, an European research project involving Liège University (Belgium), Graz University (Austria), PSP Technologien Aachen (Germany) and RDCS Arcelor Research Centre (Belgium) has been recently initiated to study both Class 3 sections and members with Class 3 sections [2]. The objective of this project is to propose new design recommendations avoiding the jump of resistance and allowing a continuous transition between Class 2 and Class 4 sections. To achieve this goal, experimental, numerical and analytical investigations on H and rectangular hollow sections as well as on members with similar cross-sections are planned to be carried out.

At Liège University, only the experimental tests on HEAA members have been performed till now. But beside that, numerical simulations of the tested members have been carried out so as to validate, through comparisons with experiments, the use of the FEM technique in view of further extensive parametrical studies.

This paper presents these first obtained results. Section 2 briefly reports on the measured material and geometrical characteristics of the tested specimens, while Section 3 presents the test set-up and the experimental results. Finally Section 4 includes the description of the FEM models and the comparison between experimental and numerical results.

2 MECHANICAL AND GEOMETRICAL PROPERTIES OF THE SPECIMENS

2.1 Material characteristics

So as to characterise the material properties of the test specimens, classical coupon tests have been realised. Table 1 summarises the results: the Young's modulus E, the actual yield stress f_y and the ultimate stress f_u. The actual yield stress is so high, in comparison with the minimum guaranteed one, that the considered HEAA240 S355 cross-section is, in reality, a Class 4 one.

Table 1: Results of coupon tests (S355).

Position of coupon	E [GPa]	f_y [MPa]	f_u [MPa]
Top flange	196	474	577
Top flange	193	478	580
Web	186	498	596
Web	199	518	610
Bottom flange	198	493	583
Average	194	492	589
Standard deviation	5	16	12

Measurements of the longitudinal residual stresses have also been undertaken as they may influence the carrying capacity of the members in a non-negligible extent.

The strip-cutting technique has been used here. It consists in cutting the cross-section into several longitudinal strips and in determining the difference in length of each strip before and after cutting. Using the Hooke's law $\sigma = E\,\varepsilon = \Delta l\,/\,l$, the actual distribution of initial residual stresses in the profiles before cutting may be approached, as illustrated in Figure 3.

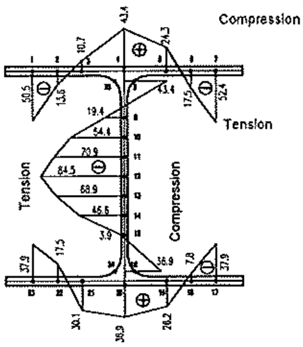

Figure 3: Measured residual stresses.

2.2 Initial geometrical imperfections

In addition to material imperfections (residual stresses), the level of geometrical imperfections needs also to be characterized, mainly for further comparisons with FEM results. The geometrical default may be seen as the sum of a *global* member imperfection and of a *local* wall imperfection.

The *global* imperfection is defined as the usual out-of-straightness measured along the member length in both main planes; in the same way as the residual stresses, it affects the ultimate resistance of the member in compression or in compression and bending.

The *local* imperfection refers to local plate-type imperfections measured on the different walls constituting the cross-section. It is usually disregarded in member buckling tests with Class 1 or Class 2 cross-sections, but is here decisive as it directly rules the potential development of plate buckling in the Class 3 walls of the cross-section. As a consequence, the ability of the member to exhibit pronounced elastic-plastic behaviour rather than a quasi-elastic behaviour is straightforwardly linked to the level of local imperfections.

In order to measure both defaults, a special measurement device has been prepared (Figure 4). It consists of three displacement transducers placed on a trolley moving along the member length, which records the level of imperfection along three longitudinal lines on the member.

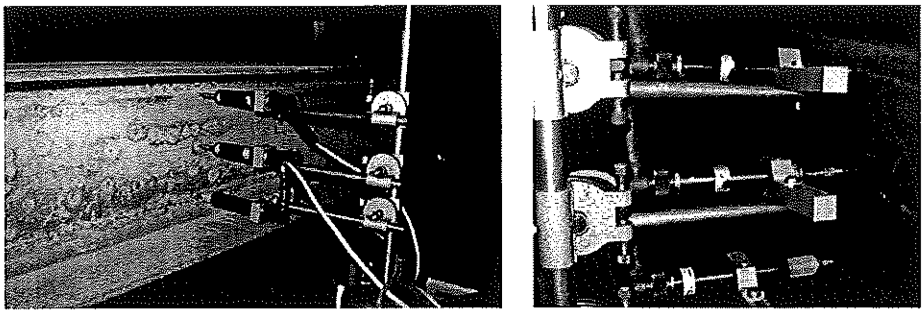

Figure 4: Measurement of the local and global initial geometrical imperfections.

Through an appropriate post-treatment of the recordings, it is possible to separate the global imperfection from the local one. This provides the necessary information on the shapes and amplitudes of both defaults. In general, the level of measured imperfections has been found quite low. Figure 5 shows, as a example, measured values for the weak axis global imperfection and the web local imperfection in one of the tested specimens.

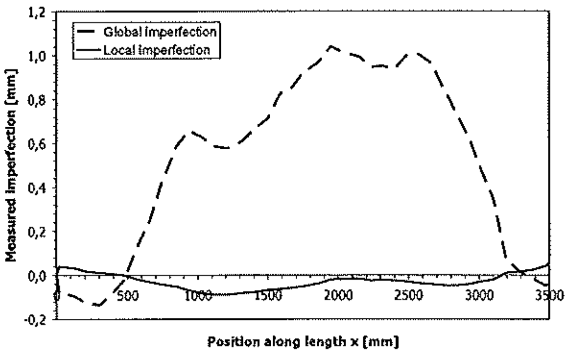

Figure 5: Geometrical global and local imperfections.

3 BUCKLING TESTS ON BEAM-COLUMN MEMBERS

3.1 Description of test program

12 test specimens with HEAA240 sections made of S355 steel have been designed so as to see the influence of the actual resistance properties of Class 3 cross-sections on the carrying capacity of structural members in compression and bending, and more especially on the possible development of plasticity during the member loading and the consecutive increase of the overall resistance and buckling of the member.

Obviously, because of the rather important number of parameters influencing the member response, 12 specimens are not sufficient to cover the whole potential range of application of such beam-columns. As a consequence, the test campaign has been "deigned" so as to point out the influence of few main parameters, but also to constitute a convenient reference in view of the assessment and the validation of the FEM models that will be further used in parametrical studies.

The test specimens selected in the experimental program carried out at Liège University is summarized in Table 2.

Table 2: Test program for member buckling.

HEAA 240 $L = 3.5\ m$	ψ_y	ψ_z	HEAA 240 $L = 4.5\ m$	ψ_y	ψ_z
H355_1_BU_1	1	/	H355_2_BU_1	1	/
H355_1_BU_2	0	/	H355_2_BU_2	0	/
H355_1_BU_3	/	1	H355_2_BU_3	/	1
H355_1_BU_4	/	0	H355_2_BU_4	/	0
H355_1_BU_5	1	1	H355_2_BU_5	1	1
H355_1_BU_6	0	0	H355_2_BU_6	0	0

Two main different situations are considered as far as loading is concerned: axial compression, respectively with monoaxial and biaxial bending; cross-sections and slenderness values have been chosen so as to cover current situations.

For practical purposes, primary bending moments (under monoaxial and biaxial bending) are applied through eccentrically applied axial thrust. The values of the eccentricities at member ends have been chosen equal to $e_y = 85$ mm for strong axis bending and $e_z = 25$ mm for weak axis bending. As a consequence, the distributions of primary bending moments along the members are linear; variables ψ_y and ψ_z indicate the ratios between end moments, respectively about y-y and z-z axes (see Table 2).

3.2 Experimental setup

A general view of the test set-up may be seen in Figure 6. The maximum compression force which may be applied to the member is equal to 500 tons, while members up to 5 m can be introduced in the test rig. In order to connect the specimens to the loading device, end plates have been welded to the member end sections.

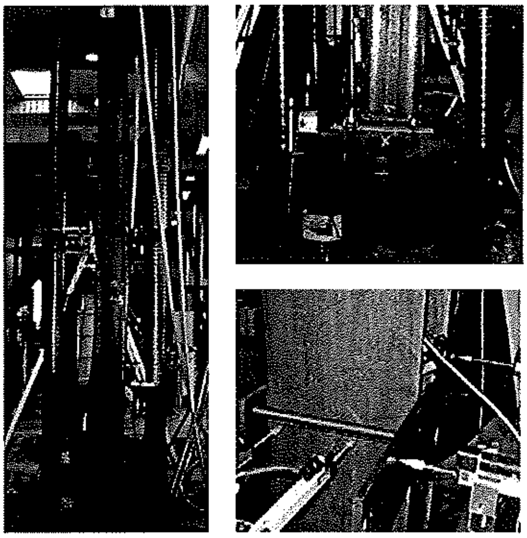

Figure 6: General view of test set-up - support conditions and instrumentation in the mid-height cross-section and at supports.

Since the nature of the supports has a significant influence on the buckling capacity of the members, special care has been devoted to the realisation of the end support conditions. In fact, two half-spheres lying on a film of oil that is continuously flowing have been used; they can freely rotate about both bending axes (with a maximum rotation of 6°). The centres of the half-spheres are exactly located at the contact surfaces between the tested specimen and the supporting plate (Figure 6); therefore, the hinged supports can be considered as acting at the actual ends of the physical member. Through an adequate system, the torsional rotation at supports is prevented. And in addition, once the end plates welded at the ends of the specimens are bolted to the supports plates, warping of the end sections can be assumed to be fully prevented. Accordingly, the end support conditions are quite close to so-called fork conditions, except for warping, which is prevented as explained hereunder.

The external loads on the beam-column specimens are applied through a controlled increase of oil pressure, which determines the axial compression. And as explained above, the first order end moments increase proportionally with the axial load.

In addition to the applied compression, several displacements and rotations are measured during the test; for instance, the axial shortening of the member as well as the rotations at the supports. The latter are determined by means of inclinometers (Figure 6).

Transverse weak and strong axis displacements together with torsional twist of the mid-height cross-section are also measured with displacement transducers. The choice of the mid-height cross-section is arbitrary (because of the dissymmetry of the loading along the axis, the mid-height section is not necessarily the one where plasticity develops). In order to ensure the reliability of the measurements, an additional device recording the variation of the distance between the flanges in the mid-height cross-section has been placed. It aims at giving qualitative information on the potential development of local buckling in this section, what could lead, when significant, to biased recordings of the displacements.

3.3 Results

The tests have been conducted without problems and the results may be considered as reliable. The experimental axial resistances are reported in Table 3; associated bending moments may be derived by multiplying these axial resistances by the adequate values of the eccentricities.

Table 3: Results of beam-column tests (axial resistances).

HEAA 240 L = 3.5 m	$N_{Exp.}$ [kN]	HEAA 240 L = 4.5 m	$N_{Exp.}$ [kN]
H355_1_BU_1	1369	H355_2_BU_1	1180
H355_1_BU_2	1636	H355_2_BU_2	1443
H355_1_BU_3	1430	H355_2_BU_3	1078
H355_1_BU_4	1650	H355_2_BU_4	1281
H355_1_BU_5	1073	H355_2_BU_5	896
H355_1_BU_6	1393	H355_2_BU_6	1161

4 COMPARISON WITH NON-LINEAR FEM RESULTS

4.1 FE-modelling

As already explained, the need to resort to FEM shell models is imperious here since the ability of a Class 3 cross-section to develop a higher resistance than the elastic one depends on the occurrence of buckling phenomena in cross-section walls subjected to compression. This effect can not be accounted for through a beam element modelling because beam elements are usually based on the Navier-Bernouilli assumption of rigid cross-sections.

The numerical model has been developed so as to be able to respect as closely as possible the actual properties of the members. In particular, special attention has been paid to the correct representation of the geometrical properties, such as area, inertia... To achieve it, it is necessary to account properly for the presence of radius of fillet at flange/web intersection. And this is not obvious with shell elements as, for the location of these ones, reference is made to the web and flange reference planes; moreover, when using such elements, a overlapping of material at the web to flange junction is unavoidable.

Consequently, it has been decided to place, in the flange radius zone, an additional square beam element, with dimensions accounting for both aforementioned effects (see Figure 7).

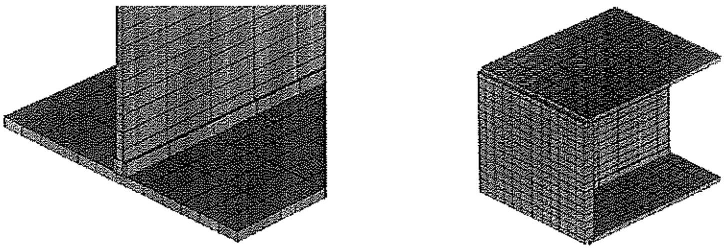

Figure 7: Simulation of the radius of fillet in H-shaped cross-sections and of member end-sections.

This beam element has the same material properties than the rest of the profile, and its centroid is located at the exact centroid of the "actual" flange radius. Doing so should ensure the model to exhibit geometrical properties in close agreement with the real properties, what has been demonstrated.

Another important aspect in the modelling of an H-shaped profile is the development of local plate buckling. Indeed, in the actual profile, the flange radius zones remain unaffected by the extent of local buckling, because of their intrinsic stiffness. Therefore, an additional "truss system" has been implemented in the numerical model so as to keep this zone almost rigid. It has to be noted that this truss system does not prevent the corresponding rigidified zone from "torsional" rotations when one (or more) cross-section wall(s) buckle(s) locally.

To fit with the actual support conditions of the tested specimens, end plates modelled with shell elements (assumed to remain elastic) have been implemented in the FEM models (Figure 7). The thickness of the plate considered in the simulation is rather significant, when compared to the actual one; this allows to introduce the external forces through nodal forces as the bending stiffness of the plate is sufficient to ensure a correct distribution of stresses in the profile. Moreover, the use of thick end plates is an alternative way to simulate the fact that the actual plates are bolted to the testing rig and therefore possess a high out-of-plane stiffness. And finally the simulated member may so be assumed to be supported at a single node (centroid of the cross-section), except for what regards restraint against torsional twist (lateral support placed at both web ends). It can so be concluded that the support conditions in the FEM models reflect accurately the experimental ones.

Initial geometrical imperfections have also been accounted for in the FEM models; global and local default have been dealt with in an independent way (Figure 8).

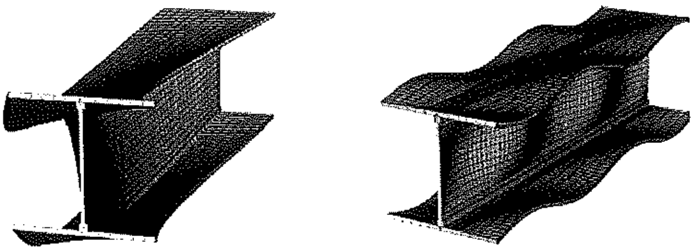

Figure 8: Global and local geometrical imperfections.

The global default is introduced through an appropriate modification of node coordinates (sinusoidal shape), i. e. affine to the member buckling shape. Such global defaults are introduced for strong axis, weak axis and torsional twist in a fully independent way. The maximum amplitude (at mid-span) of each default conforms to the measured values (see paragraph 2.2).

The local defaults are also introduced through a modification of the node coordinates. Full independence between flanges and web defaults is therefore enhanced. In accordance with the above mentioned considerations, the "truss system zones" remain unaffected by the initial imperfections.

The shapes are chosen with analogy to plate instability modes, i.e. through a combination of sine in both directions. For the web, a square half-wave pattern has been introduced, with the measured amplitude (Figure 8). It has to be noted that the chosen local default patterns are quite severe, especially for flanges, the experimental imperfection measurements being more favourable (see paragraph 2.2).

Finally, initial residual stresses have been introduced in the models by means of an auto-equilibrated parabolic distribution over the cross-section (see paragraph 2.2).

4.2 Validation of the FEM models against test results

In Table 4 the experimental results are compared to the numerical ones. A rather good agreement is found. The discrepancy is the highest (16%) for members subject to weak axis bending and axial compression. For such cases, the distribution of local geometrical imperfections in the Class 3 flanges is decisive; additional FEM calculations performed with a different but less unfavourable local default pattern in the flanges allow to get a much better agreement. These examples clearly show that the Class 3 cross-section walls can have a very important influence on the member carrying capacity.

Table 4: Comparison between experimental and numerical ultimate axial loads.

HEAA 240 L = 3.5 m	$N_{Exp.}$ [kN]	N_{FEM} [kN]	HEAA 240 L = 4.5 m	$N_{Exp.}$ [kN]	N_{FEM} [kN]
H355_1_BU_1	1369	1296	H355_2_BU_1	1180	1073
H355_1_BU_2	1636	1503	H355_2_BU_2	1443	1324
H355_1_BU_3	1430	1229	H355_2_BU_3	1078	959
H355_1_BU_4	1650	1480	H355_2_BU_4	1281	1150
H355_1_BU_5	1073	1003	H355_2_BU_5	896	822
H355_1_BU_6	1393	1303	H355_2_BU_6	1161	1023

On the basis of these results, the FEM simulations are found to be safe and accurate enough to simulate adequately the behaviour of structural members with semi-compact cross-sections.

5 CONCLUSIONS AND FURTHER DEVELOPMENTS

In present paper, the results of 12 beam-column experimental tests on members with Class 3 HEAA cross-sections have been presented. Beside this, FEM models developed in view of the accurate numerical simulation of such semi-compact members have been detailed. These models have been shown to be safe and accurate when compared to experimental results; as a conclusion they may be extensively used in parametrical studies to investigate the response of both Class 3 cross-sections and members with Class 3 cross-sections.

The next step of present research project will consist in developing a mechanical model for sections and members that would allow a full continuity along the Class 3 field. This model shall be finally validated against both experimental and numerical results.

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