

Full paper

Four-point bending tests on thin-walled cold-formed members with open cross-sections

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Abstract

The stability behavior of thin-walled cold-formed beams made of sigma and channel cross-sections usually used in rack structures and subjected to bending is experimentally investigated in the present paper. The experimental campaign consists of ten 4-point bending test, accompanying by initial imperfection measurements and coupon tests for the characterization of the actual geometric and mechanical material properties. The aim is to widen the knowledge on such members prone to lateral-torsional buckling combined with local and/or distortional deformations. Finally, an assessment of the design member resistance according to Eurocodes is performed.

Keywords

Lateral-torsional buckling, Thin-walled members, Cold-formed profiles, Open cross-sections, Stability

1 Introduction

Thin-walled cold-formed steel members are often used as primary or secondary structural elements in different type of constructions such as storage system structures or residential buildings. Despite the significant advantages of their use, monosymmetric sections about their major axis, such as channel or sigma profiles considered in the present study, exhibit specific features that significantly influence their structural response. They are open sections with very low torsional rigidity, and due to their small thicknesses, they are prone to local and distortional buckling. In addition, they are susceptible to lateral-torsional buckling when they are not laterally restrained.

A series of experimental studies have been conducted to investigate the stability behaviour of such beams subjected to bending. Wang et al. [1] performed major axis bending tests on single channels sections with different shaped intermediate and edge stiffeners made of G500 and G550 steel grades and compare the experimentally obtained resistances with those resulting from the application of Direct Strength Method (DSM). Chen et al. [2] executed experimental tests in order to study the behavior of cold-formed steel lipped channel beams affected by local-distortional interaction under non-uniform bending,

while Dinis et al. [3] investigated experimentally the interactive failure of web-stiffened lipped channel columns exhibiting distortional buckling. Wang et al. [4] conducted experimental and numerical studies on the bending strength and behavior of cold-formed steel Z275 C-section members with upright, inclined and complex edge stiffeners. Experimental bending tests on beams made of one or more cold-formed steel C or U profiles made of S280GD+Z structural steel grade are reported in Ref. [5].

In addition to the experimental studies, a substantial amount of numerical and analytical research has also been performed. Schafer et al. [6] investigated the behavior of thin-walled cold-formed steel members that employ complex edge stiffeners by finite element method. Vermeylen et al. [7] performed numerical and analytical investigations in order to validate the formula given in CEN/TR 1993-1-103 [8] for the calculation of the critical bending moment of monosymmetric about their major axis thin-walled sections. Lindner et al. [9] proposed an alternative design procedure to address the resistance of cold-formed steel beams subjected to both lateral-torsional buckling and local plate buckling, while Basaglia et al. [10] performed extensive numerical and analytical studies aiming to investigate the buckling and post-buckling behaviour of cold-formed steel lipped channel beams, and performed

an assessment of the DSM by comparing all the numerically obtained results with estimates provided by the DSM equations. Finally, different research teams have also conducted numerical studies on the strength of sigma section beams subjected to bending [11]–[12].

In order to further investigate the complex stability behaviour of thin-walled cold-formed monosymmetric about their major axes sections subjected to bending, where local, distortional and global instabilities could occur simultaneously, an experimental campaign consisting of ten 4-point bending tests has been launched at the “Laboratoire de Mécanique des Matériaux et Structures” of the University of Liège. The campaign aims at widening the existing database of experimental tests on beams made of thin-walled cold-formed C and sigma sections subjected to bending, as observed by Haidarali et al. [13], the shape, the size, and the location of the intermediate longitudinal stiffeners on such sections have a significant impact on the stability of these members. The bending tests were accompanied by initial imperfection measurements and coupon tests for the characterization of the actual geometrical and mechanical material properties respectively. The experimentally obtained resistances have been then compared with the normative ones resulting from the application of EN 1993-1-3 [14] provisions.

2 Description of the experimental campaign

2.1 Details of the specimens

Both sigma and channel profiles with lips made of HX420LAD steel grade have been considered in this study. The profiles have been selected among profiles usually used in racking structures aiming to represent compact and slender sections for which local instability phenomena (local/distortional buckling) may occur or not. All the details of the tested specimens are summarised in Table 1; the name of each specimen consists of one number that indicates the profile (i.e. 1 for SISB 130/60/2.0, 2 for SISB 180/70/1.5, 3 for SISB 160/60/2.0, 4 for C 240/65/15/1.5 and 5 for C 240/65/25/.3.5), and the letter a or b which is referring to the number of the test, as each test is performed twice.

Table 1 Details of the tested profiles

Label	Profile	Steel grade	Sectional behaviour
Sp1a/Sp1b	SISB 130/60/2.0	HX420LAD	Compact
Sp2a/Sp2b	SISB 180/70/1.5	HX420LAD	Slender
Sp3a/Sp3b	SISB 160/60/2.0	HX420LAD	Compact
Sp4a/Sp4b	C 240/65/15/1.5	HX420LAD	Slender
Sp5a/Sp5b	C 240/65/25/3.5	HX420LAD	Compact

For all the specimens, the length between the end supports L (see Figure 1) was set constant and equal to 3000 mm. This value corresponds to a quite common beam length met in racking structures, case study considered in this research project (see Acknowledgments). Furthermore, the prevention of local buckling on the web due to concentrated loads at the end supports and at the load

application points was dealt with using stiffeners at these sections. More details can be found in Ref [15].

2.2 Testing setup

The set-up for the bending tests is schematized in Figure 1. In order to uniformly distribute the load applied by the jack at the two loading location, a repartition beam made of a HEB140 cross-section (green element in Figure 1) has been used. The jack was connected to the testing frame beam through a bride which allows an out-of-plane rotation about Y axis. All the specimens were pin-ended and laterally restraint at their extremities with forks (magenta elements in Figure 1), which allow the rotation about Y axis in both extremities.

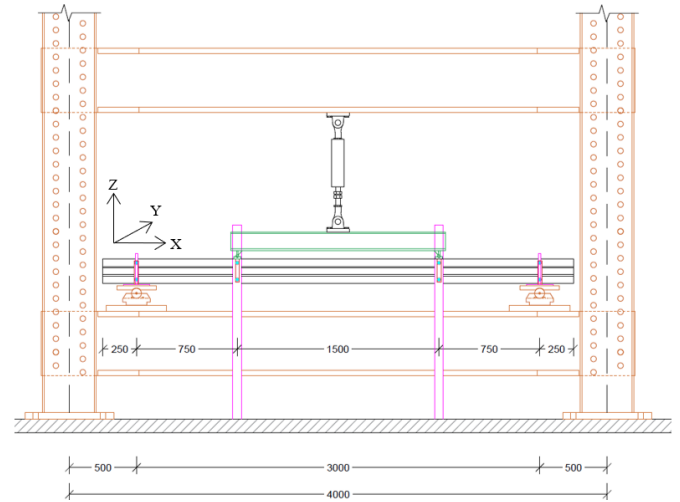


Figure 1 Drawing of the test set-up for the bending test

The horizontal movement along X axis was only possible at the left support. Lateral restraints were also applied at the load application points. The presence of the forks and the stiffeners at these positions prevent the twisting of the specimen due to the unintentional non-coincidence between the applied loading and shear center vertical planes.

2.3 Instrumentation of the tests

Different measurements have been recorded during the bending tests, as summarized below:

1. Applied load (jack)
2. Vertical displacement at $L/4$ (mid-upper flange width)
3. Vertical displacement at $L/2$ (mid-upper flange width)
4. Vertical displacement at $3L/4$ (mid-bottom flange width)
5. Lateral displacement at $L/2$ (mid-height of the web)
6. Out-of-plane rotation at $L/2$ (mid-height of the web)

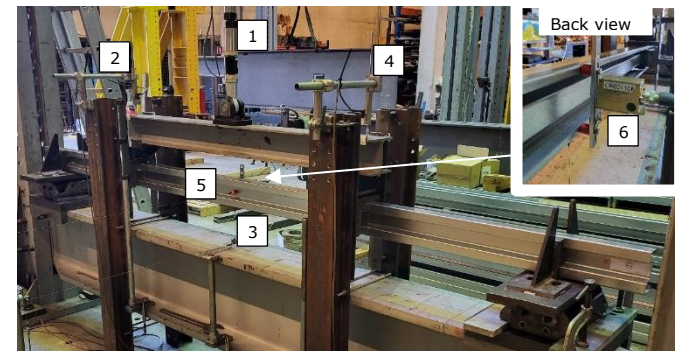


Figure 2 Instrumentation of bending tests

The tests were force-controlled while the load applied by the jack was recorded by means of a load cell. The lateral displacement at $L/2$ was measured at mid-height of the specimens, while the vertical displacement at the same position was recorded at mid-width of the bottom flange. In addition, the vertical displacements at $L/4$ and $3L/4$ were measured on the HEB 140 beam as it is expected to be the same in both the specimen and the HEB 140 at these positions due to the forks; these measurements allow to check if the HEB 140 beam remains parallel to the specimen during the test while their mean value provides the axial elongation of the jack. All the displacements have been measured with displacement transducers (LVDTs) that have been placed at a distance from the specimen by using a wire, in order to minimize the possible error of the measurement due to the potential rotation of the specimen. Finally, the out-of-plane rotation at midspan has been recorded using an inclinometer. Figure 2 depicts the instrumentation on the test setup, while the illustrated numbers are in line with the numbering system (N°) given in this subsection.

3 Preliminary measurements

3.1 Measurements of mechanical properties

The actual material properties of the specimens were determined through 4 tensile tests per profile and in accordance with ISO 6892-1 [16]. Table 2 summarizes the mean values of the upper yield stress (R_{eH}) or the proof strength ($R_{p0.2}$), the lower yield stress (R_{eL}), the tensile strength (R_m) and the modulus of elasticity (E) for each profile.

Table 2 Coupon tests results

Specimen	R_{eH} or $R_{p0.2}$ [MPa]	R_{eL} [MPa]	R_m [MPa]	E [MPa]
Sp1a/Sp1b	497,65	490,19	573,07	200041
Sp2a/Sp2b	413,88	413,88	538,39	204105
Sp3a/Sp3b	469,76	461,31	546,06	204940
Sp4a/Sp4b	435,06	424,44	488,06	208192
Sp5a/Sp5b	416,53	411,71	497,15	200864

3.2 Measurements of geometrical properties

The actual geometry of the profiles was measured in three cross-sections along each specimen: close at both extremities and at the mid-span section. The total length of the specimen has also been measured, as well as the angles of the four corners. Through the measured values it has been observed that, globally, the actual geometry of the cross-sections was not differing a lot from the nominal ones (maximum measured difference was 4%).

Further to the actual geometry of the cross-sections, the initial geometrical imperfections have been also measured. Two measurements M1 & M2 on the three external faces and along the member's length have been performed for all specimens. These measurements allow to capture the bow imperfection along the length, to identify local imperfections but also to calculate the distortion of the

flanges, knowing also the angle of the external corners.

Figure 3 shows the details of the set-up of measuring system. The latter was made of a chariot equipped with two LVDTs moving on a beam approximately parallel to the specimen, so that the transducers (LVDTs) could measure the imperfections at two points on the external faces of the member. As the chariot is moving onto a horizontal guiding bar, a small rotation of the metric system can possibly develop. Given that this rotation can significantly affect the results, this rotation was measured by an inclinometer, allowing thus to correct the measurements during the post-treatment of the results. The reference axis for all measurements was the pretensioned wire shown in Figure 3, while a measurement has been taken every 50 mm along the member length. Furthermore, two support columns were used to stabilize the specimen at the extremities, only when imperfections on face C were measured. Obviously these elements were not required for measurements performed on faces A and B (bottom and upper flanges of the specimen). As these restraint points are coincide with the positions of the end supports/forks where it is assumed that there are no imperfections, it can be concluded that they are not affecting the measured results. More details can be found in Ref [15].

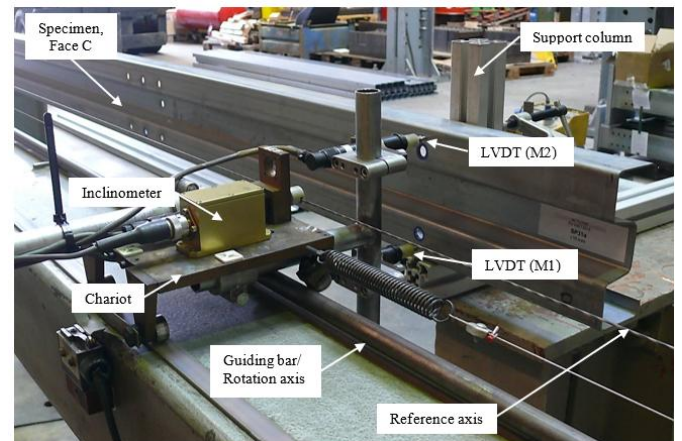


Figure 3 Measurement system for the initial geometrical imperfections

In EN1993-1-3, it is stated that the execution of steel structures made of cold-formed steel members should comply with EN 1090-4 [17], which refers to EN 10162 [18] for the fabrication tolerances of cold-rolled profiles. According to the latter, the out-of-straightness bow imperfection should be less than $L[mm]/500$, while the twist of the member should not exceed 1,0 degree per meter. Furthermore, the tolerance for the distortional angle of flanges with 40-80 mm width, is 1,15°. Through the elaborated measurements it has been seen that measured bow and twist imperfections, as well as the distortional angle of the flanges, are smaller than the geometrical tolerances prescribed in the normative standard for all specimens.

4 Test results

Prior to the experimental tests, two loading-unloading cycles were performed for each specimen. During the 1st cycle, the specimens were loaded approximately up to 33% of the estimated resistance calculated according to EN 1993-1-3:2006, and then, they were unloaded up to 10% of the resistance. This first loading cycle was aiming to ensure the full contact between all the elements of the

testing set-up and absorb possible lack-of-fit, while it allows to better catch the initial elastic stiffness of the member. Subsequently, a 2nd loading cycle was applied up to failure, after which, the specimens were fully unloaded. In order to make the graphs presented in the section more readable, the first loading and unloading branches have been erased from the presented graphs. Figure 4 shows some representative load-displacement and load-rotation curves of the bending tests; the definition of the axis is in line with Figure 1.

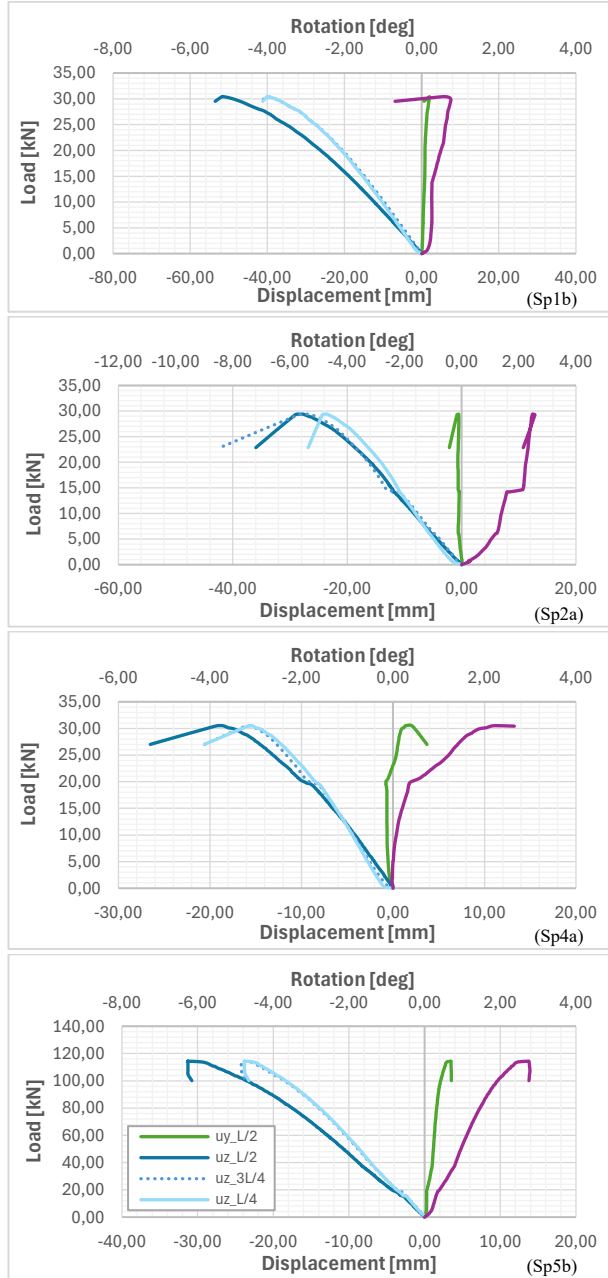


Figure 4 Load-displacement and load-rotation curves of the tests

Although the vertical displacements $u_{z,L/4}$ and $u_{z,3L/4}$ have been measured on the upper flange of the repartition beam HEB 140 (see Figure 2), it is expected to be the same at every point of this cross-section of the specimen due to the presence of the forks and the stiffeners at these locations. For all specimens, except Sp2a, both vertical displacements $u_{z,L/4}$ and $u_{z,3L/4}$ are almost identical, ensuring thus that the applied load is equally and symmetrically

distributed to the two load application points on the specimen (4-point bending test); the failure is also located between these two lateral restraints, as expected. However, for Sp2a, a small slip occurred at about 14,2 kN, after which the specimen is loaded more at the position of $3L/4$ creating so an asymmetric loading; this explains why the failure mode differs from the one of Sp2b and is located at the load application position (see Table 3). In addition, for all these tests, the vertical displacement at mid-section ($u_{z,L/2}$) has been measured at mid-width of the bottom flange, and as expected, it was higher than the vertical displacements at the quarter lengths (i.e. $u_{z,L/4}$ and $u_{z,3L/4}$). Furthermore, the horizontal deflection $u_{y,L/2}$ was measured at mid-height of the section and it was small for most of the specimens (maximum deflection 2,14 mm for Sp4a), except Sp5a and Sp5b that have deflections of 2,44 mm and 3,53 mm respectively. Obviously the lateral deflections of the upper flanges are a bit higher. The measured rotation of the mid-sections was also remaining low with the maximum measured value equal to 2,75°. All the measurements are available in Ref [15].

Table 3 Experimental test results

Specimen	P_{exp} [kN]	Failure mode
Sp1a	30,51	Local/global buckling + yielding
Sp1b	30,42	Local/global buckling + yielding
Sp2a	29,42	Yielding + crushing of the upper flange
Sp2b	29,25	Local/global buckling + yielding
Sp3a	32,29	Local/global buckling + yielding
Sp3b	34,22	Local/global buckling + yielding
Sp4a	30,53	Yielding + local buckling
Sp4b	31,56	Yielding + local buckling
Sp5a	115,18	Lateral-torsional buckling
Sp5b	114,32	Lateral-torsional buckling



Figure 5 Indicative failure mode of local/global buckling interaction and yielding of the cross-section (Sp1a)

Table 3 summarizes the failure mode of all specimens and the maximum obtained experimental loads applied by the jack (P_{exp}), while Figure 5 presents the indicative observed failure mode of these tests. It can be seen that all the specimens failed due to coupled instabilities (global & local) and yielding of the member, except specimens Sp5a and Sp5b for which lateral-torsional buckling (LTB) was more pronounced.

5 Comparison with the Eurocode provisions

Subsequently, the experimentally obtained resistances

have been compared with the ones calculated applying the provisions of EN1993-1-3:2006, and considering actual geometrical and material properties. According to §6.2.4, the design resistance of a member in bending prone to lateral-torsional buckling should be determined according to EN 1993-1-1:2005, §6.3.2, using the lateral buckling curve *b*. Therefore, the design buckling resistance moment of a laterally unrestrained beam should be taken as:

$$M_{b,Rd} = \chi_{LT} \frac{W_{y,eff} f_{yb}}{\gamma_{M1}} \quad (1)$$

where f_{yb} is the basic yield stress, γ_{M1} is the partial factor for resistance of members to instability (equal to 1,0 as recommended in EN 1993-1-1) and $W_{y,eff}$ is the effective section modulus according to EN 1993-1-3 using the effective width method, accounting for both local and distortional aspects; for compact sections $W_{y,eff}$ is equal to W_y of the gross cross-section. The reduction factor for lateral torsional buckling χ_{LT} should be determined as a function of the relative slenderness $\bar{\lambda}_{LT}$ of the member:

$$\bar{\lambda}_{LT} = \sqrt{\frac{W_{y,eff} f_{yb}}{M_{cr}}} \quad (2)$$

where the technical report CEN/TR 1993-1-103 [8] is used for the computation of the elastic critical moment, as justified in Ref. [7]. The actual sectional properties of the tested profiles, considering the measured geometry, are summarized in Table 4. The gross cross-sectional inertias (I_z , I_T and I_w) have been calculated taking into account the rounded corners using Calpro software, a specific tool available in the FINELG software suite [20].

Table 4 Mean actual sectional properties of the tested profiles

Specimen	$I_z \cdot 10^4$ [mm ⁴]	I_T [mm ⁴]	$I_w \cdot 10^9$ [mm ⁶]	W_y [mm ³]
Sp1a/Sp1b	23,96	901	1,212	21827
Sp2a/Sp2b	34,44	487	3,247	25573
Sp3a/Sp3b	28,19	970	2,056	28989
Sp4a/Sp4b	28,55	383	3,175	24685
Sp5a/Sp5b	70,95	5180	8,164	93981

Obviously the section moduli W_y are referring to the elastic ones for the compact sections (section moduli of the gross cross-section), while for the slender sections to the effective ones (i.e. $W_{eff,y}$). The effective moduli have been calculated accounting for both local and distortional buckling according to the provisions of EN 1993-1-3, §5.5. The notional flat widths of the plane elements have been taken according to EN 1993-1-3, §5.1(1). Although the rounded corners have been neglected according to EN 1993-1-3, §5.1(3), their influence is expected to be rather small (about 2-3%) according to [21], given that the radius and the thicknesses of the considered profiles are rather small. The effective widths of the compressed plated have been performed according to EN1993-1-5, §4.4 provisions.

For the analytical calculations, the critical length is defined as the length between two successive lateral restraints (i.e. $L_{crit} = 1500$ mm), while the C_1 coefficient is equal to 1 for constant bending moment distribution. Additionally,

even if the load is implemented at the upper flange, it is assumed that $z_g = 0$ due to the presence of the lateral restraints and the stiffeners at these positions. Moreover, as it has been observed during the tests that the presence of the stiffeners is not allowing for warping to freely develop at these positions, the actual effective length factors k_w and k_z should be equal to 0,5 and 1,0 respectively. The ratio m_{by} of the experimentally obtained moment (M_{exp}) to the analytically one ($M_{by,Rk}$) is calculated for all test in Table 5. The experimental resistance corresponds to the maximum first order bending moment developed in the specimen (i.e. $P_{exp} \cdot L/8$, where P_{exp} is given in Table 3 and $L = 3,0$ m for all tests), while the analytical one is calculated according to EN1993-1-3, §6.2.4.

Table 5 Ratio of the experimental to the analytical resistances

Specimen	M_{exp} [kNm]	M_{cr} [kNm]	$\bar{\lambda}_{LT}$ [-]	$M_{by,Rk}$ [kNm]	m_{by} [-]
Sp1a	11,44	30,16	0,596	8,98	1,27
Sp1b	11,41	30,16	0,596	8,98	1,27
Sp2a	11,03	59,98	0,420	9,72	1,14
Sp2b	10,97	59,98	0,420	9,72	1,13
Sp3a	12,11	43,51	0,554	11,49	1,05
Sp3b	12,83	43,51	0,554	11,49	1,12
Sp4a	11,45	55,06	0,436	9,55	1,20
Sp4b	11,84	55,06	0,436	9,55	1,24
Sp5a	43,19	135,04	0,535	33,59	1,29
Sp5b	42,87	135,04	0,535	33,59	1,28

It can be seen that all the experimentally obtained resistances are on the safe side compared with the ones calculated analytically by applying the provisions of EN 1993-1-3 in combination with EN 1993-1-1 and considering actual geometrical and material properties. More specifically, the mean value of the ratio m_{by} is equal to 1,20 with a CoV of 7,9%. The higher experimental resistances of these tests could be explained by the three following reasons. Firstly, due to the enhanced properties at the corners of the sections caused by strain hardening effects that were not taken into account analytically. Secondly, due to the assumptions adopted by the effective width method as recommended in Eurocode 3. Lastly, the fact that the small lengths between the external and the intermediate forks in combination with the stiffeners is slightly restraining the bending of the beam about *z* axis results to actual k_z factors slightly smaller than 1,0. However, the determination of the exact k_z value is not common in practice, where discrete design values are directly adopted depending on the boundary conditions. Therefore, no further investigations are made here. Finally, the use of buckling curve *b* seems to be adequate for both C and Σ sections.

6 Conclusions

The resistance and stability behaviour of small to medium range slenderness beams with monosymmetric thin-walled cold-formed sections subjected to bending are investigated in this paper through experimental and analytical studies. The conducted experimental campaign was made of ten 4-point bending tests, accompanying by initial

imperfection measurements and coupon tests for the characterization of the actual geometric and mechanical material properties. The tested beams failed due to a combination of global and local instabilities accompanying by a small yielding of the critical section, while for some, lateral-torsional buckling was more pronounced. In addition, the experimentally obtained resistances were compared with the ones calculated by applying the provisions of Eurocode 3. Through these comparisons, it has been shown that Eurocode 3 provides safe resistance predictions for thin-walled cold-formed unrestrained members subjected to bending, while the use of lateral-torsional buckling curve *b* seems to be verified for both C and Σ sections. Relevant outcomes of ACTIONS project related to the design of rack structures can be found in [22]-[23].

Acknowledgments

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