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Author(s)	Young, B; Camotim, D; Silvestre, N
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ULTIMATE STRENGTH AND DESIGN OF LIPPED CHANNEL COLUMNS EXPERIENCING LOCAL-DISTORTIONAL MODE INTERACTION – PART I: EXPERIMENTAL INVESTIGATION

Ben Young[1], Dinar Camotim[2] and Nuno Silvestre[2]

[1]Department of Civil Engineering, The University of Hong Kong, Hong Kong, China
[2]Department of Civil Engineering, ICIST/IST, Technical University of Lisbon, Lisbon, Portugal

KEYWORDS

Local-distortional interaction, Cold-formed lipped channel columns, Experimental investigation, High-strength steel, Mild steel, Initial geometrical imperfections, Ultimate strength.

ABSTRACT

This paper reports the results of an experimental investigation aimed at assessing the post-buckling behaviour and ultimate strength of fixed-ended cold-formed steel lipped channel columns experiencing local/distortional mode interaction. A total of 26 columns were tested and the specimens were carefully selected to ensure various levels of local/distortional interaction effects (more or less close local and distortional critical stresses). The experimental results presented consist of the specimen geometries, material properties, initial imperfections, non-linear equilibrium paths and ultimate strength values. Since the collapse of most columns combines local and distortional deformations, these experimental results may be used to (i) assess the relevance of local/distortional interaction, (ii) calibrate and validate numerical simulations and (iii) provide experimental data aimed at developing a Direct Strength Method (DSM) approach to design cold-formed steel lipped channel columns against local/distortional interaction – such a DSM approach is addressed in Part II of this paper.

INTRODUCTION

Most cold-formed steel members display very slender thin-walled open cross-sections, a feature making them highly susceptible to localised instability phenomena, namely local and distortional buckling. Moreover, since several commonly used members exhibit cross-section geometries (shape and/or dimensions) associated with close similar local and distortional bifurcation stresses, their overall structural behaviour is likely to be affected by the occurrence of mode interaction phenomena involving the above two buckling modes. In order to assess such overall structural behaviour, steel designers are currently faced with two alternative options: either (i) resort to highly complex and computer intensive numerical methods (an approach still prohibitive for routine applications), or (ii) take those effects into account indirectly, through their incorporation into member global analyses (*e.g.*, FEM analyses adopting non-linear beam finite elements). The latter strategy can only be rational and fully efficient if the knowledge about the member local and distortional post-buckling behaviour is deep enough to enable the development of reliable and physically based models. For instance, this is the case of (i) the well-known "plate effective width" concept, accounting for local effects, or (ii) the recently developed and increasingly popular "Direct Strength Method" (DSM), which can handle both local and distortional effects and takes into account the whole cross-section behaviour. However, its application to members affected by local/distortional interaction is still under development

It is well known that experimental investigations play a key role in understanding the behaviour and developing efficient (safe and economic) design rules for cold-formed steel members, namely uniformly compressed columns. Careful test programs were conducted in the last few years by (i) Young and Rasmussen [1], on plain channel columns, (ii) Kwon and Hancock [2] and Young and Rasmussen [3], on lipped channel columns, (iii) Young and Hancock [4], on lipped channel column with sloping lips, and (iv) Yan and Young [5], on channel columns with return lips – all these studies dealt with fixed-ended columns. Concerning fixed-ended lipped channel columns affected by local/distortional interaction, the only tests available were carried out by Yang and Hancock [6] and, more recently, by Yapp and Hancock [7] and Kwon *et al.* [8] – some of these tests involve lipped channel columns with intermediate stiffeners.

The objective of this paper is to report the results of an experimental investigation carried out at the University of Hong Kong to assess the non-linear (post-buckling) behaviour and ultimate strength of fixed-ended cold-formed steel lipped channel columns affected by local/distortional mode interaction. The first step of this work consisted of carefully selecting column geometries (cross-section dimensions and lengths) that ensure the occurrence of various levels of local/distortional interaction effects, *i.e.*, exhibiting more or less close local (f_{crl}) and distortional (f_{crd}) critical stresses. This goal was achieved by means of a trial-and-error procedure involving the performance of several buckling analyses carried out in the codes ABAQUS [9] (shell finite elements) and GBTUL [10, 11] (beam finite elements) – it led to the identification of 26 column geometries exhibiting commonly used cross-section dimensions and lengths, and associated with various f_{crd}/f_{crl} ratio values. Then, lipped channel specimens with the selected geometries were fabricated, carefully measured, in order to determine their real geometries and material properties, as well as to acquire relevant information concerning the existing initial geometrical imperfections. Finally, the specimens were tested as uniformly compressed fixed-ended columns. The experimental results presented consist of the specimen geometries, material properties (stress strain curves), initial imperfections, non-linear equilibrium paths (applied load *vs.* axial shortening*) and ultimate strength values. Since the collapse of most columns occurs in modes combining local and distortional deformations, these experimental results are ideally suited to (i) draw conclusions on the relevance of local/distortional interaction, (ii) calibrate and validate elastic-plastic shell finite element numerical analyses and (iii) provide experimental data aimed at developing a Direct Strength Method (DSM) approach to design cold-formed steel lipped channel columns against local/distortional interaction – such a DSM design approach is addressed in Part II of this paper [13].

(*Other experimental non-linear column equilibrium non-linear equilibrium paths are presented in [12])

TEST SPECIMENS

The cold-formed steel lipped channel test specimens were brake-pressed from high strength (HSS) and mild (MS) zinc-coated structural steel sheets. The specimens were cut to a specified length, ranging from 615 to 2500 mm, and their ends were first milled flat by an electronic milling machine and then welded to 25 mm thick steel end plates to ensure full contact between the specimens and end bearings. Finally, the specimens were uniformly compressed between fixed ends.

The test specimens had the nominal web, flange and lip widths ranging from 95 to 235 mm, 45 to 190 mm and 15 to 30 mm, respectively. The nominal plate thickness values were equal 1.0, 1.2, 1.5, 1.9 and 2.4 mm, and the base metal thickness (t^*) was measured by removing the zinc coating by acid etching – the zinc coating layer thickness was found to be equal to 18, 17, 28, 26 and 27 μm for the above five plate thicknesses. Finally, the measured external corner radius (r_e) ranged from 2.6 to 5.5 mm. All the measured cross-section dimensions and column length L for each test specimen are given in Table 1, following the nomenclature defined in Figure 1 – the cross-section dimensions are the averages of values measured at both column ends.

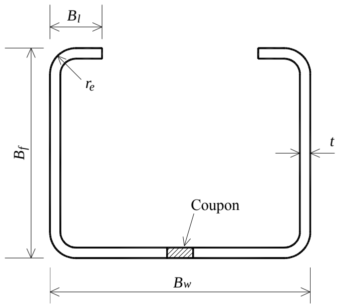


Figure 1: Nomenclature and location of the tensile coupon

TABLE 1
MEASURED SPECIMEN DIMENSIONS AND EXPERIMENTAL RESULTS

Specimen	Lips	Flanges	Web	Thinkness		External radius	Length	Experimental ultimate load	Failure mode
	B_l (mm)	B_f (mm)	B_w (mm)	t (mm)	t^* (mm)	r_e (mm)	L (mm)	P_{Exp} (kN)	
T1.0-HSS-1	15.2	81.6	104.9	0.997	0.962	2.8	2498.0	39.9	L+D
T1.0-HSS-2	15.5	82.1	101.8	1.019	0.984	2.8	2499.0	42.1	L+D
T1.0-HSS-3	16.9	80.9	94.9	1.013	0.978	2.8	2499.0	42.0	L+D+FT
T1.2-HSS-1	14.7	131.2	152.5	1.260	1.227	2.6	1424.5	68.1	L+D
T1.2-HSS-2	15.8	131.0	152.4	1.260	1.227	2.9	1426.0	71.0	L+D
T1.2-HSS-3	15.0	141.0	154.5	1.239	1.206	3.0	1426.0	67.7	L+D
T1.5-HSS-1	16.1	82.2	110.5	1.515	1.459	3.3	1148.0	109.0	L+D
T1.5-HSS-2	15.7	82.0	118.5	1.509	1.453	3.4	1148.5	102.8	L+D
T1.5-HSS-2R	15.9	81.9	118.6	1.525	1.469	3.4	1148.0	103.6	L+D
T1.5-HSS-3	19.0	192.7	203.7	1.534	1.478	3.9	1851.5	92.9	L+D
T1.5-HSS-4	20.6	191.9	204.7	1.515	1.459	3.4	1849.0	94.7	L+D
T1.9-MS-1	19.2	113.1	182.1	1.985	1.934	5.5	1030.0	145.2	L+D
T1.9-MS-2	20.2	112.5	181.1	1.966	1.915	5.5	1026.0	146.1	L+D
T1.9-MS-3	19.4	122.5	182.5	2.025	1.974	5.5	1027.0	142.5	L+D
T1.9-MS-4	25.8	102.5	115.0	2.022	1.971	5.5	1756.5	164.0	D
T1.9-MS-5	28.2	103.1	114.7	1.998	1.947	5.5	1760.5	170.8	L+D
T1.9-MS-6	21.1	162.7	238.9	2.017	1.966	5.5	1945.5	129.7	L+D
T1.9-MS-7	23.1	162.3	238.2	1.998	1.947	5.0	1947.0	131.6	L+D
T1.9-MS-8	30.3	103.4	103.7	2.011	1.960	5.3	2101.5	174.9	FT
T2.4-HSS-1	19.0	47.0	103.8	2.481	2.427	5.0	617.5	248.2	D
T2.4-HSS-2	19.2	51.9	105.2	2.476	2.422	4.8	618.5	256.7	D
T2.4-HSS-3	19.3	52.8	101.4	2.481	2.427	4.8	616.0	254.1	D
T2.4-HSS-4	19.5	88.5	109.8	2.473	2.419	4.8	936.5	296.6	D
T2.4-HSS-5	24.5	86.4	114.8	2.482	2.428	4.8	940.5	299.2	D
T2.4-HSS-6	26.6	86.5	113.9	2.479	2.425	5.0	939.0	309.1	D
T2.4-MS-1	27.2	103.5	105.0	2.444	2.390	5.5	2098.5	212.6	FT

Note: 1 in. = 25.4 mm; 1 kip = 4.45 kN; L = Local buckling; D = Distortional buckling; FT = Flexural-Torsional buckling.

Specimen Labelling

The lipped channel test specimens are labelled so that the plate thickness, strength of steel material and test series can be readily identified by looking at the label – for instance, the labels "T1.5-HSS-2R" and "T1.9-MS-4" define the following specimens:

(i) The first three letters indicate the specimen plate thickness, where the prefix letter "T" refers to thickness and "1.5" and "1.9" indicate the nominal thicknesses equal to 1.5 and 1.9 mm.
(ii) The second part indicates the strength of the steel material, where "HSS" refers to high strength steel and "MS" refers to mild steel material.
(iii) The third part provides the column number – the dimensions of each column are given in Table 1.
(iv) If a test was carried out twice, the letter "R" indicates the repeated test.

Material Properties

The specimen material properties were obtained by means of tensile coupon tests. The coupons were extracted, in the longitudinal direction, from the centre of the specimen web, as shown in Figure 1 – one coupon test was carried out for each specimen batch (series). The coupon dimensions conformed to the Australian Standard AS 1391 [14] for the tensile testing of metals – 12.5 mm wide coupons of gauge length 50 mm were used. An MTS displacement controlled testing machine using friction grips was used to conduct the coupon tests, which were also performed according to the Australian Standard AS 1391. A calibrated extensometer of 50 mm gauge length was employed to measure the coupon specimen longitudinal strains. In addition, two linear strain gauges were attached at the two face centres of each coupon – their readings were used to determine the initial Young's modulus.

A data acquisition system was used to record the load and the strain readings at regular intervals during the coupon tests. The static load was obtained by pausing the applied straining for 1.5 minutes near the 0.2% proof stress and the ultimate tensile strength, thus allowing the stress relaxation associated with plastic straining to take place. The material properties obtained from the coupon tests, summarised in

TABLE 2
MEASURED MATERIAL PROPERTIES OF TEST SPECIMENS

Series	E (GPa)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	ε_f (%)
T1.0-HSS	211.7	536.4	563.6	7.7
T1.2-HSS	213.3	587.5	604.5	8.0
T1.5-HSS	211.2	493.7	526.3	12.0
T1.9-MS	203.4	335.6	441.0	30.9
T2.4-HSS	212.6	525.9	544.5	9.5
T2.4-MS	205.0	342.7	463.9	31.6

Note: 1 ksi = 6.89 MPa.

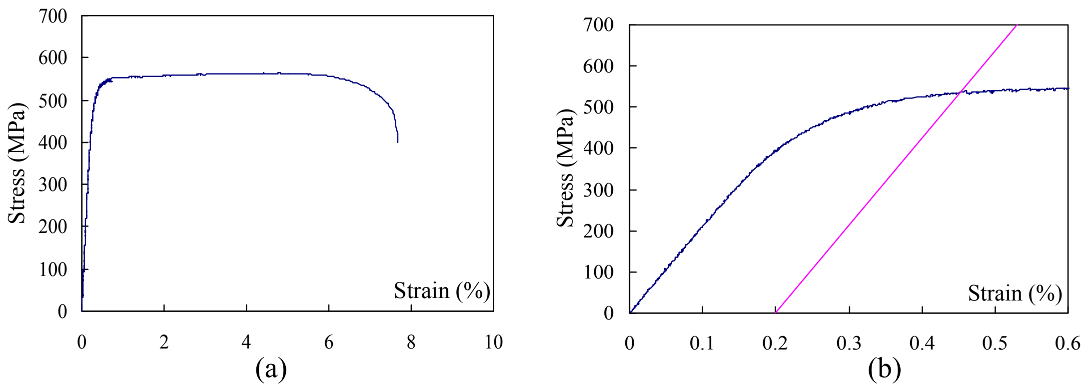
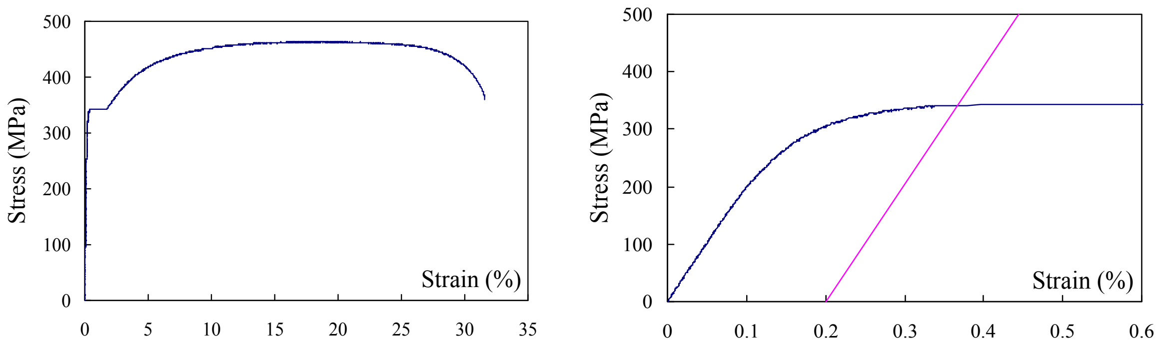


Figure 2: Stress-strain curve for test series T1.0-HSS: (a) complete curve and (b) initial part



(a) (b)

Figure 3: Stress-strain curve for test series T2.4-MS: (a) complete curve and (b) initial part

Table 2, consist of the values of (i) Young's modulus (*E*), (ii) static 0.2% proof stress ($\sigma_{0.2}$), (iii) static tensile strength (σ_u) and (iv) elongation after fracture (ε_f), based on a gauge length of 50 mm. The stress-strain curves obtained from the coupon tests are displayed in Figures 2(a)-(b) and 3(a)-(b) for the test series T1.0-HSS and T2.4-MS, respectively – Whiles Figures 2(a) and 3(a) show the complete stress-strain curves, Figures 2(b) and 3(b) provide information about the initial parts of those curves.

Initial Geometrical Imperfections

Two local initial geometrical imperfection measurements were made at the column specimen mid-length cross-section prior to testing – they are indicated in Figure 4 and provide information concerning the local (Δ_w) and distortional (Δ_d) imperfections. The measured values are shown in Table 3, where Δ_w and Δ_d are the initial values of the (i) mid-web plate bending displacement and (ii) flange-lip junction horizontal (normal to the flange) displacement. Positive Δ_w and Δ_d values indicate inward (towards the lips) and outward deformations, respectively – *i.e.*, those show in Figure 4.

Moreover, the initial overall flexural geometrical imperfections (about the minor axis) were measured in all column specimens – they were measured along the specimen web-flange longitudinal edge and a theodolite was used to obtain readings at mid-length and near both specimen ends. The measured values at mid-length (δ), normalised with respect to the length *L*, are also shown in Table 3. A positive δ/L value indicates that the column is curved towards the lips – *i.e.*, δ has the sense of Δ_w in Figure 4.

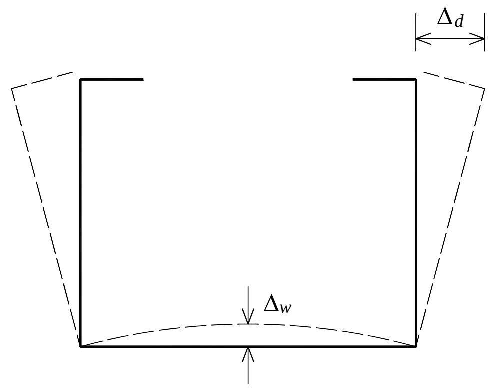


Figure 4: Initial local geometric imperfections measured at the mid-length cross-section

TEST RIG AND OPERATION

The test rig and test set-up of a typical fixed-ended cold-formed steel lipped channel column test are shown in Figures 5(a) (front view) and 5(b) (side view) – they concern specimen T1.5-HSS-1. A servo-controlled hydraulic testing machine was used to apply the compressive axial force to the column specimens, which have steel plates welded to their end cross-sections ends. A rigid flat bearing plate was connected to the upper testing machine end support, and the specimen top end plate was bolted to this bearing plate, which was restrained against warping, twist and major and/or minor axis flexural rotations – this setting may be said to correspond to a fully fixed column end support condition.

TABLE 3
MEASURED INITIAL LOCAL AND OVERALL GEOMETRIC IMPERFECTIONS AT MID-LENGTH

Specimen	Local imperfection		Overall imperfection
	Δ_w (mm)	Δ_d (mm)	δ/L
T1.0-HSS-1	0.20	3.96	1/9850
T1.0-HSS-2	0.38	1.89	-1/13130
T1.0-HSS-3	1.04	3.61	1/3580
T1.2-HSS-1	0.09	-1.91	-1/22480
T1.2-HSS-2	0.37	1.68	1/5630
T1.2-HSS-3	0.44	-2.75	-1/1880
T1.5-HSS-1	0.17	0.70	-1/6040
T1.5-HSS-2	0.23	0.96	1/4530
T1.5-HSS-2R	0.04	-0.57	-1/2270
T1.5-HSS-3	0.47	-0.32	1/9740
T1.5-HSS-4	0.13	5.96	1/3240
T1.9-MS-1	0.56	4.54	1/8130
T1.9-MS-2	0.25	3.23	-1/16210
T1.9-MS-3	0.44	3.81	1/8110
T1.9-MS-4	0.38	3.50	1/13850
T1.9-MS-5	0.26	2.08	1/1630
T1.9-MS-6	0.59	-0.51	1/4380
T1.9-MS-7	1.34	-0.91	1/3410
T1.9-MS-8	0.31	2.78	1/2370
T2.4-HSS-1	0.06	-0.02	-1/9770
T2.4-HSS-2	0.13	-0.36	1/9790
T2.4-HSS-3	0.05	-0.57	1/4870
T2.4-HSS-4	0.08	-0.70	1/7400
T2.4-HSS-5	0.46	3.79	1/1060
T2.4-HSS-6	0.53	3.40	1/1350
T2.4-MS-1	0.40	6.87	1/1440

Note: 1 in. = 25.4 mm.

A special bearing located at the lower end support was initially free to rotate in any direction. The actuator ram was moved slowly until this special bearing was in full contact with the specimen bottom end plate, for a very small applied load level (approximately 2 kN). This procedure made it possible to eliminate any gaps between the special bearing and specimen bottom end plates, which were then bolted together. The use of vertical and horizontal bolts enabled the full restraint of the bearing plate – once full contact was achieved, these bolts were used to lock the bearing plate into position, thus creating a fully fixed end support bearing. Finally, it is still worth mentioning that the use of a moveable end support allowed the performance of tests on columns with various lengths.

Three displacement transducers were used to measure the column specimen axial shortening. In addition, seven transducers were positioned around the specimen mid-length cross-section, as shown in Figure 6 – two transducers located 15 mm apart from the flange-lip junctions, four transducers located 15 mm apart from the web-flange junctions and one transducer located at the mid-web point. These transducers are able to capture the full specimen mid-length cross-section deformations. Displacement control was adopted to drive the hydraulic actuator, at a constant speed of 0.2 mm/min in all tests, thus allowing the tests to be carried out beyond the ultimate load (*i.e.*, the post-ultimate range). A data acquisition system was used to record the applied load and displacement transducer readings at regular intervals during the tests.

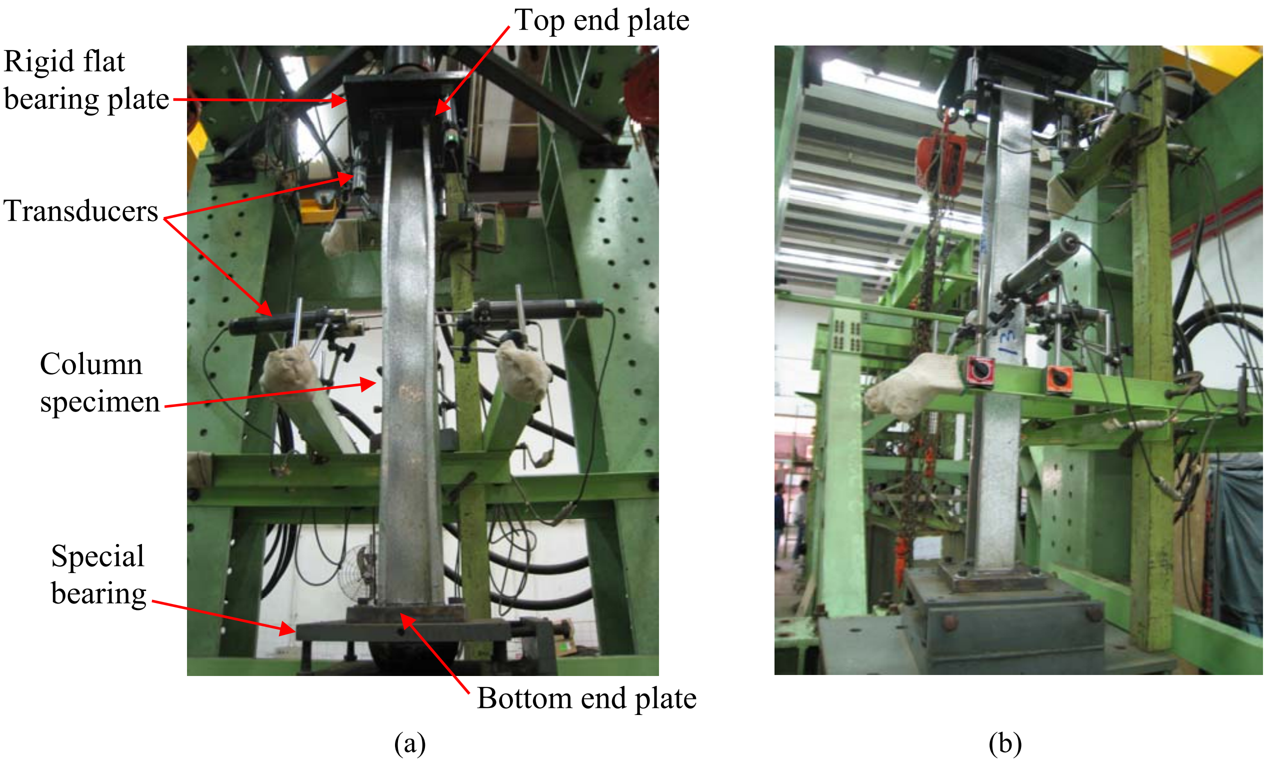


Figure 5: Test setup for specimen T1.5-HSS-1: (a) front and (b) side views

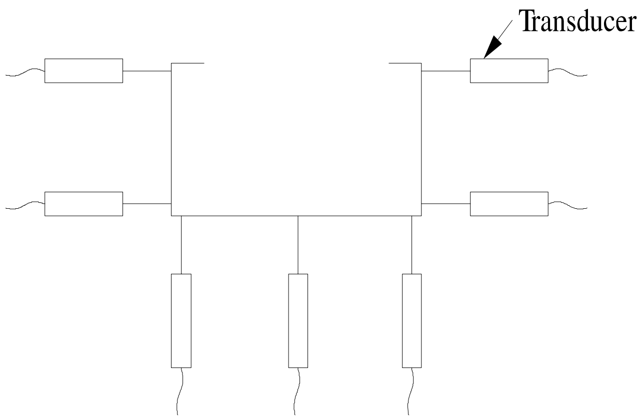


Figure 6: Transducer arrangement located at mid-length of the columns

TEST RESULTS

The experimental ultimate loads (P_{Exp}) obtained from the tests are shown in Table 1, which also includes an indication of the nature of the column specimen failure – L, D and FT stand for local, distortional and flexural-torsional collapse modes. Local/distortional interaction was observed in most of the column specimens belonging to test series T1.0-HSS, T1.2-HSS, T1.5-HSS and T1.9-MS – the exceptions were specimens T1.0-HSS-3, T1.9-MS-4 and T1.9-MS-8. Clear experimental evidence of the occurrence of Local/distortional interaction can be inspected in Figure 7, which concerns specimen T1.5-HSS-1 and is a "blow-out" of the column specimen central region depicted in Figure 5(a).

It should be noted that (i) it was perceptible in the specimen T1.0-HSS-3 failure mode the interaction between local, distortional and flexural-torsional deformations, and that (ii) the specimen T1.9-MS-4 and T1.9-MS-8 collapse mechanisms were purely distortional and global (flexural-torsional), respectively. Finally, note also that (i) no local deformations were detected in the column specimens belonging to the test series T2.4-HSS and T2.4-MS, both having a 2.4 mm wall thickness – moreover, (i) all the specimens in the test series T2.4-HSS exhibited purely distortional failure modes and (ii) the specimen T2.4-MS-1 failed in a pure flexural-torsional mode.

Figure 7: Experimental evidence of the occurrence of local/distortional interaction (specimen T1.5-HSS-1)

Figures 8 and 9 concern specimen T1.5-HSS-3 and display curves providing the relation between the applied axial load and the column (i) axial shortening and (ii) mid-length web-flange junction (distortional) displacements and (iii) mid-length mid-web (local) displacements * – it is clear that the emergence of significant local and distortional deformations starts at approximately 35 kN and that this column specimen experiences local/distortional interaction. (*It should be noted that the mid-web displacement has components stemming from is both local and distortional deformations.)

Finally, one last word to mention that two column test specimens T1.5-HSS-2 were tested and that the two ultimate loads obtained were practically identical (0.8% difference) – therefore, it seems fair to conclude that these test results are quite reliable.

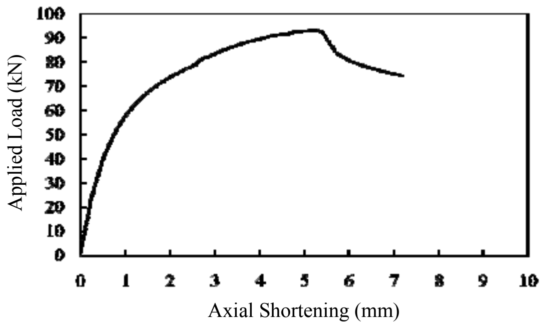


Figure 8: Load vs. axial shortening curve for specimen T1.5-HSS-3

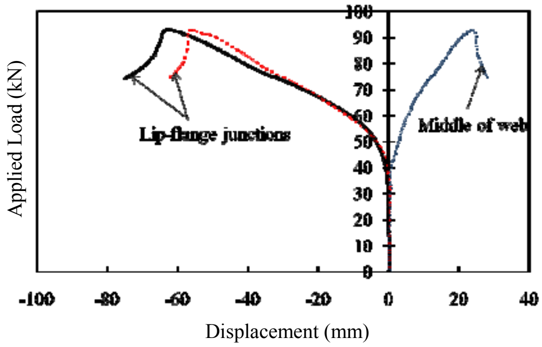


Figure 9: Load vs. mid-length cross-section displacement curves for specimen T1.5-HSS-3

CONCLUSION

This paper reported the results of an experimental investigation on the post-buckling behaviour and ultimate strength of fixed-ended cold-formed steel lipped channel columns experiencing local/distortional interaction. The 26 specimens were brake-pressed from high strength and mild zinc-coated structural steel sheets with measured 0.2% proof stresses in the 336-588 MPa range, nominal thicknesses varying from 1.0 to 2.4 mm and lengths comprised between 615 to 2500 mm. The experimental results consisted of specimen local, distortional and global initial imperfections, non-linear equilibrium paths and ultimate strengths – most specimens failed in mechanisms involving local/distortional interaction (with the consistent exception of those with 2.4 mm wall thickness). These results will be very useful to (i) calibrate and validate numerical simulations and (ii) develop a DSM approach to design cold-formed steel lipped channel columns against local/distortional interaction – see Part II of this paper and reference [12].

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