Steel and Composite Structures, *Vol. 28, No. 2 (2018) 233-250*
DOI: https://doi.org/10.12989/scs.2018.28.2.233

Nonlinear behavior of axially loaded back-to-back built-up cold-formed steel un-lipped channel sections

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(*Received February 2, 2018, Revised April 27, 2018, Accepted May 9, 2018*)

Abstract. Back-to-back built-up cold-formed steel un-lipped channel sections are used in cold-formed steel structures; such as trusses, wall frames and portal frames. In such built-up columns, intermediate fasteners resist the buckling of individual channel-sections. No experimental tests or finite element analyses have been reported in the literature for back-to-back built-up cold-formed steel un-lipped channel sections and specially investigated the effect of screw spacing on axial strength of such columns. The issue is addressed in this paper. The results of 95 finite element analyses are presented covering stub to slender columns. The finite element model is validated against the experimental tests recently conducted by authors for back-to-back built-up cold-formed steel lipped channel sections. The verified finite element model is then used for the purposes of a parametric study to investigate the effect of screw spacing on axial strength of back-to-back built-up cold-formed steel un-lipped channel sections. Results are compared against the built-up lipped channel sections and it is shown that the axial strength of un-lipped built-up sections are 31% lesser on average than the built-up lipped channel sections. It was also found that the American Iron and Steel Institute (AISI) and the Australian and New Zealand Standards were over-conservative by around 15% for built-up columns failed through overall buckling, however AISI and AS/NZS were un-conservative by around 8% for built-up columns mainly failed by local buckling.

Keywords: cold-formed steel; built-up sections; un-lipped channels; screw spacing; back-to-back sections; axial strength; finite element analysis

1. Introduction

In recent times, cold-formed steel is increasingly used in residential and commercial buildings because of its superior strength to self-weight ratio and ease of construction (Darcy and Mahendran (2008), Schafer (2002)). Back-to-back built-up cold-formed steel un-lipped channel sections (see Fig. 1) are used as compression members in structures. Such sections are used in steel trusses and space frames, wall studs in wall frames, and columns in portal frames (Lawson *et al.* (2008)). In built-up sections, intermediate fasteners along the length are used to prevent the channel-sections from buckling independently. Current design guidelines i.e. The American Iron and Steel Institute (AISI 2012) and Australian and New Zealand Standards (Standards Australia 2005) recommends the use of modified slenderness approach to take into account the spacing of screws in built-up sections. It should be noted that this modified slenderness approach has been adapted from design guidance for hot-rolled steel.

In the literature, significant research has been described for cold-formed steel channel sections under axial compression to understand the buckling behaviour of such columns (Shi *et al.* (2011), Silvestre and Camotim (2004), Young (2005), Zhou and Jiang (2017)). However, very limited research has been described in past, for the back-to-back built-up cold-formed steel un-lipped channel-sections under compression, in the arrangement shown in Fig. 1. Ting *et al.* (2018) recently presented an experimental and numerical investigation on the behaviour of back-to-back built-up CFS lipped channel sections under axial compression. To extend this work, Roy *et al.* (2018a, b), has investigated the effect of thickness on the behavior of back-to-back built-up cold-formed steel lipped channel sections. On the other hand, Fratamico *et al.* (2016) investigated the effect of screw spacing on the behavior of back-to-back built-up columns but these were lipped channel sections. Anbarasu *et al.* (2015) investigated the behaviour and strength of cold-formed steel web stiffened built-up batten columns and proposed a recommendation to the current Direct strength method (DSM), while calculating axial strength of such columns. Dabaon *et al.* (2015) investigated built-up battened columns and reported that AISI and Eurocodes were un-conservative when the steel battened columns failed through local buckling, but were conservative when they failed through flexural buckling. While, Stone and LaBoube (2005) considered back-to-back lipped channel-sections but these had stiffened flanges and

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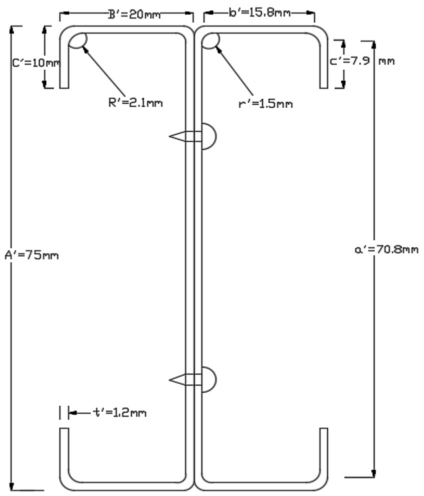
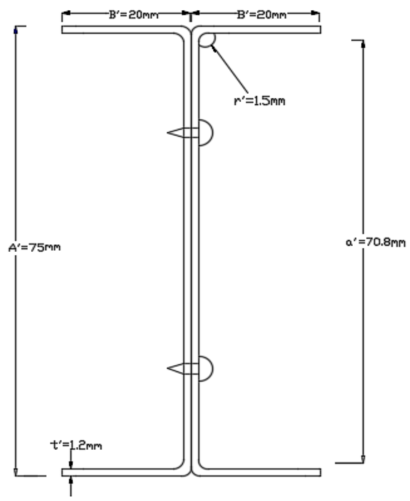
http://www.techno-press.org/?journal=scs&subpage=6 ISSN: 1229-9367 (Print), 1598-6233 (Online)

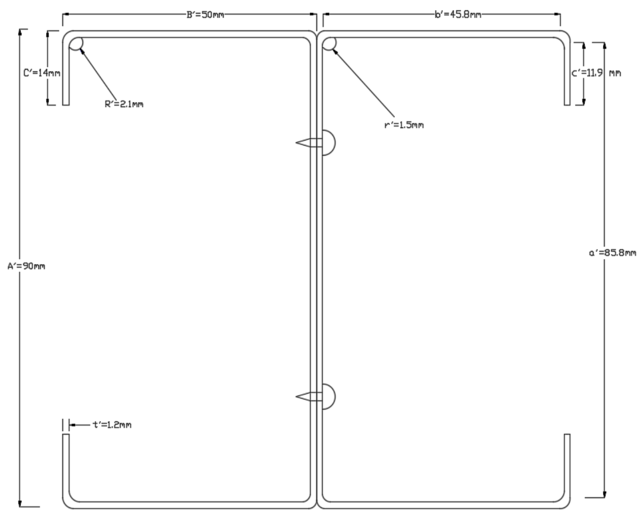


(i) Lipped

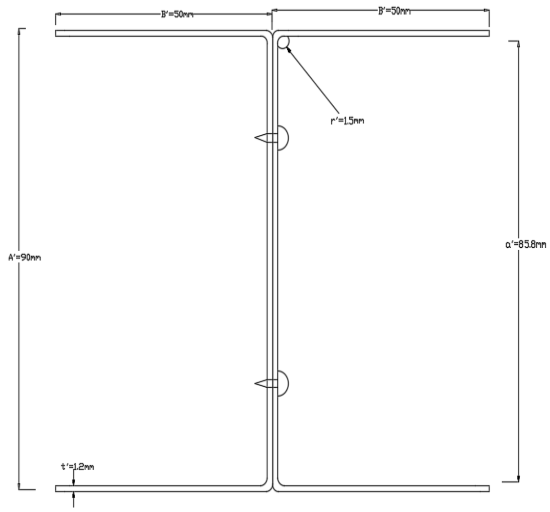


(ii) Un-lipped

(a) BU75



(i) Lipped



(ii) Un-lipped

(b) U90

Fig. 1 Details of back-to-back built-up cold-formed steel channel-sections

track sections. Whittle and Ramseyer (2009) considered welded to-to-toe built-up channel-sections and investigated the strength of such sections. Piyawat *et al*. (2013) considered back-to-back welded lipped channel-sections. Zhang and Young (2012) considered back-to-back built-up lipped channel-sections, but with an opening, as shown in Fig. 2. On the other hand, cold-formed steel built-up closed sections with intermediate stiffeners were investigated by Young and Chen (2008). Roy *et al*. (2018d, f) has studied experimentally and numerically, the axial capacity of back-to-back gapped built-up cold-formed steel lipped channel sections and concluded that the current design guidelines by AISI and AS/NZS, can be too conservative while predicting the axial capacity of such columns. An analytical criterion for buckling strength of built-up compression members were studied by Aslani and Goel (1991). Similar work was carried out by Reyes and Guzman (2011) to evaluate the slenderness ratio in built-up cold formed box sections. On the other hand, Biggs *et al*. (2015) investigated the axial

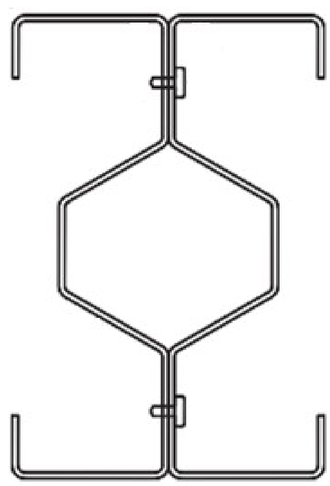


Fig. 2 Back-to-back built-up cold-formed steel channel sections with an opening after Young and Zhang (2012)

strength of rectangular and I-shaped welded built-up cold-formed steel columns under compression and concluded that AISI (2012) can be more conservative for thicker members but less conservative for wider members. Roy *et al*. (2018c) recently conducted experiments tests on back-to-back built-up CFS channels, which were validated against the finite element results presented in another paper by Roy *et al*. (2018e). Roy *et al*. (2018g), also investigated the nonlinear behavior of axially loaded back-to-back built-up cold-formed stainless steel channel sections. However, no previous work in the literature has considered the back-to-back built-up cold-formed steel un-lipped channel sections under compression and specially investigated the effect of screw spacing on axial strength of such columns.

This article presents a finite element investigation into the axial strength of back-to-back built-up cold-formed steel un-lipped channel sections, covering wide range of lengths i.e., stub (length of 300 mm) to slender (length of 2000 mm) columns. Finite element model includes material non-linearity and initial imperfections. Explicit modeling of web fasteners has been described. The axial capacity, failure modes and deformed shapes at failure have been predicted and reported. To verify the modeling technique, two types of back-to-back channels are considered: (i) Lipped and (ii) Un-lipped. Firstly the finite element models for built-up lipped channels are validated against the test results conducted by the authors recently (Ting *et al*. 2018). Finite element results of built-up lipped channel showed good agreement with experimental results. Based on the same modeling technique, built-up un-lipped channels are modeled in finite element software ABAQUS (2014). The verified finite element models are then used to perform a parametric study to investigate the effect of screw spacing on the axial strength of back-to-back built-up cold-formed steel un-lipped channels under compression and compared against the design strengths calculated in accordance with AISI and the AS/NZS Standard. AISI and AS/NZS standards were shown to be over-conservative by as much as 15% for short, intermediate and slender columns, which failed through a combination of local and overall buckling and/or overall buckling, however, the AISI and AS/NZS standards were un-conservative for columns which failed by local buckling.

2. Design guidelines in accordance with AISI and AS/NZ Standard

The finite element strengths are compared against the un-factored design strengths calculated in accordance with the American Iron and Steel Institute specification and the Australia/New Zealand standard. Effective width area (EWA) method is used, when calculating the design strengths using AISI and the Australia/New Zealand standard. For built-up un-lipped channel sections, the un-factored design strength of axially loaded compression members calculated in accordance with AISI & AS/NZ standard are as follows

$$P_{AISI\,\&\,AS/NZS} = A_e F_n \tag{1}$$

The critical buckling stress (F_n) can be calculated as follows

For $\lambda_c \leq 1.5$

$$F_n = \left(0.658^{\lambda_c^2}\right) F_y \tag{2}$$

For $\lambda_c > 1.5$

$$F_n = \left(\frac{0.877}{\lambda_c^2}\right) F_y \tag{3}$$

The non-dimensional critical slenderness (λ_c) can be calculated as follows

$$\lambda_c = \sqrt{\frac{F_y}{F_e}} \tag{4}$$

All the calculations were based on the modified slenderness ratio which is calculated as per the equation below

$$\left(\frac{KL}{r}\right)_{ms} = \sqrt{\left(\frac{KL}{r}\right)_o^2 + \left(\frac{s}{r_{yc}}\right)^2}\,; \qquad \text{For which } \left(\frac{s}{r_{yc}}\right) \leq 0.5\left(\frac{KL}{r}\right)_o \tag{5}$$

3. Summary of experimental study

The finite element models developed in this study for back-to-back built-up cold-formed steel lipped channels were verified against the tests results, recently conducted and reported by the authors (Ting *et al*. 2018), (see Fig. 1). The built-up lipped channels were tested under compression for different column lengths starting from stub (length of 300 mm) to slender (length of 2000 mm) columns. Built-up columns consisted of two cold-formed steel lipped channels placed back-to-back and screwed to the webs of the back to back channels at various spacing. The cold-formed carbon steel channel sections were brake-pressed from a plate thickness of 1.2 mm. Figs. 1(a) and (b) shows details of the channel-sections considered in the experimental program (Ting *et al*. 2018), to be referred to as BU75 and BU90 respectively. The measured specimen dimensions are shown in Tables 1(a) and (b) for BU75 and BU90 respectively. In total, 59 specimens were tested, subdivided into four different column lengths: 300 mm, 500 mm, 1000 mm, and 2000 mm. Specimens were labelled such that the type of section, longitudinal spacing between the fasteners, nominal ength of specimen and specimen number were expressed by the label. Fig. 2 shows an example of the labelling used in the experimental program.

Tensile coupon tests were conducted to determine the material properties of the steel used in the experimental program. The coupon dimensions conformed to the British standard BS EN (2001) for the tensile testing of metals using 12.5 mm wide coupons with a gauge length 50 mm. The measured average yield and ultimate stresses were 560 MPa and 690 MPa respectively, while the Young's modulus

Table 1 Comparison of FEA results against test results (Ting *et al*. 2018) for back-to-back built-up lipped channel sections

(a) BU75 (Lipped channel sections)

Specimen	Web	Flange	Lip	Length	Thickness	Spacing	Experimental results	FEA Results	
	A'	B'	C'	L	t	s	P_{EXP}	P_{FEA}	P_{EXP}/P_{FEA}
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	-
Stub									
BU75-S50-L300-1	73.1	19.8	11.1	273	1.2	50.0	120.7	116.73	1.09
BU75-S50-L300-2	73.1	19.8	11.2	280	1.2	50.0	118.8	114.9	1.03
BU75-S50-L300-3	72.7	19.5	10.8	270	1.2	50.9	118.7	114.4	1.04
BU75-S100-L300-2	73.1	19.8	11.2	267	1.2	99.7	117.5	113.6	1.03
BU75-S100-L300-3	73.1	19.9	11.2	273	1.2	100.2	122.7	117.4	1.05
BU75-S100-L300-4	73.6	19.7	11.2	273	1.2	99.5	115.4	112.6	1.02
BU75-S200-L300-1	73.7	19.8	11.2	266.5	1.2	200.0	122.5	120.8	1.01
BU75-S200-L300-2	73.6	19.9	11.2	266	1.2	199.5	119.1	116.4	1.02
BU75-S200-L300-3	72.9	20.0	11.2	268	1.2	200.0	113.1	108.4	1.04
Mean									1.04
COV									0.02
Short									
BU75-S100-L500-1	73.6	19.8	11.2	655.0	1.2	100.0	83.0	79.5	1.04
BU75-S100-L500-3	73.6	19.7	11.2	680.0	1.2	100.5	74.1	78.4	0.95
BU75-S200-L500-1	73.5	19.5	11.3	653.0	1.2	195.0	86.2	80.3	1.07
BU75-S200-L500-2	73.6	19.6	11.3	678.0	1.2	195.0	88.9	82.7	1.07
BU75-S200-L500-3	73.4	19.7	11.3	680.0	1.2	200.5	93.6	88.1	1.06
BU75-S400-L500-1	73.6	19.7	11.3	678.0	1.2	400.0	74.8	74.6	1.00
BU75-S400-L500-2	73.5	19.7	11.3	679.0	1.2	401.0	80.6	76.3	1.06
Mean									1.04
COV									0.05
Intermediate									
BU75-S225-L1000-1	75.3	20.2	10.4	1133	1.2	225.3	47.0	45.7	1.03
BU75-S225-L1000-2	75.7	19.9	10.4	1131	1.2	225.3	46.3	44.9	1.03
BU75-S450-L1000-1	75.8	19.9	10.4	1131	1.2	447.0	50.4	42.4	1.19
BU75-S450-L1000-2	75.6	19.9	10.4	1133	1.2	450.0	45.0	40.12	1.12
BU75-S450-L1000-3	75.9	19.8	10.3	1182	1.2	450.0	41.8	35.8	1.17
BU75-S900-L1000-1	76.0	19.9	10.3	1131	1.2	900.0	39.9	34.2	1.17
BU75-S900-L1000-2	76.3	19.8	9.1	1133	1.2	900.0	33.7	31.5	1.07
BU75-S900-L1000-3	75.9	19.8	10.3	1183	1.2	901.0	31.5	29.6	1.06
Mean									1.11
COV									0.07
Slender									
BU75-S475-L2000-2	73.9	20.3	10.7	2184	1.2	474.5	10.9	10.6	1.03
BU75-S475-L2000-3	73.9	20.2	10.8	2183	1.2	462.0	10.8	10.5	1.03
BU75-S950-L2000-2	73.9	20.3	10.8	2184	1.2	949.5	8.8	8.6	1.02
BU75-S950-L2000-3	73.9	20.2	10.8	2184	1.2	950.0	8.6	8.5	1.01
BU75-S1900-L2000-2	73.9	20.3	10.9	2183	1.2	1900.0	7.6	7.4	1.03
BU75-S1900-L2000-3	73.9	20.4	10.7	2184	1.2	1901.0	7.5	7.4	1.01
Mean									1.02
COV									0.01

Table 1 Continued

(b) BU90 (Lipped channel sections)

Specimen	Web	Flange	Lip	Length	Thickness	Spacing	Experimental results	FEA Results	
	A'	B'	C'	L	t	s	P_{EXP}	P_{FEA}	P_{EXP}/P_{FEA}
	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	-
Stub									
BU90-S50-L300-1	91.3	49.8	14.6	277.0	1.20	50.0	172.5	162.7	1.06
BU90-S50-L300-2	91.8	49.7	14.5	272.0	1.19	49.8	171.6	160.4	1.07
BU90-S50-L300-3	92.9	49.4	14.5	261.0	1.21	50.0	170.6	160.9	1.06
BU90-S100-L300-1	90.8	49.7	14.6	262.0	1.20	99.9	166.2	152.5	1.09
BU90-S100-L300-2	90.6	49.5	14.6	268.0	1.18	100.0	165.8	156.4	1.06
BU90-S200-L300-1	90.7	49.4	14.6	273.5	1.18	201.0	163.3	157.0	1.04
BU90-S200-L300-2	90.7	49.4	14.6	269.5	1.20	199.0	163.5	155.7	1.05
BU90-S200-L300-3	89.5	48.3	14.0	280.5	1.20	199.0	162.9	158.2	1.03
Mean									1.06
COV									0.02
Short									
BU90-S100-L500-1	90.6	49.5	14.6	656.0	1.21	100.5	160.4	152.8	1.05
BU90-S100-L500-2	90.6	49.4	14.6	678.0	1.20	100.5	158.1	153.5	1.03
BU90-S200-L500-1	90.4	49.3	14.7	653.0	1.18	199.5	152.2	142.2	1.07
BU90-S200-L500-2	90.4	49.3	14.7	678.0	1.19	199.5	150.9	142.4	1.06
BU90-S200-L500-3	90.4	49.3	14.6	680.0	1.21	200.5	149.2	143.5	1.04
BU90-S400-L500-1	90.6	49.4	14.7	678.0	1.18	400.0	132.4	127.3	1.04
BU90-S400-L500-2	90.4	49.4	14.7	678.0	1.20	399.0	134.5	128.1	1.05
Mean									1.05
COV									0.01
Intermediate									
BU90-S225-L1000-1	90.8	49.6	14.4	1182	1.21	225.0	102.6	100.6	1.02
BU90-S225-L1000-2	90.6	49.6	14.3	1132	1.20	225.0	102.0	99.03	1.03
BU90-S450-L1000-1	90.6	49.7	14.4	1130	1.21	450.0	96.51	90.20	1.07
BU90-S450-L1000-2	90.4	49.7	14.4	1182	1.18	448.0	94.42	89.08	1.06
BU90-S450-L1000-3	90.5	49.8	14.5	1180	1.19	452.0	93.33	87.22	1.07
BU90-S900-L1000-1	90.5	49.6	14.4	1131	1.20	897.0	89.55	85.29	1.05
BU90-S900-L1000-2	91.0	49.3	14.4	1182	1.21	899.0	87.58	82.62	1.06
BU90-S900-L1000-3	90.1	49.2	14.5	1129	1.22	896.0	87.51	84.14	1.04
Mean									1.05
COV									0.02
Slender									
BU90-S475-L2000-1	90.6	49.5	14.5	2164	1.20	474.2	65.40	62.88	1.04
BU90-S475-L2000-2	90.7	49.4	14.3	2172	1.20	466.6	66.01	62.87	1.05
BU90-S950-L2000-1	90.5	49.5	14.6	2169	1.18	960.4	54.02	52.45	1.03
BU90-S950-L2000-2	90.4	49.2	14.5	2148	1.17	949.3	45.62	44.73	1.02
BU90-S1900-L2000-1	90.5	49.3	14.6	2158	1.18	1902.4	48.04	48.53	0.99
BU90-S1900-L2000-2	90.9	49.7	14.2	2152	1.19	1906.7	43.21	43.21	1.00
Mean									1.02
COV									0.02

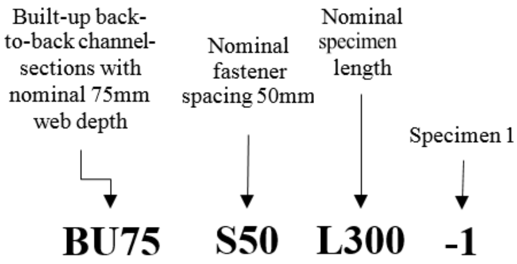
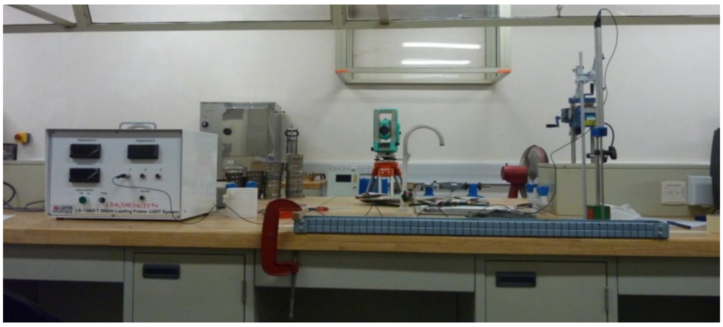


Fig. 3 Specimen labelling

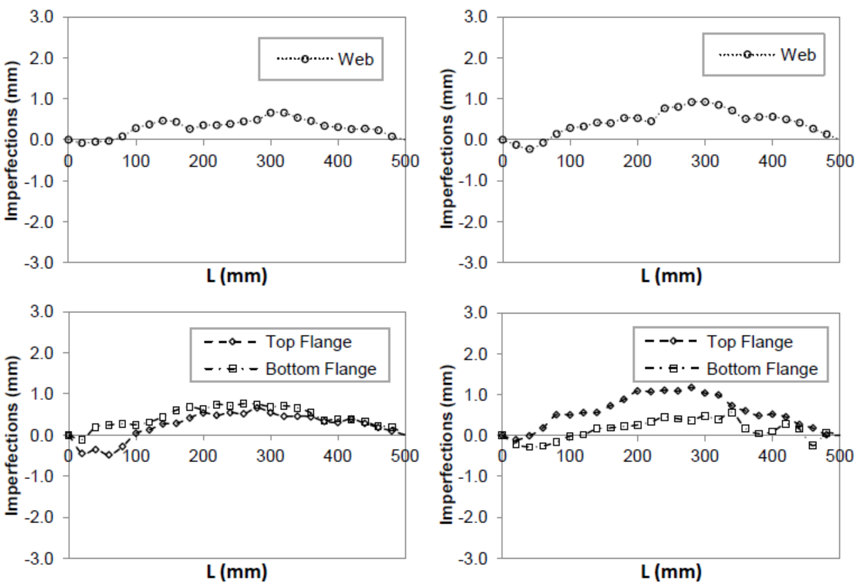
Fig. 4 Photograph of test set-up for back-to-back built-up CFS un-lipped-channel sections (Ting *et al*. 2018)

was 207 GPa.

Load was applied axially to the specimens via a 600 kN capacity GOTECH, GT-7001-LC60 Universal Testing Machine (UTM). Fig. 3 shows a photograph of the test set-up for the intermediate column. Prior to testing an LVDT with 0.11 mm accuracy was used to measure initial geometric imperfections present in the channel sections. A typical plot of the imperfections versus length is shown in Fig. 4. These imperfections are included in finite element models developed in this study: both for lipped and un-lipped channels. Further details regarding the experimental tests can be found from the study reported by Ting *et al*. (2018).



(a) Photograph of imperfection measurement setup



(b) Typical imperfection profile for BU75-S100-L500-1

Fig. 5 Details of imperfection measurements from experimental investigation (Ting et al. 2018)

4. Numerical study

ABAQUS 6.14-2 was used to develop a non-linear elasto-plastic finite element model. The finite element model was based on the centerline dimensions of the cross-section of built-up channels. Two types of channel section were considered: (i) lipped channel; (ii) un-lipped channel. Lipped channel was used to validate the numerical models against the experimental tests conducted by Ting *et al*. 2018). Built-up un-lipped channels were modeled using the same modeling technique as built-up lipped channel sections. Two types of finite element analysis were performed for buckling of built-up sections: The buckling modes of the built-up columns are determined, first, through the eigenvalue analysis, which is a linear elastic analysis performed using the (*BUCKLE) procedure available in the ABAQUS library. The number of buckling modes were determined using the eigenvalue analysis and the adequate buckling mode was predicted from the eigenvalue analysis was used. A load displacement nonlinear analysis is, then, carried out using RIKS algorithm available in the ABAQUS library. The geometric imperfections and material nonlinearity are included in the finite element model. From this analysis, the failure loads, buckling modes and load-axial shortenings are determined. Specific modeling issues are described below.

4.1 Geometry and material properties

The full geometry of the built-up un-lipped channels including web-fasteners were modelled in this study. True values of stresses and strains were specified in the finite element model to incorporate the material non-linearity.The ABAQUS classical metal plasticity model was used for the analysis and validation purpose. Isotropic yielding, associated plastic flow theory, and isotropic hardening behavior was considered in the finite element model. For the parametric study, a simplified elastic perfect plastic stress–strain curve obeying Von Mises yield criterion was used. Yield stress of 560 MPa, ultimate stress of 690 MPa, along with Young's modulus of 207 GPa, and was used in finite element modeling. As per the ABAQUS manual, the engineering material curve is converted into a true material curve in the FE analysis by using the following equations

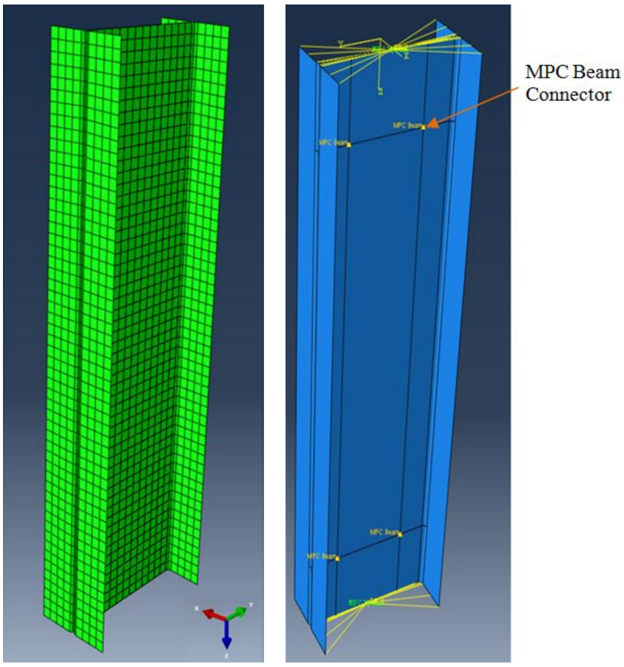
$$\sigma_{true} = \sigma(1+\varepsilon) \tag{6}$$

$$\varepsilon_{true(pl)} = \ln(1+\varepsilon) - \frac{\sigma_{true}}{E} \tag{7}$$

Where E is the Young's Modulus, σ and ε is the engineering stress and strain respectively in ABAQUS (2014).

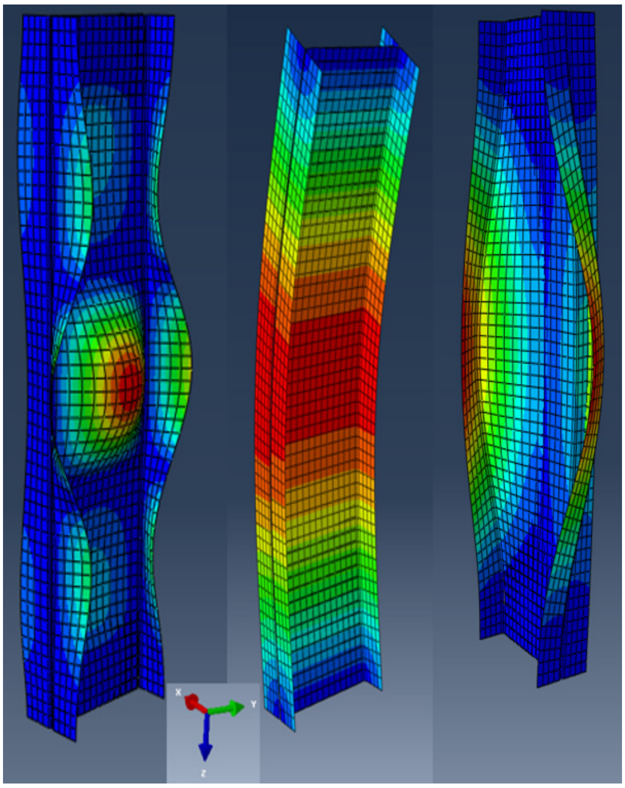
4.2 Element type and finite element mesh

A linear 4-noded quadrilateral thick shell element (S4R5), available in ABAQUS element library, was used to model the built-up section. A mesh size of 5 mm × 5 mm (length×width) was used for the convergence of the model. Along the length of the sections, the number of elements was chosen so that the aspect ratio of the elements was as



(a) Finite element mesh (b) Boundary condition applied in FE model

Fig. 6 Details of typical finite element model (BU75-S100-L500-1)



(a) Local buckling (b) Overall buckling (c) Distortional buckling

Fig. 7 Initial imperfection contours (BU75-S100-L500-1) close to one as possible. A mesh sensitivity analysis was performed to verify the number of elements. The typical finite element mesh of the back-to-back built-up un-lipped channel section is shown in Fig. 6(a).

4.3 Boundary conditions and load application

Pin-ended boundary conditions were applied for all built-up columns investigated herein. In order to simulate pin-ended boundary conditions, displacements and rotations were applied to the upper and lower ends of the back-to-back built-up cold-formed steel un-lipped channels through reference points. The reference point was considered as the centre of gravity (CG) of the cross section of built-up un-lipped channels. The load was applied to the reference points of the upper end of the built-up un-lipped channels as shown in Fig. 6(b). Fasteners between two back-to-back un-lipped channels were modelled using MPC

Table 2 Comparison of FEA results against AISI & AS/NZS results for back-to-back built-up un-lipped channel sections

(a) BU75 (Un-lipped channel sections)

Specimen	Web	Flange	Length	Thickness	Spacing	FEA results	AISI design strengths	
	A'	B'	L	t	s	P_{FEA}	P_{AISI}	P_{FEA}/P_{AISI}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	-
Stub								
BU75-S50-L300-1	73.1	19.8	273.0	1.20	50.0	86.4	92.1	0.94
BU75-S50-L300-2	73.1	19.8	280.0	1.21	50.0	84.2	93.3	0.90
BU75-S50-L300-3	72.7	19.5	270.0	1.19	50.9	85.2	90.2	0.94
BU75-S100-L300-1	73.1	19.8	267.0	1.20	99.7	83.2	91.4	0.91
BU75-S100-L300-2	73.1	19.9	273.0	1.20	100.2	86.3	91.8	0.94
BU75-S100-L300-3	73.6	19.7	273.0	1.21	99.5	81.6	89.7	0.91
BU75-S200-L300-1	73.7	19.8	266.5	1.22	200.0	80.4	82.4	0.98
BU75-S200-L300-2	73.6	19.9	266.0	1.20	199.5	80.4	82.6	0.97
BU75-S200-L300-3	72.9	20.0	268.0	1.21	200.0	80.2	82.8	0.97
Mean								0.94
COV								0.03
Short								
BU75-S100-L500-1	73.6	19.8	655.0	1.19	100.0	51.4	46.3	1.11
BU75-S100-L500-2	73.6	19.7	680.0	1.20	100.5	50.3	45.7	1.10
BU75-S200-L500-1	73.5	19.5	653.0	1.20	195.0	48.1	42.9	1.12
BU75-S200-L500-2	73.6	19.6	678.0	1.21	195.0	49.2	43.2	1.14
BU75-S200-L500-3	73.4	19.7	680.0	1.20	200.5	48.4	42.8	1.13
BU75-S400-L500-1	73.6	19.7	678.0	1.18	400.0	45.1	40.3	1.12
BU75-S400-L500-2	73.5	19.7	679.0	1.19	401.0	45.0	39.8	1.13
Mean								1.12
COV								0.01
Intermediate								
BU75-S225-L1000-1	75.3	20.2	1133	1.20	225.3	33.4	28.8	1.16
BU75-S225-L1000-2	75.7	19.9	1131	1.22	225.3	30.5	26.1	1.17
BU75-S450-L1000-1	75.8	19.9	1131	1.20	447.0	29.4	25.6	1.15
BU75-S450-L1000-2	75.6	19.9	1133	1.21	450.0	26.8	23.5	1.14
BU75-S450-L1000-3	75.9	19.8	1182	1.19	450.0	21.6	19.1	1.13
BU75-S900-L1000-1	76.0	19.9	1131	1.18	900.0	20.3	17.5	1.16
BU75-S900-L1000-2	76.3	19.8	1133	1.20	900.0	20.7	17.7	1.17
BU75-S900-L1000-3	75.9	19.8	1183	1.21	901.0	18.9	16.0	1.18
Mean								1.16
COV								0.02

(a) Continued

Specimen	Web	Flange	Length	Thickness	Spacing	FEA results	AISI design strengths	
	A'	B'	L	t	s	P_{FEA}	P_{AISI}	P_{FEA}/P_{AISI}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	-
Slender								
BU75-S475-L2000-1	73.9	20.3	2184	1.20	474.5	8.1	7.4	1.10
BU75-S475-L2000-2	73.9	20.2	2183	1.21	462.0	7.9	7.1	1.11
BU75-S950-L2000-1	73.9	20.3	2184	1.22	949.5	6.4	5.7	1.12
BU75-S950-L2000-2	73.9	20.2	2184	1.23	950.0	6.2	5.4	1.14
BU75-S1900-L2000-1	73.9	20.3	2183	1.20	1900.0	5.3	4.8	1.10
BU75-S1900-L2000-2	73.9	20.4	2184	1.18	1901.0	5.2	4.6	1.13
Mean								1.12
COV								0.02

beam connector elements available in the ABAQUS library (see Fig. 6(b)). MPC beam connector elements were assigned a stress of 6210 MPa to incorporate the stiffness of the fasteners. RIKS algorithm, available in the ABAQUS library, was used to apply the load in increments. By using RIKS method, post buckling behaviour of the back-to-back built-up un-lipped channel columns can be predicted.

4.4 Contact modelling

"*Surface to surface*" contact was used for modeling the interaction between the webs of back-to-back un-lipped channels. The web of one un-lipped channel was modeled as slave surface, while the web of other un-lipped channel section was considered as master surface. There was no

Table 2 Continued

(b) BU 90 (Un-lipped channel sections)

Specimen	Web	Flange	Length	Thickness	Spacing	FEA results	AISI design strengths	
	A'	B'	L	t	s	P_{FEA}	P_{AISI}	P_{FEA}/P_{AISI}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	-
Stub								
BU90-S50-L300-1	91.3	49.8	277.0	1.20	50.0	126.9	140.2	0.91
BU90-S50-L300-2	91.8	49.7	272.0	1.19	49.8	129.4	140.6	0.92
BU90-S50-L300-3	92.9	49.4	261.0	1.21	50.0	130.3	140.1	0.93
BU90-S100-L300-1	90.8	49.7	262.0	1.20	99.9	122.7	141.2	0.87
BU90-S100-L300-2	90.6	49.5	268.0	1.18	100.0	123.0	132.3	0.93
BU90-S200-L300-1	90.7	49.4	273.5	1.18	201.0	117.8	129.5	0.92
BU90-S200-L300-2	90.7	49.4	269.5	1.20	199.0	116.9	128.9	0.91
BU90-S200-L300-3	89.5	48.3	280.5	1.20	199.0	115.4	128.2	0.90
Mean								0.91
COV								0.02
Short								
BU90-S100-L500-1	90.6	49.5	656.0	1.21	100.5	114.2	103.4	1.10
BU90-S100-L500-2	90.6	49.4	678.0	1.20	100.5	113.1	106.4	1.06
BU90-S200-L500-1	90.4	49.3	653.0	1.18	199.5	107.3	95.8	1.12
BU90-S200-L500-2	90.4	49.3	678.0	1.19	199.5	104.8	92.7	1.13
BU90-S200-L500-3	90.4	49.3	680.0	1.21	200.5	106.9	96.3	1.11
BU90-S400-L500-1	90.6	49.4	678.0	1.18	400.0	96.5	86.2	1.12
BU90-S400-L500-2	90.4	49.4	678.0	1.20	399.0	97.7	88.8	1.10
Mean								1.10
COV								0.02

(b) Continued

Specimen	Web	Flange	Length	Thickness	Spacing	FEA results	AISI design strengths	
	A'	B'	L	t	s	P_{FEA}	P_{AISI}	P_{FEA}/P_{AISI}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	-
Intermediate								
BU90-S225-L1000-1	90.8	49.6	1182	1.21	225.0	62.2	54.5	1.14
BU90-S225-L1000-2	90.6	49.6	1132	1.20	225.0	63.9	56.6	1.13
BU90-S450-L1000-1	90.6	49.7	1130	1.21	450.0	58.9	51.7	1.14
BU90-S450-L1000-2	90.4	49.7	1182	1.18	448.0	58.6	50.5	1.16
BU90-S450-L1000-3	90.5	49.8	1180	1.19	452.0	59.9	51.2	1.17
BU90-S900-L1000-1	90.5	49.6	1131	1.20	897.0	54.8	48.1	1.14
BU90-S900-L1000-2	91.0	49.3	1182	1.21	899.0	52.6	45.8	1.15
BU90-S900-L1000-3	90.1	49.2	1129	1.22	896.0	53.5	46.1	1.16
Mean								1.15
COV								0.01
Slender								
BU90-S475-L2000-1	90.6	49.5	2164	1.20	474.2	48.2	43.4	1.11
BU90-S475-L2000-2	90.7	49.4	2172	1.20	466.6	48.8	44.4	1.10
BU90-S950-L2000-1	90.5	49.5	2169	1.18	960.4	40.7	36.7	1.11
BU90-S950-L2000-2	90.4	49.2	2148	1.17	949.3	34.1	29.9	1.14
BU90-S1900-L2000-1	90.5	49.3	2158	1.18	1902.4	36.4	32.3	1.13
BU90-S1900-L2000-2	90.9	49.7	2152	1.19	1906.7	33.6	30.0	1.12
Mean								1.12
COV								0.01

penetration between the two contact surfaces.

4.5 Modelling of local, distortional and overall geometric imperfections

Local, distortional and overall buckling behavior of back-to-back built-up cold-formed steel un-lipped channel sections depends on many factors such as: Depth of channel-thickness ratio (D/t), width of channel-thickness ratio (b/t), slenderness around x and y axis and spacing of screws. Initial imperfections are caused in compression members as a result of transportation and fabrication processes. Hence, local, distortional and overall buckling modes are superimposed for accurate finite element analysis. Eigenvalue analyses of the built-up columns were performed with very small to large channel thickness to determine the contours for the local, distortional and overall imperfections. The lowest buckling mode (Eigen mode 1) in ABAQUS, is used as the shape of local and overall buckling mode. The imperfections used in the modelling of built-up un-lipped channels were scaled to the values given in the experimental program by Ting *et al*. (2018) for back-to-back built-up cold-formed steel lipped channel sections. In addition, local imperfections of magnitude 0.5% of the section thickness were incorporated as recommended by Ellobody and Young (2005). In Fig. 7, local, distortional and overall buckling modes obtained for BU75-S50- L300-1, are shown.

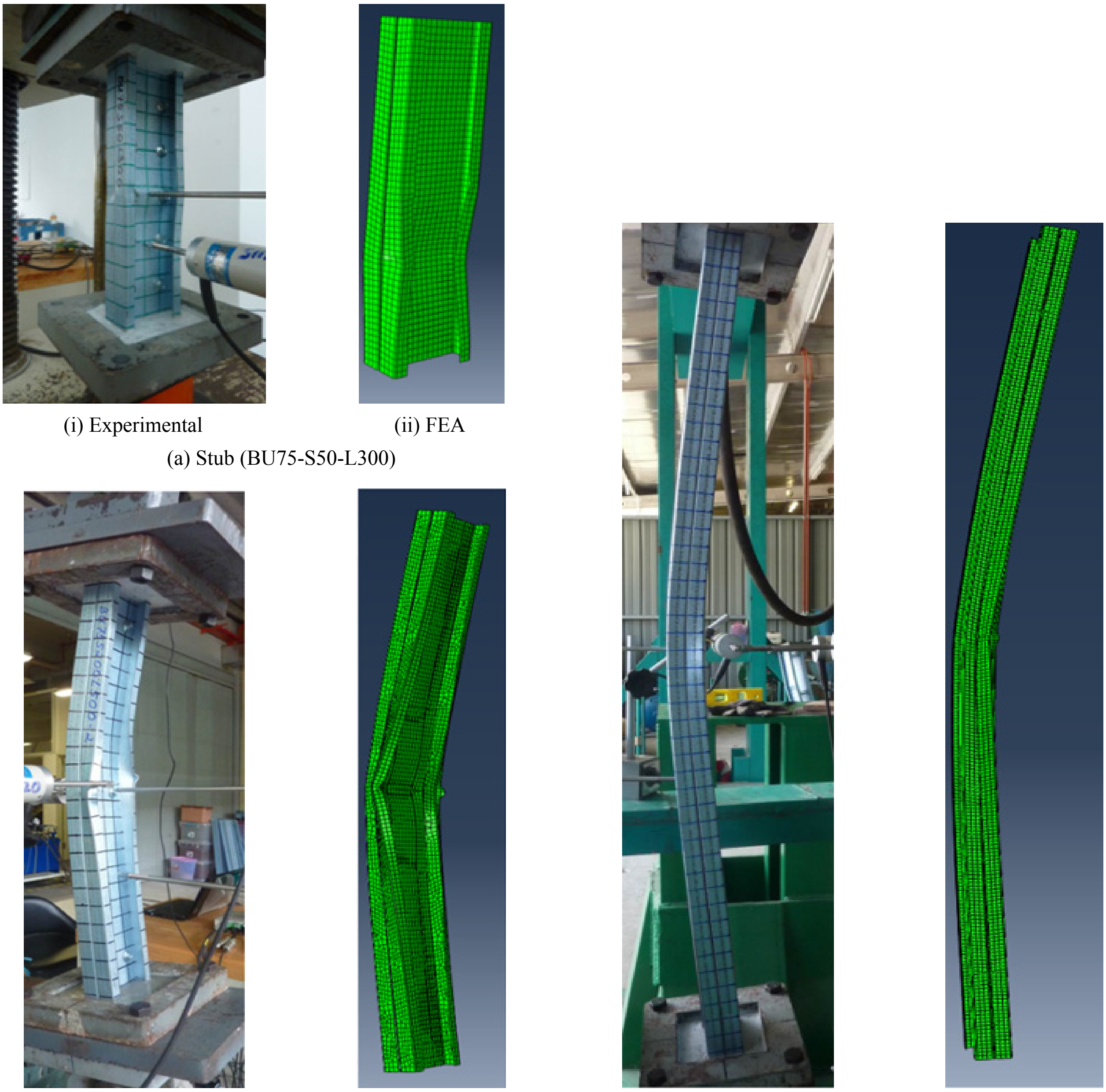
4.6 Finite element model verification

In order to verify the FE models, results from the experimental tests conducted on back-to-back built-up lipped channels by Ting *et al*. (2018), are compared to the results from the finite element analysis described herein. Fig. 8, shows the failure modes of stub, short and intermediate columns obtained from experimental tests conducted by Ting *et al*. (2018) and finite element models for back-to-back built-up cold-formed steel lipped channel sections. Also, in Fig. 9, experimental and finite element strengths are compared for BU75-S50-L300-1. As can be seen, the experimental and FE results shows good agreement for both the ultimate strength and the failure modes.

Tables 1(a) and (b) compares the failure load obtained from the experimental tests (Ting *et al*. 2018) with that of the finite element analyses for back-to-back built-up lipped channel sections. It is shown that, the mean value of the ratio P_{EXP}/P_{FEA} is 1.04, with a co-efficient of variation of 0.02 for stub column of BU75 series and P_{EXP}/P_{FEA} is 1.06, with a co-efficient of variation of 0.02 for stub column of BU90 series.

5. Parametric study for built-up un-lipped channels

In this study, in order to investigate the effect of screw



(i) Experimental (ii) FEA

(a) Stub (BU75-S50-L300)

(i) Experimental (ii) FEA

(b) Short column (BU75-S100-L500)

(i) Experimental (ii) FEA

(c) Intermediate column (BU75-S225-L1000)

Fig. 8 Back-to-back built-up cold-formed steel built-up lipped channel sections at failure (Ting *et al*. 2018)

spacing on axial strength of back-to-back built-up cold-formed steel un-lipped channels, a total of 95 finite element analyses with various section dimensions, lengths and screw spacing were considered. The results were compared against the axial strength of back-to-back built-up cold-formed steel lipped channel sections, investigated recently by the authors (Ting *et al*. 2018).

As can be seen from Fig. 9, the axial strength of built-up un-lipped channel is reduced by around 40% when compared to the built-up lipped channel of BU75-S50-L300-1. Tables 2(a) and (b) compares the axial strength of built-up un-lipped channels calculated from finite element analyses and AISI&AS/NZS for BU75 and BU90 respectively. It is shown that the mean value of the ratio $P_{\mathrm{FEA}}/P_{\mathrm{AISI}}$ is 0.94, with a co-efficient of variation of 0.03 for built-up un-lipped stub column of BU75 series.

Load versus axial displacement curves for back-to-back built-up un-lipped channel sections, covering stub to slender columns, with different screw spacing are shown in Figs. 10(a) and (b) for BU75 and BU90 respectively. As can be seen, significant strength reduction occurred for all columns beyond 1000 mm length. The failure modes of back-to-back built-up cold-formed steel un-lipped channels are also shown in Fig. 11.

To investigate the effect of fastener spacing on the axial strength of built-up un-lipped channel columns, three different numbers of screws were considered: 10, 5, and 3.These number of screws include screws at the top and bottom. Both BU75 and BU90 were considered for the parametric study, covering stub (300 mm length) to slender

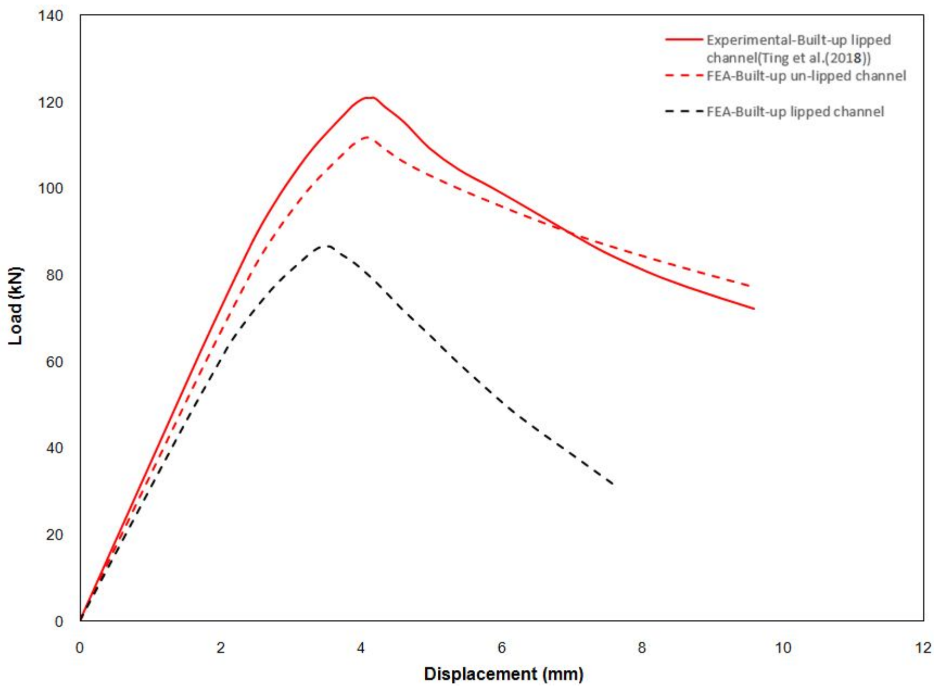
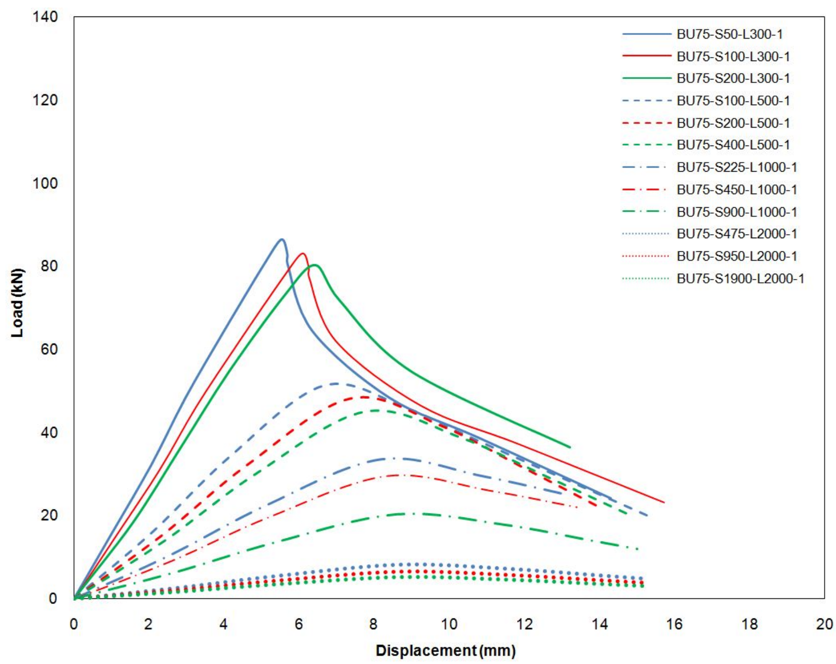


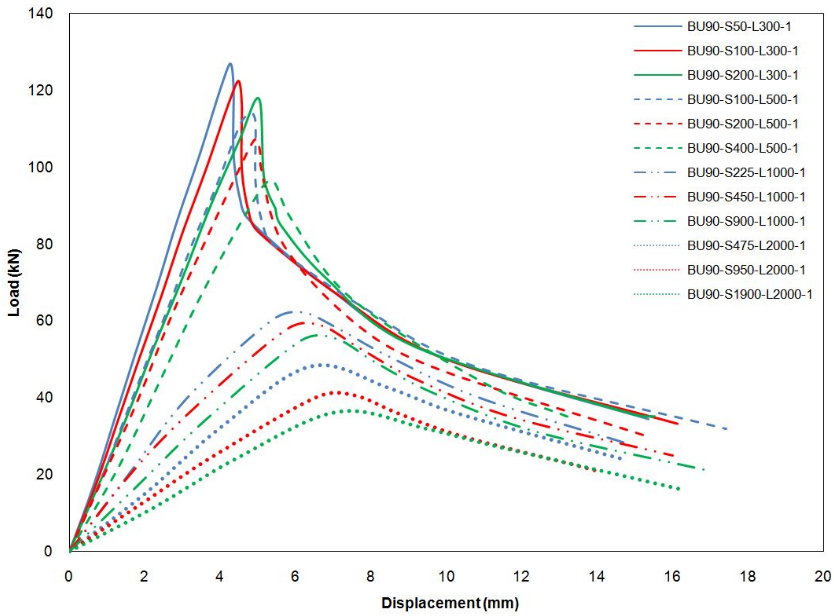
Fig. 9 Validation of finite element model for (BU75-S50-L300-1)

(2000 mm length) columns. Tables 3(a) and (b) summarizes the dimensions of built-up un-lipped channels considered in this study for BU75 and BU90 respectively. Failure modes and axial strength of built-up un-lipped channels with 3, 5 and 10 screws are also shown in Table 3. In Figs. 12(a) and (b) the strength of built-up un-lipped channels are plotted against the length and slenderness for BU75. The axial strength of back-to-back built-up cold-formed steel lipped channel sections (Ting *et al*. 2018) is also shown in Figs. 12(a) and (b), in order to compare the results with built-up un-lipped channels. As can be seen from Fig. 12(b), FEA data points for built-up un-lipped channels are away from design strengths when modified slenderness is higher than 40. Also, for BU90, axial strengths are shown in Figs. 13(a) and (b) with varying length and slenderness. Again, for comparison of axial strength, built-up lipped channel column strengths are also plotted in Figs. 13(a) and (b). For BU90, similar trend is noticed as BU75, i.e., the design



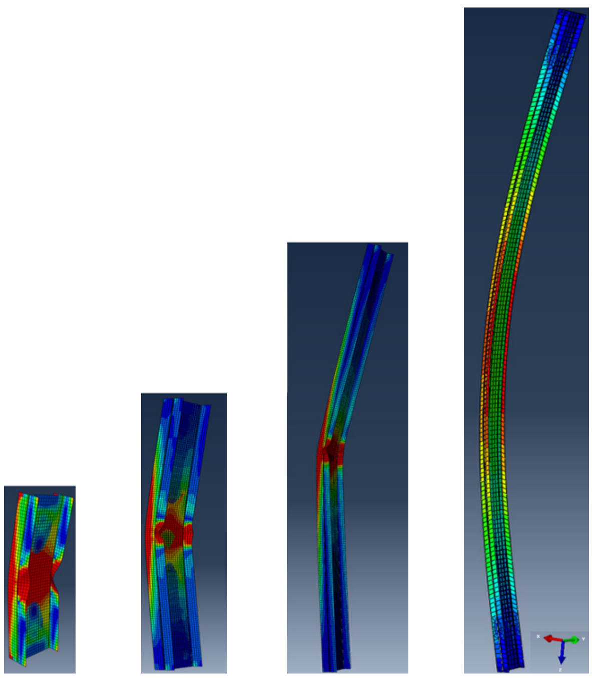
(a)

Fig. 10 Load versus axial displacement curves for back-to-back built-up un-lipped channel sections



(b) BU90

Fig. 10 Continued



(a) Stub (BU75-S50-L300) | (b) Short (BU75-S100-L500) | (c) Intermediate (BU75-S225-L1000) | (d) Slender (BU75-S950-L2000)

Fig. 11 Back-to-back built-up CFS un-lipped channel sections at failure

standards are away from the FEA data points for strength of built-up un-lipped channels, although when compared to the axial strength of built-up lipped channels, design standards were close but conservative.

The effect of fastener spacing on axial strength was observed with the length of the columns from the parametric study. For the case of the built-up un-lipped stub columns, no significant strength gain was observed by increasing the number of fasteners, while for the case of the short and intermediate columns, the axial strength of the built-up un-lipped channels were significantly dependent on the number of fasteners. In case of short column, when the spacing of the screws was doubled, the strength of the section was reduced by around 6%-9%. The axial strength of the intermediate columns was decreased by around 18%-8% when the fastener spacing was doubled. On the other hand, for built-up un-lipped slender columns, the axial strength was reduced approximately by 20-26%, when the spacing of fastener was doubled.

6. Comparison with design standards

Axial strengths calculated from finite element analyses and in accordance with AISI and AS/NZS, are compared in Tables 2(a) and (b) for BU75 and BU90 columns respectively. As can be seen, AISI & AS/NZS standard is safe while predicting the axial strength of back-to-back built-up cold-formed steel un-lipped channel sections for short, intermediate and slender columns, however for stub columns which failed mainly by local buckling, AISI & AS/NZS are un-conservative by approximately 8% on average.

Fig. 12(a) shows the variation of strength against the length of back-to-back built-up un-lipped channels of BU75 series. Fig. 12(a) also shows the strengths predicted by AISI and AS/NZS Standards. In Fig. 12(b), the axial strength of built-up un-lipped channels are plotted against modified slenderness. As can be seen, the AISI and AS/NZ Standards are un-conservative for the 300 mm long column but conservative for all other built-up un-lipped columns. The mean value of P_{FEA}/P_{AISI} for the stub column is 0.94 with a corresponding COV of 0.03 (see Table 2(a)). The corresponding mean values of P_{FEA}/P_{AISI} for the short,

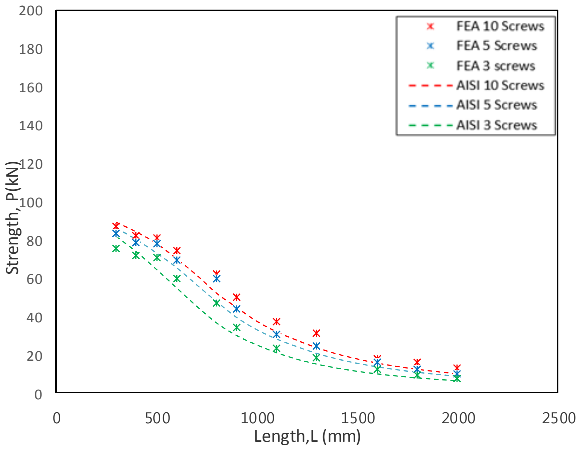
Table 3 Finite element and AISI&AS/NZS strength with varying length of the back-to-back built-up un-lipped channel sections for 3, 5 and 10 screws

(a) BU75

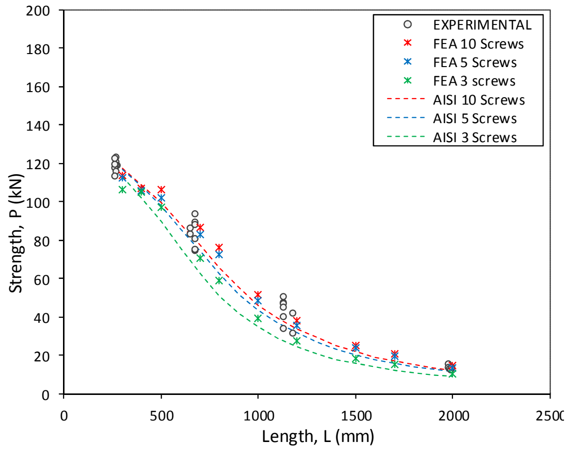
Specimen	Web A'	Flange B'	Length L	Spacing(s) for 3 screws	Spacing(s) for 5 screws	Spacing(s) for 10 screws	Failure mode(s)	$P_{AISI/AS/NZS}$ for 3 screws	$P_{AISI/AS/NZS}$ for 5 screws	$P_{AISI/AS/NZS}$ for 10 screws	P_{FEA} for 3 screws	P_{FEA} for 5 screws	P_{FEA} for 10 screws
	mm	mm	mm	mm	mm	mm		kN	kN	kN	kN	kN	kN
BU75-L300	73.6	19.8	300	75	50.00	27.27	Local	81.63	86.02	89.12	75.67	83.06	87.21
BU75-L400	73.6	19.8	400	100	66.67	36.36	Local	73.60	80.12	84.42	72.00	78.29	82.42
BU75-L500	73.6	19.8	500	125	83.33	45.45	Local	64.45	73.14	78.14	70.80	81.50	81.02
BU75-L600	73.6	19.8	600	150	100.00	54.55	Local	54.81	65.38	70.05	59.74	69.39	74.63
BU75-L700	73.6	19.8	700	175	116.67	63.64	Local + Distortional	45.26	56.43	61.50	51.24	63.42	66.49
BU75-L800	73.6	19.8	800	200	133.33	72.73	Local + Distortional	36.45	47.61	52.03	46.66	59.34	62.78
BU75-L900	73.6	19.8	900	225	150.00	81.82	Local	29.91	39.35	44.56	34.10	44.15	50.46
BU75-L1000	73.6	19.8	1000	250	166.67	90.91	Local + Flexural	25.01	32.98	37.37	30.18	35.97	42.55
BU75-L1100	73.6	19.8	1100	275	183.33	100.00	Local + Flexural	20.91	28.07	31.82	23.42	30.61	36.96
BU75-L1200	73.6	19.8	1200	300	200.00	109.09	Flexural	17.57	24.11	27.44	20.49	26.30	31.42
BU75-L1300	73.6	19.8	1300	325	216.67	118.18	Flexural	14.97	20.55	23.55	18.42	24.61	31.11
BU75-L1400	73.6	19.8	1400	350	233.33	127.27	Flexural + Distortional	12.91	17.72	20.31	16.10	21.22	24.57
BU75-L1500	73.6	19.8	1500	375	250.00	136.36	Local + Flexural	11.25	15.43	17.69	12.75	17.43	21.33
BU75-L1600	73.6	19.8	1600	400	266.67	145.45	Flexural	9.88	13.56	15.55	12.16	16.24	18.25
BU75-L1700	73.6	19.8	1700	425	283.33	154.55	Local+ Flexural	8.76	12.01	13.77	10.69	14.39	15.43
BU75-L1800	73.6	19.8	1800	450	300.00	163.64	Flexural	7.81	10.72	12.28	9.14	12.21	16.54
BU75-L1900	73.6	19.8	1900	475	316.67	172.73	Flexural	7.01	9.62	11.03	8.25	10.96	14.50
BU75-L2000	73.6	19.8	2000	500	333.33	181.82	Flexural	6.33	8.68	9.95	7.40	9.89	13.11

(b) BU90

Specimen	Web A'	Flange B'	Length L	Spacing(s) for 3 screws	Spacing(s) for 5 screws	Spacing(s) for 10 screws	Failure mode(s)	$P_{AISI/AS/NZS}$ for 3 screws	$P_{AISI/AS/NZS}$ for 5 screws	$P_{AISI/AS/NZS}$ for 10 screws	P_{FEA} for 3 screws	P_{FEA} for 5 screws	P_{FEA} for 10 screws
	mm	mm	mm	mm	mm	mm		kN	kN	kN	kN	kN	kN
BU75-L300	90.4	49.4	300	75	50.00	27.27	Local	126.63	134.17	138.31	120.36	124.30	135.06
BU75-L400	90.4	49.4	400	100	66.67	36.36	Local	114.18	123.89	128.51	110.11	117.31	126.32
BU75-L500	90.4	49.4	500	125	83.33	45.45	Local+ Distortional	99.98	111.84	117.13	106.32	112.45	122.20
BU75-L600	90.4	49.4	600	150	100.00	54.55	Local	85.02	98.72	104.30	90.21	96.67	110.74
BU75-L700	90.4	49.4	700	175	116.67	63.64	Local + Distortional	70.21	85.20	90.95	80.26	90.16	100.41
BU75-L800	90.4	49.4	800	200	133.33	72.73	Local	56.55	71.89	77.66	64.87	70.49	82.69
BU75-L900	90.4	49.4	900	225	150.00	81.82	Local + Distortional	46.40	59.41	64.81	54.18	64.25	74.14
BU75-L1000	90.4	49.4	1000	250	166.67	90.91	Local + Flexural	38.80	49.80	54.35	44.35	53.89	63.66
BU75-L1100	90.4	49.4	1100	275	183.33	100.00	Local + Flexural	32.44	42.38	46.29	37.08	45.37	54.21
BU75-L1200	90.4	49.4	1200	300	200.00	109.09	Flexural+ Distortional	27.26	36.41	39.90	33.60	36.19	50.51
BU75-L1300	90.4	49.4	1300	325	216.67	118.18	Flexural	23.23	31.02	34.26	27.23	36.87	44.06
BU75-L1400	90.4	49.4	1400	350	233.33	127.27	Local+ Flexural	20.03	26.75	29.54	24.44	25.89	38.70
BU75-L1500	90.4	49.4	1500	375	250.00	136.36	Local+ Flexural	17.45	23.30	25.73	20.66	26.12	32.11
BU75-L1600	90.4	49.4	1600	400	266.67	145.45	Flexural	15.33	20.48	22.61	18.64	20.78	29.79
BU75-L1700	90.4	49.4	1700	425	283.33	154.55	Flexural	13.58	18.14	20.03	17.05	21.56	26.95
BU75-L1800	90.4	49.4	1800	450	300.00	163.64	Flexural	12.12	16.18	17.87	15.46	17.64	23.09
BU75-L1900	90.4	49.4	1900	475	316.67	172.73	Flexural	10.87	14.52	16.04	13.48	15.88	20.48
BU75-L2000	90.4	49.4	2000	500	333.33	181.82	Flexural	9.81	13.11	14.47	11.72	14.82	17.71

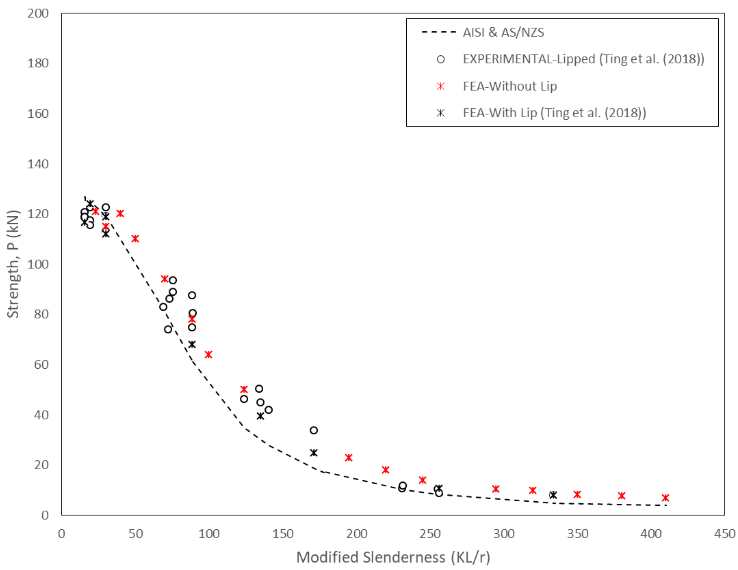


(i) Back-to-back built-up cold-formed steel un-lipped channel section



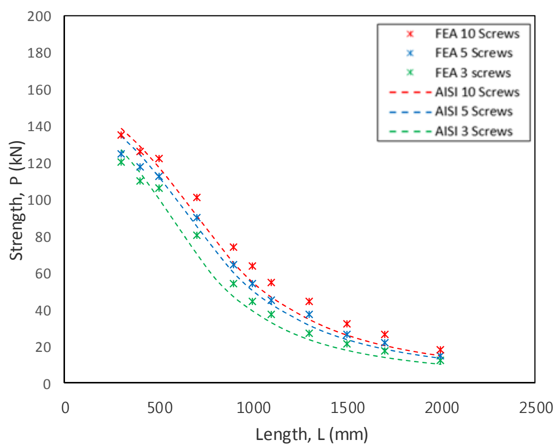
(ii) Back-to-back built-up cold-formed steel lipped channel section (Ting *et al*. 2018)

(a) Variation of strength against length

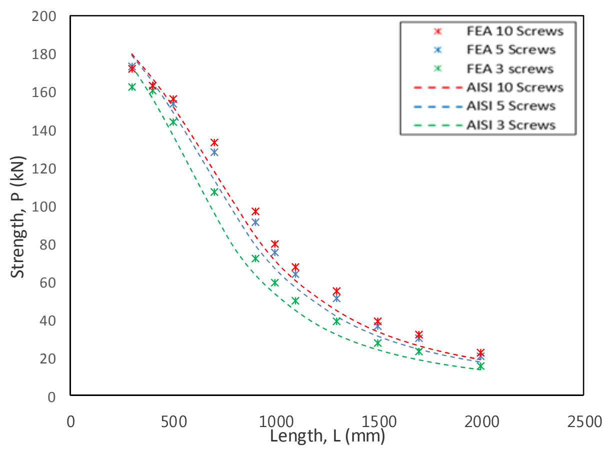


(b) Variation of strength against modified slenderness

Fig. 12 Effect of varying number of screws and slenderness for BU75 Section



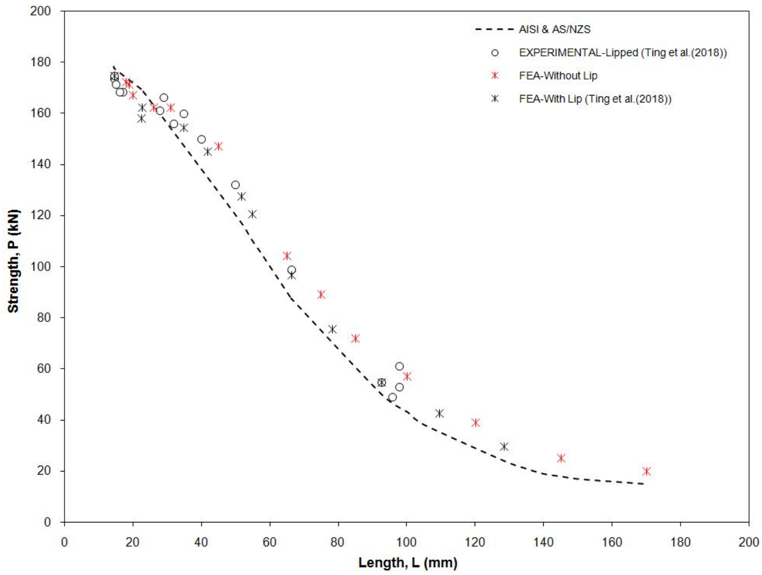
(i) Back-to-back built-up cold-formed steel un-lipped channel section



(ii) Back-to-back built-up cold-formed steel lipped channel section (Ting *et al*. (2018))

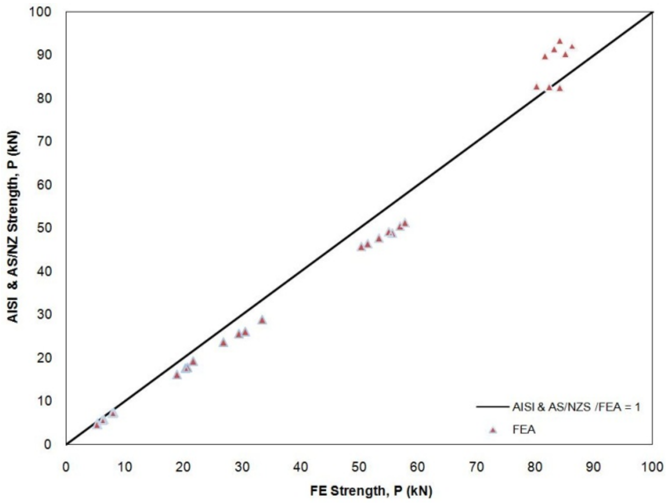
(a) Variation of strength against length

Fig. 13 Effect of varying number of screws and slenderness for BU90 Section

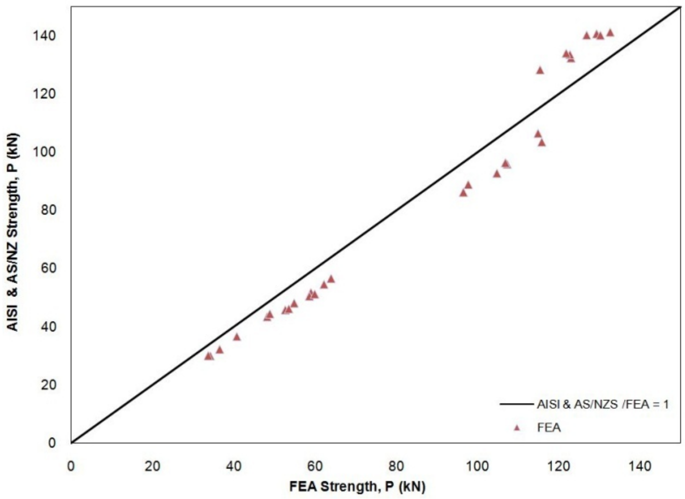


(b) Variation of strength against modified slenderness

Fig. 13 Continued



(a) BU 75 section



(b) BU 90 section

Fig. 14 Comparison of FEA strength and design strength (AISI & AS/NZ Standards) for back-to-back built-up CFS un-lipped channel sections intermediate, and slender columns of built-up un-lipped channels are 1.12, 1.16, and 1.12, respectively, with COVs of 0.01, 0.02, and 0.02 respectively for BU75 series. On the other hand, for BU90 series, the mean value of P_{FEA}/P_{AISI} for the stub column is 0.91 with a corresponding COV of 0.02. The corresponding mean values of P_{FEA}/P_{AISI} for the short, intermediate, and slender columns of BU90 series are 1.10, 1.15, and 1.12, with COVs of 0.02, 0.01 and 0.01 respectively.

Fig. 13 shows the strength of BU90 sections for varying slenderness and length. As mentioned previously, for the BU90 stub columns, the AISI and AS/ NZS standards are un-conservative while for the other columns they are conservative (Fig. 14). From Figs. 12 and 13, it can be seen that columns having modified slenderness less than 35.8 failed mainly by local buckling, while columns having a modified slenderness greater than 53.4 failed through global buckling.

7. Conclusions

This paper has presented a finite element investigation on the behavior of back-to-back built-up cold-formed steel un-lipped channels, subjected to axial load. Finite element models are validated against the experimental tests conducted by the authors recently for back-to-back built-up CFS lipped channels. Comparison of test results against FEA have shown good agreement and that the finite element models can predict the buckling behavior of the built-up columns. The failure modes and deformed shapes at failure have been discussed. The results are compared against the AISI& AS/NZ Standard design calculations.

The validated finite element models were used to perform a parametric study to investigate the effect of screw spacing on the axial strength of back-to-back built-up cold-formed steel un-lipped channel sections. The column strengths predicted from the finite element analyses were compared against the design strengths calculated in accordance with the AISI and the AS/NZ Standard. The finite element results were shown to be conservative to the design standards for short, intermediate and slender columns, which failed through a combination of local and global buckling and/or global buckling. The AISI and AS/NZ Standards, however, are un-conservative for stub columns, which failed through local buckling.

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Nomenclature

A'	Overall web length of section;
A_e	Effective area of the section;
B'	Overall flange width of section;
C'	Overall lip width of section;
COV	Coefficient of variation;
CFS	Cold-formed steel
E	Young's modulus of elasticity;
FEA	Finite element analysis;
F_n	Critical buckling stress;
$(KL/r)_{ms}$	Modified slenderness;
$(KL/r)_o$	Overall Slenderness;
P_{AISI}	Compressive strength obtained from American Iron and Steel Institute;
P_{EXP}	Compressive strength obtained from Experiment;
P_{FEA}	Compressive strength obtained from Finite element analysis;
S	Screw spacing;
$\sigma_{0.2}$	Static 0.2% proof stress;
σ_{true}	True stress;
σ_u	Tensile ultimate strength;
λ_c	Non dimensional slenderness ratio;