Steel and Composite Structures, *Vol. 33, No. 1* (*2019*) *37-66*
DOI: https://doi.org/10.12989/scs.2019.33.1.037

Finite element modelling of back-to-back built-up cold-formed stainless-steel lipped channels under axial compression

Krishanu Roy[*1], Hieng Ho Lau[2b] and James B.P. Lim[1c]

[1] *Department of Civil and Environmental Engineering*, *The University of Auckland*, *Auckland*, *New Zealand*
[2] *Faculty of Engineering*, *Computing and Science*, *Swinburne University of Technology*, *Kuching*, *Sarawak*, *Malaysia*

(*Received December 19, 2018, Revised July 14, 2019, Accepted September 24, 2019*)

Abstract. In cold-formed steel structures, such as trusses, wall frames and portal frames, the use of back-to-back built-up cold-formed stainless-steel lipped channels as compression members are becoming increasingly popular. The advantages of using stainless-steel as structural members are corrosion resistance and durability, compared with carbon steel. The AISI/ASCE Standard, SEI/ASCE-8-02 and AS/NZS do not include the design of stainless-steel built-up channels and very few experimental tests or finite element analyses have been reported in the literature for such back-to back cold-formed stainless-steel channels. Current guidance by the American Iron and Steel Institute (AISI) and the Australian and New Zealand (gAS/NZS) standards for built-up carbon steel sections only describe a modified slenderness approach, to consider the spacing of the intermediate fasteners. Thus, this paper presents a numerical investigation on the behavior of back-to-back cold-formed stainless-steel built-up lipped channels. Three different grades of stainless steel i.e., duplex EN1.4462, ferritic EN1.4003 and austenitic EN1.4404 have been considered. Effect of screw spacing on the axial strength of such built-up channels was investigated. As expected, most of the short and intermediate columns failed by either local-global or local-distortional buckling interactions, whereas the long columns, failed by global buckling. All three grades of stainless-steel stub columns failed by local buckling. A comprehensive parametric study was then carried out covering a wide range of slenderness and different cross-sectional geometries to assess the performance of the current design guidelines by AISI and AS/NZS. In total, 647 finite element models were analyzed. From the results of the parametric study, it was found that the AISI & AS/NZS are conservative by around 10 to 20% for cold-formed stainless-steel built-up lipped channels failed through overall buckling, irrespective of the stainless-steel grades. However, the AISI and AS/NZS can be un-conservative by around 6% for all three grades of stainless-steel built-up channels, which failed by local buckling.

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

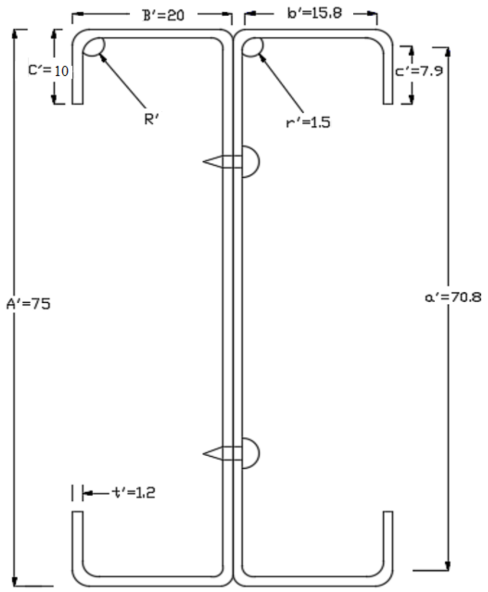
1. Introduction

Structural applications of cold-formed stainless-steel is increasing steadily (Baddoo 2008, Dai and Lam 2010, Roy and Lim 2019, Theofanous *et al.* 2009, Zhou *et al.* 2013, Kiymaz and Seckin 2014, Hasan *et al.* 2017) and the use of back-to-back cold-formed stainless-steel built-up lipped channels are becoming increasingly popular as compression members (Dobric *et al.* 2018a, b). Cold-formed steel is popular because of its superior strength to self-weight ratio and ease of construction (Darcy and Mahendran 2008, Roy *et al.* 2019c, Schafer 2002, Dar *et al.* 2018b, 2019) Lawson *et al.* 2019, Mathison *et al.* 2019) the back-to-back built-up cold-formed stainless steel lipped channels are used in struts in steel trusses and space frames, wall studs in wall frames and columns in portal frames. Despite the popularity of CFS stainless steel channels, the stainless steel standard SEI/ASCE-8-02 (2002) do not include the design of stainless-steel built-up channels. However, the carbon steel standards AISI (2016) and AS/NZS (2018) prescribe the use of modified slenderness approach to include the effect of fastener spacing while calculating the axial strength of CFS built-up columns.

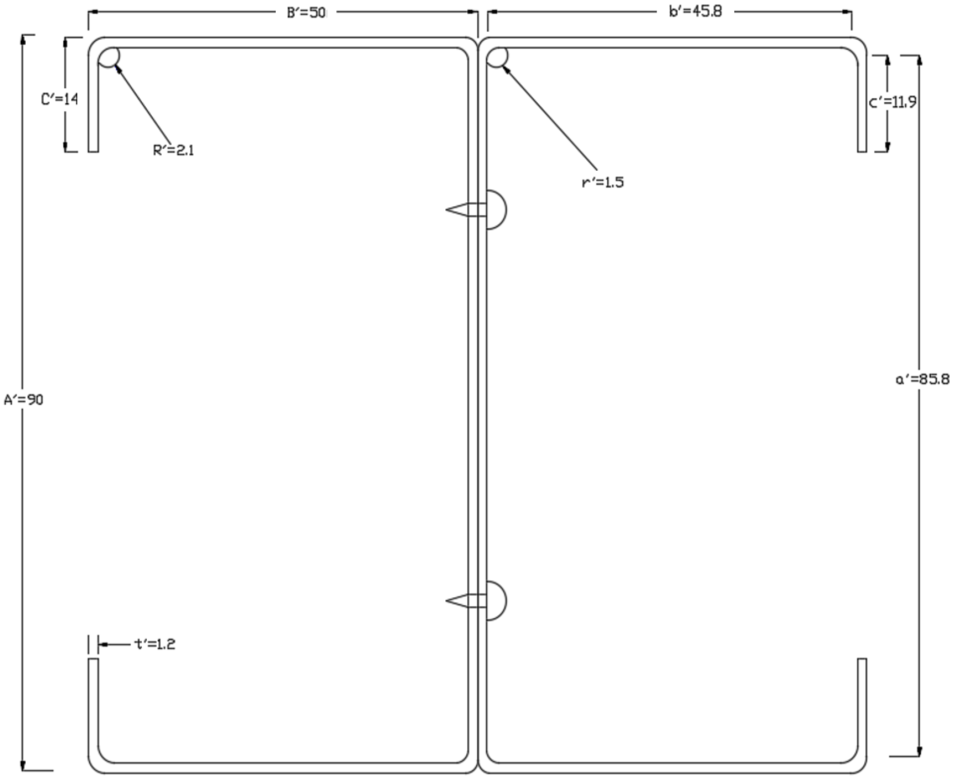
In the literature, very limited research has been described for such back-to-back screw-fastened built-up cold-formed stainless-steel lipped channels under compression, in the arrangement shown in Fig. 1. Ting *et al.* (2018) recently investigated the axial strength of built-up cold-formed carbon steel channels, connected back-to-back with intermediate screw fasteners (Fig. 1). This paper extends the work reported by Ting *et al.* (2018) for cold-formed carbon steel to cold-formed stainless steel. The main difference of stainless steel behaviour from carbon steel behaviour is material nonlinearity where the carbon steel's elastic-linear behaviour is up to the yield strength and then plastic-nonlinear behavior before strain hardening. However, stainless steel has no clearly defined yield plateau thus design procedures needs to consider this material nonlinearity due to reduction in the stiffness and higher strain hardening of stainless steel. In addition, the applicability of the modified slenderness approach as prescribed in the current carbon steel AISI (2018) and AS/NZS (2018) codes to calculate the axial capacity of back-to-back built-up cold-formed stainless-steel lipped

∗Corresponding author, Ph.D. Student,
E-mail: kroy405@aucklanduni.ac.nz
[a] Professor, E-mail: hhlau@swinburne.edu.my
[b]Associate Professor, E-mail james.lim@auckland.ac.nz

ISSN: 1229-9367 (Print), 1598-6233 (Online)



(a) BU75



(b) BU90

(All dimensions are in mm)

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

channels, was investigated in this paper.

In the literature, limited work has been reported for back-to-back built-up cold-formed stainless-steel channels to specially investigate the effect of screw spacing on axial strength of such columns. However, Dobrić *et al.* (2018a, b) investigated the compression capacity of back-to-back cold-formed stainless-steel channels through experimental and numerical investigations. Roy *et al.* (2018d) investigated the behaviour of back-to-back cold-formed duplex stainless-steel built-up channel sections under compression. Yuan *et al.* (2014) considered built-up stainless-steel columns, these were fabricated from three plates welded together to form an I section and were not from c-channel connected back to-back with screw fasteners; furthermore, only stub columns were considered. For back-to-back channels, Becque and built-up compression members over the last 3 decades. As

Table 1 Research in cold-formed carbon steel built-up compression members

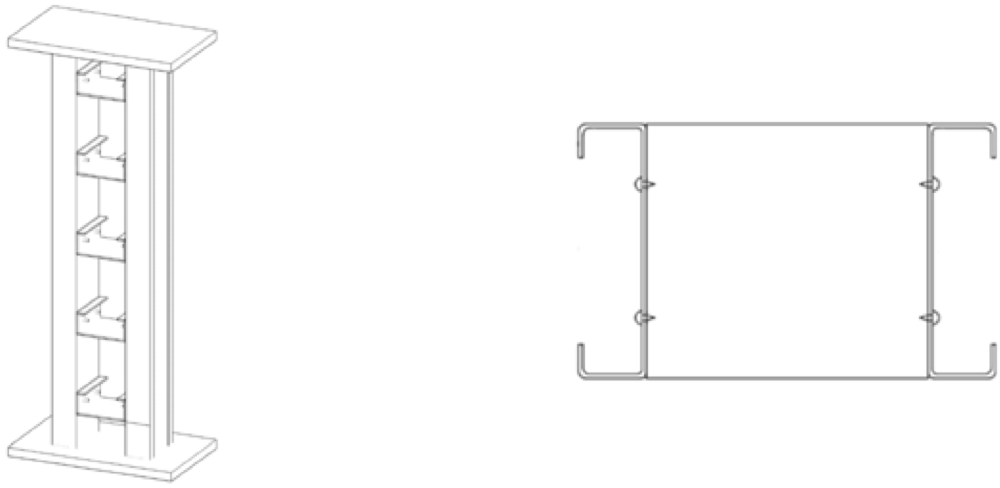
Researcher	Cross-section type	Topic	Conclusions
Dabaon *et al*. (2015)	back-to-back built-up CFS section battened columns.	Nonlinear behavior of built-up cold-formed steel section battened columns.	The specifications were unconservative for the built-up CFS battened columns failing mainly by local buckling, while the specifications were conservative for the built-up columns failing mainly by elastic flexural buckling.
Stone and LaBoube (2005)	Back-to-back built-up CFS channel section columns.	Behavior of cold-formed steel built-up I section (studs) formed with c-channels and screw attachments.	Modified slenderness approach by the AISI is conservative on average for thin members and exceedingly for thick members.
Whittle and Ramseyer (2009)	Back-to-back built-up CFS channel section columns.	Buckling capacities of axially loaded, cold-formed, built-up C-channels formed by toe-to-toe welding.	Use of the modified slenderness ratio was exceedingly conservative. Capacities based on the unmodified slenderness ratio was consistently conservative.
Ting *et al*. (2018)	Back-to-back built-up CFS channel section columns.	Effect of screw spacing on behavior of axialy loaded back-to-back cold-formed steel built-up channel sections, connected by screw fasteners.	The modified slenderness approach is in general conservative for columns failed by global buckling, however, for stub columns it can be unconservative by around 10%.
Roy *et al*. (2018b)	Back-to-back built-up CFS un-lipped channel section columns.	Nonlinear behavior of axially loaded back-to-back built-up cold-formed steel un-lipped channel sections, connected by intermediate screw fasteners.	The American Iron and Steel Institute (AISI) and the Australian and New Zealand Standards are over-conservative by around 15% for built-up columns failed through overall buckling, however AISI and AS/NZS are un-conservative by around 8% for built-up columns mainly failed by local buckling.
Zhang and Young (2012)	Back-to-back built-up CFS I-shaped open sections with edge and web stiffeners.	Compression tests of cold-formed steel I-shaped open sections with edge and web stiffeners, connected bny screw fasteners.	Testing verified the appropriateness of the direct strength method for I-shaped open sections with edge and web stiffeners. It was shown that the direct strength method can be used for CFS I-shaped open sections with edge and web stiffeners.
Fratamico *et al*. (2018)	Back-to-back built-up CFS channel section columns.	Experiments on the global buckling and collapse of built-up cold-formed steel columns, connected by screw fasteners.	Rational design approaches extending the application of the Direct Strength Method (DSM) and employing current state-of-the-art numerical modeling techniques were proposed and validated with test data.
Anbarasu *et al*. (2015)	Back-to-back built-up CFS web stiffened channel section battened columns.	Investigation on the behaviour and strength of cold-formed steel web stiffened built-up battened columns.	The column strength predicted by the finite element analysis was compared with the design column strengths predicted by direct strength method (DSM). Based the comparison, a recommendation was proposed to DSM.
Roy *et al*. (2018c)	Back-to-back built-up CFS channel section columns.	Effect of thickness on the behaviour of axially loaded back-to-back cold-formed steel built-up channel sections - Experimental and numerical investigation (back-to-back channels were connected by screw fasteners).	The AISI& AS/NZS standards are un-conservative for stub and short columns which were failed by local buckling whereas standards were over-conservative for the strength of intermediate and slender columns which were failed mainly by overall member buckling. Improved design rules were proposed for back-to-back built-up CFS channel sections, subjected to axial compression.

Table 1 Continued

Researcher	Cross-section type	Topic	Conclusions
Roy *et al*. (2019a)	Face-to-face built-up CFS channel section columns.	Experimental and numerical investigation into the behaviour of face-to-face built-up cold-formed steel channel sections under compression (face-to-face channels were connected by screw fasteners).	From the results of experiments and finite element investigations, it was found that the design in accordance with the AISI & AS/NZS and Eurocode (EN 1993-1-3) is generally conservative by around 15%, however, AISI & AS/NZS and Eurocode (EN 1993-1-3) can be un-conservative by 8% on average for face-to-face built-up columns failed through local buckling.
Dar *et al.* (2018a)	CFS built-up section columns formed by angle sections connected by single lacing systems.	Behaviour of laced built-up cold-formed steel columns: Experimental investigation and numerical validation.	Test results were used to develop the column strength curves for built-up laced CFS columns. Finally, the tests and FEA results were compared with the design strength predictions by North American Standards and European Standards for CFS sections.
Aslani and Goel (1991)	Hot-rolled steel built-up compression members.	An analytical criterion for buckling strength of built-up compression members.	Testing verified the AISC slenderness modification ratio and built-up member design method.
Reyes and Guzman (2011)	CFS built-up box section columns.	Evaluation of the slenderness ratio in built-up CFS welded box sections.	The test results showed that the strength reduction considered in AISI S100-2007is not applicable to determine the ultimate load capacity for CFS built-up welded box sections.
Biggs *et al.* (2015)	CFS built-up welded channel section columns.	Experimental testing of cold-formed built-up members in pure compression.	The AISI-2001 and AISI-2007 were found to give inconsistent results that at times were un-conservative or overly conservative in terms of axial strength. It was also found that orientation of the member has an important impact on the maximum failure load on the member.
Roy *et al.* (2018e)	Back-to-back gapped built-up CFS channel section columns	Nonlinear behaviour of back-to-back gapped built-up cold-formed steel channel sections under compression.	Using the experimental and FE results, it is shown that design in accordance with the AIS and AS/NZS can be conservative by as much as 53%. However, use of a modification to the non-dimensional slenderness, that considers the gap, results in the design standards being within 5% conservative with respect to the experimental and FE results.
Roy *et al.* (2019b)	CFS built-up box section columns.	Experimental and numerical investigations on the axial capacity of cold-formed steel built-up box sections, connected by screw fasteners.	The AISI & AS/NZS are conservative by around 17% while determining the axial capacity of such built-up CFS box columns, when compared to the test and numerical strengths.

Rasmussen (2009) conducted an experimental investigation to study the interaction of local and overall buckling of cold-formed stainless steel. In terms of single channels, stub columns have been investigated by Rasmussen and Hancock (1993), Gardner and Nethercot (2004a), Gardner *et al.* (2006), Young and Lui (2003) and Fan *et al.* (2014). Macdonald *et al.* (2007) studied the effect of combined bending and axial loading, again on stainless steel single channel stub columns. The beneficial effect of gap between two back-to-back cold-formed stainless-steel channels was investigated by Roy *et al.* (2018a) under axial compression.

In terms of cold-formed carbon steel built-up channels, significant research is available in the literature. Table 1 presents the research works in cold-formed carbon steel



(a) General arrangement (b) Cross section

Fig. 2 Back-to-back gapped built-up cold-formed steel channels investigated by Roy *et al.* (2018e)

can be seen from Table 1, Dabaon *et al.* (2015) investigated the axial strength of back-to-back built-up cold-formed steel section battened columns. The behaviour of cold-formed steel back-to-back built-up channels was studied by Stone and LaBoube (2005). Whittle and Ramseyer (2009) investigated the axial strength of built-up channels which were welded toe-to-toe. Ting *et al.* (2018) studied the effect of fastener spacing. Roy *et al.* (2018b) studied the axial capacity of un-lipped channels connected back-to-back. Zhang and Young (2012) investigated back-to-back channels with an opening. Fratamico *et al.* (2018) investigated experimentally, the global buckling and collapse behaviour of back-to-back cold-formed steel channels. Anbarasu *et al.* (2015) studied the behaviour of cold-formed steel built-up batten columns, which were web stiffened, again without any gap between the back-to-back channels. Recently, Roy *et al.* (2018c) investigated the effect of thickness on the behavior of cold-formed steel back-to-back built-up lipped channels, under compression and proposed improved design rules. Roy *et al.* (2019a) also studied the axial capacity of built-up face-to-face cold-formed steel channels. On the other hand, Dar *et al.* (2018a) investigated the behaviour of laced built-up cold-formed steel columns, through experimental and numerical investigations. 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 Guzmán (2011) to evaluate the slenderness ratio in built-up cold-formed carbon steel box section. On the other hand, Biggs *et al.* (2015) investigated the axial strength of rectangular and I-shaped welded built-up cold-formed steel columns under compression. Furthermore, Roy *et al.* (2018e) investigated experimentally the axial strength of built-up cold-formed carbon steel channels, with a gap between the back-to-back channels (Fig. 2). Most recently, the axial capacity of CFS built-up box sections were studied by Roy *et al.* (2019b), through experimental and numerical investigations. On the other hand, concrete filled steel tubes and steel-composite beams are becoming popular in recent time as structural members (Kanishchev and Kvočák 2019, Jiang *et al.* 2018). However, no work has been reported in the literature to investigate the effect of screw spacing on the axial strength of back-to-back built-up cold-formed stainless-steel lipped channels under axial compression. The issue is addressed in this paper.

This paper investigates the axial strength of built-up cold-formed stainless-steel lipped channels, connected back-to-back with the help of intermediate screws (Fig. 1). The three most commonly used stainless steel grades (duplex grade EN 1.4462, ferritic grade 1.4003 and austenitic grade 1.4404) were considered for the numerical investigation. Typical stress-strain curves for the three grades of stainless steel were taken from Chen and Young (2006), Yang *et al.* (2016) and Arrayago *et al.* (2015) (Fig. 3). A non-linear finite element model is presented which includes material non-linearity, initial imperfections, corner strength enhancements and strain hardening of stainless steel in tension and compression sides. The validated/established finite element model was then used to conduct a parametric study to investigate the effect of screw spacing on axial strength of back-to-back built-up cold-formed stainless-steel lipped channels. The applicability of the current carbon steel design guidance by the AISI (2016) and and AS/NZS (2018) for stainless steel back-to-back lipped

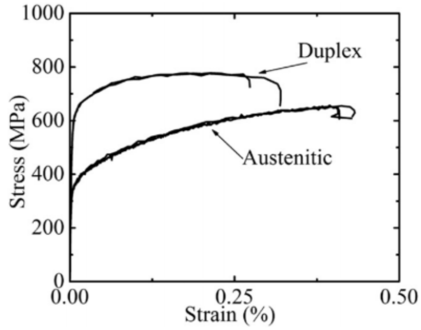


Fig. 3 Stress–strain curves of cold-formed Duplex and Austenitic stainless steel used in this research (Yang *et al.* 2016)

channels were also verified in this paper.

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

The finite element strengths were compared against the un-factored design strengths calculated in accordance with the American Iron and Steel Institute's specification (AISI 2016) and the Australia/New Zealand standards (AS/NZS 2018) for back-to-back built-up cold-formed stainless-steel lipped channels. Effective width area (EWA) method was used, when calculating the design strengths in accordance with the AISI (2016) and AS/NZS (2018). For back to-back built-up lipped channels, the un-factored design strength of axially loaded compression members calculated in accordance with the AISI (2016) and AS/NZS (2018) standards are as follows

$$P_{AISI\&AS/NZS} = A_e F_n \qquad (1)$$

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

$$\text{For} \quad \lambda_c \leq 1.5, \quad F_n = \left(0.658^{\lambda^2{}_c}\right) F_y \qquad (2)$$

$$\text{For} \quad \lambda_c \leq 1.5, \quad F_n = \left(\frac{0.877}{\lambda^2{}_c}\right) F_y \qquad (3)$$

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

$$\lambda_c = \sqrt{\frac{F_y}{F_e}} \qquad (4)$$

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

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

3. Summary of experimental study

The finite element models, developed in this study, were validated against Ting *et al.* (2018) for carbon steel and Dobrić *et al.* (2018a) for stainless steel built-up lipped channels. A brief summary of the tests reported by Ting *et al.* (2018) for carbon steel built-up channels, is described in this Section.

The tests by Ting *et al.* (2018) reported the axial strengths, failure modes and load-displacement behavior of back-to-back built-up carbon steel lipped channels. Fig. 1 shows the details of channel sections considered in the experimental program, which was referred as C75 and C90. The measured specimen dimensions are shown in Table 2. In total, 60 back-to-back built-up cold-formed carbon steel lipped channels were tested, subdivided into four different column heights: 300 mm, 500 mm, 1000 mm, and 2000 mm, with different screw spacing. The spacing of the fasteners were designed to consider the spacing requirement within and beyond the clause of C4.5 in the AISI Specification. In order to cover a wide range of column slenderness and to investigate the effect of fastener spacing on axial strength, column lengths were varied from 300 mm to 2000 mm, in the experimental investigation.

The built-up channels were tested with pin-ended boundary conditions, apart from the stub column, which was tested as fixed ended columns for obtaining the squash load. In Table 2, the specimens have been sub-divided into stub, short, intermediate and slender columns. The specimens tested were labelled such that the type of section, screw spacing, nominal length of specimen and specimen number was expressed by the label. Fig. 4 shows an example of the labelling used in the experimental program.

Material properties of cold-formed carbon steel channel sections were determined from the tensile coupon tests, which was conducted according to British Standard for

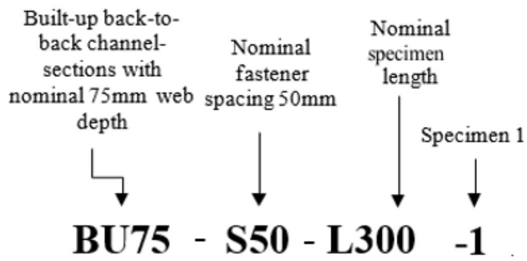


Fig. 4 Specimen labelling

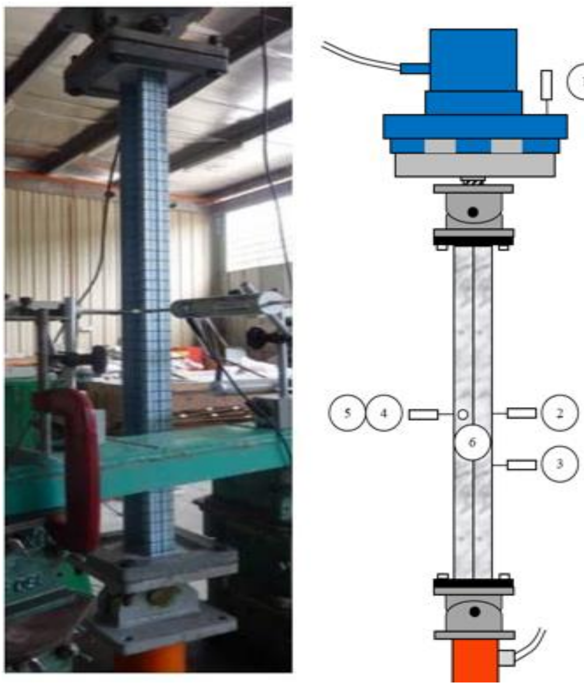


Fig. 5 Photograph of the test set-up for intermediate column (Ting *et al.* 2018)

Table 2 Comparison of FEA results against test results (Ting *et al.* 2018) for back-to-back built-up cold-formed carbon steel lipped channels

(a) BU75

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 2 Continued
(b) BU90

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

Testing and Materials (2001). The coupons were tested in an MTS displacement controlled universal testing machine using friction grips. Two strain gauges and a calibrated extensometer of 50 mm gauge length were used to measure the longitudinal strain. Five coupons were cut from the longitudinal directions of the web of the channels and tested. The average Young's modulus and yield stress were 207 N/mm^2 and 560 N/mm^2, respectively.

Load was applied axially to the specimens via a 600 kN capacity GOTECH, GT-7001-LC60 Universal Testing Machine (UTM). Fig. 5 shows a photograph of the test set-up used by Ting *et al.* (2018). Prior to testing a LVDT with 0.11 mm accuracy was used to measure the initial imperfections present in the channels. These imperfections are included in finite element models described in Section 4. Further details of the experimental tests are available in Ting *et al.* (2018).

4. Finite element modelling

Numerical models were developed using the finite element package ABAQUS (2018). The finite element model was based on the centerline dimensions of the cross-section of built-up lipped channels. Two types of built-up channels were considered: (i) Cold-formed carbon steel built-up channels (ii) Cold-formed stainless-steel built-up channels. The FE model of carbon steel built-up lipped channels was validated against the experimental tests reported by Ting *et al.* (2018) and the FE model of stainless-steel built-up channels was validated against the test results of stainless-steel back-to-back channels reported by Dobrić *et al.* (2018a). The FE model for stainless-steel built-up channels considered significant strain hardening of stainless steel in tension and compression (Dobrić *et al.* 2018b). Also, for the FE modelling of stainless-steel built-up channels, the average stress-strain values were considered from Chen and Young (2006), Yang *et al.* (2016) and Arrayago *et al.* (2015). For the parametric study, the analytical stress–strain curve was defined by employing a modified Ramberg–Osgood material model according to Arrayago *et al.* (2015) for stainless steel built-up channels. Firstly, Eigen value analyses were used to determine the contours of the initial imperfections. Eigen modes of the back-to-back built-up stainless-steel lipped channels were used for the contours of the initial imperfections. A load-displacement nonlinear analysis was then carried out using the Riks algorithm. In total, 100 increments were used. The initial arc length increment was 1, whereas the minimum and maximum arc length increments were 1×10^{-5} and 1×10^{36}, respectively, with an estimated total arc length of 1. The Riks method includes the post buckling behaviour of back-to-back built-up stainless-steel lipped channels. Specific modelling techniques are described below.

4.1 Material properties used in the FE model

The full geometry of the back-to-back built-up stainless-steel lipped channels were modelled including the web-fasteners. True values of stresses and strains were specified in the finite element model to incorporate the material non-linearity. The ABAQUS (2018) modified Ramberg–Osgood material 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.

4.2 Finite element mesh

The back-to-back built-up cold-formed stainless-steel lipped channels were modelled using the S4R shell elements available in ABAQUS (2018). The S4R elements are linear 4-noded quadrilateral thick shell elements, with six degrees of freedom per node with reduced integration and a large strain formulation. S4R elements have three translational and three rotational degrees of freedom at each node. This element accounts for finite membrane strains and arbitrarily large rotations, and therefore, is suitable for large strain analyses and geometrically non-linear problems. The aspect ratio of the elements was close to one. Based on

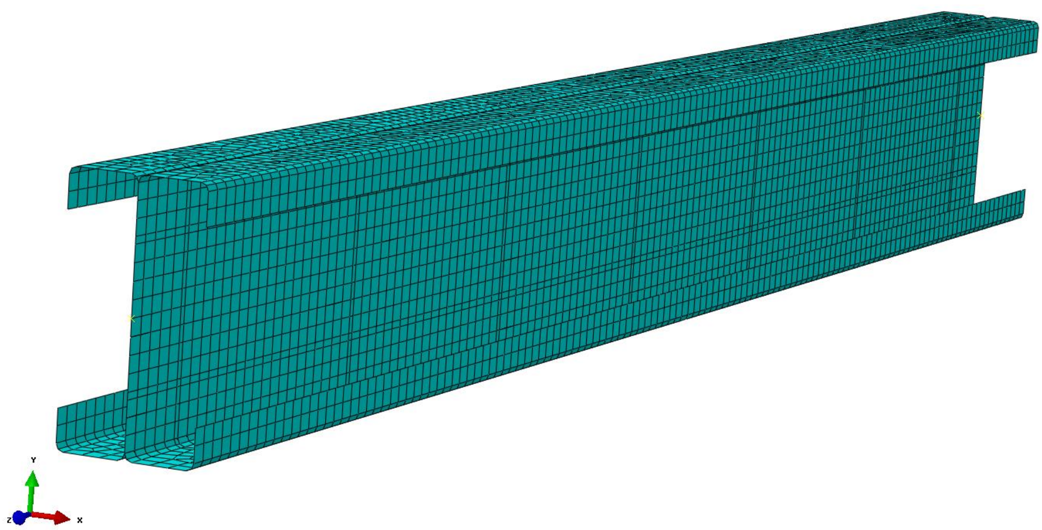


Fig. 6 Typical finite element mesh (BU75-S100-L500-1 (Duplex EN1.4462))

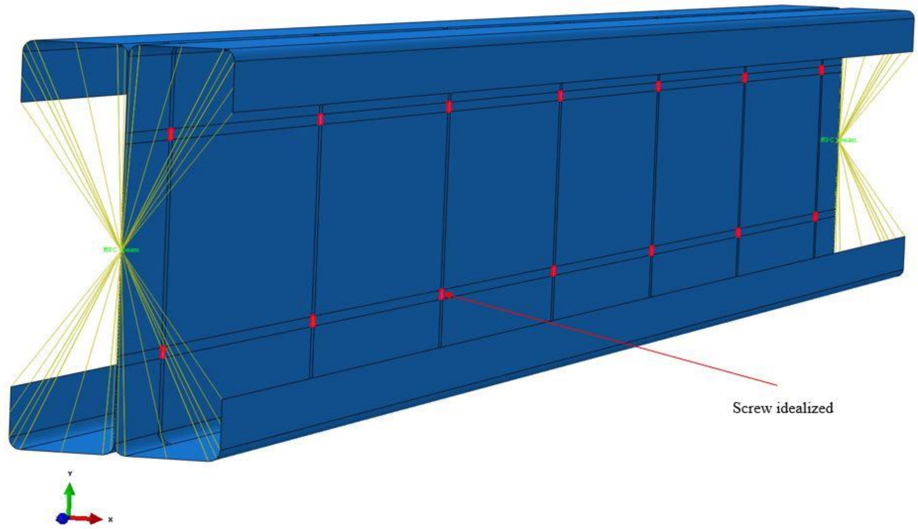


Fig. 7 Boundary condition applied in the finite element model (BU75-S100-L500-1(Duplex EN1.4462))

the mesh sensitivity study, across the length and width, a mesh size of 5 mm × 5 mm was used for the back-to-back lipped channels. A mesh sensitivity analysis was performed to verify the number of elements. A typical finite element mesh of the back-to-back built-up cold-formed stainless-steel lipped channels is shown in Fig. 6.

4.3 Boundary conditions and loading procedure

Pin-ended boundary conditions were applied for all built-up columns, other than stub columns which were modelled as fixed-ended columns. The pin-pin boundary condition was modelled by applying translational constraints to both end plates using a reference point. The reference point was considered as the centre of gravity (CG) of the cross-section of the built-up channels. The load was applied to the reference points of the upper end of the built-up channels as shown in Fig. 7. Screw fasteners between the back-to-back stainless-steel lipped channels were modelled using Multi-point constraints (MPC) available in the ABAQUS library (Fig. 7). MPCs allow constraints to be imposed between different degrees of freedom of the model; and can be used for nonlinear and nonhomogeneous problems. MPC beam connector elements were assigned a stress of 62.10 MPa to incorporate the stiffness of the fasteners (Roy *et al.* (2019a, c)). The connector element stress was calculated based on the screw diameter and channel thickness. Both the bearing stress and shear stress were considered while calculating the connector element stress. The maximum of the bearing and shear stress was considered as the connector element stress. However, the exact number "62.10" MPa as used in the finite element model for connector element stress, was determined based on the result of a sensitivity study (ABAQUS 2018) which was conducted for such back-to-back built-up cold-formed stainless-steel lipped channels.

4.4 Contact modeling

"*Surface-to-surface*" contact interactions describe contact between two deformable surfaces or between a deformable surface and a rigid surface. This type of contact (*Surface-to-surface)* can be defined in any analysis steps, including the initial step. "*Surface-to-surface*" contact was used for modelling the interaction between the webs of back-to-back channels. The web of one channel was modeled as slave surface, while the web of another channel was considered as master surface. Frictionless contact was used to model the tangential behaviour between the back-to-back channels. There was no penetration between these two contact surfaces.

4.5 Modelling of geometric imperfections

Local and overall buckling behavior of back-to-back built-up cold-formed stainless-steel lipped channels depend on many factors such as: Depth of channel-thickness ratio (D/t), width of channel-thickness ratio (b/t), slenderness around x axis and y axis and spacing of the screws. Initial imperfections in compression members occurred/happened/ caused as a result of transportation and fabrication processes. Hence, local and overall buckling modes are superimposed for accurate finite element analysis. Eigen value analyses of the built-up columns were performed with very small to large channel thickness to determine the contours for the local and overall imperfections. The lowest buckling mode (Eigen mode 1) in ABAQUS (2018) was used to model the shape of the local and overall buckling modes. Similar modelling techniques were used for single and built-up carbon steel channels by Chen *et al.* (2019) and Ananthi *et al.* (2019) Gardner and Nethercot (2004b) proposed equations to determine the magnitudes of local and overall imperfections for stainless-steel channels, which were used to as the imperfection magnitudes of back-to-back built-up cold-formed stainless-steel channels in this study. Typical local and overall buckling modes from

ABAQUS (2018) are shown in Fig. 8 for BU75-S100-L500-1 (Duplex EN1.4462).

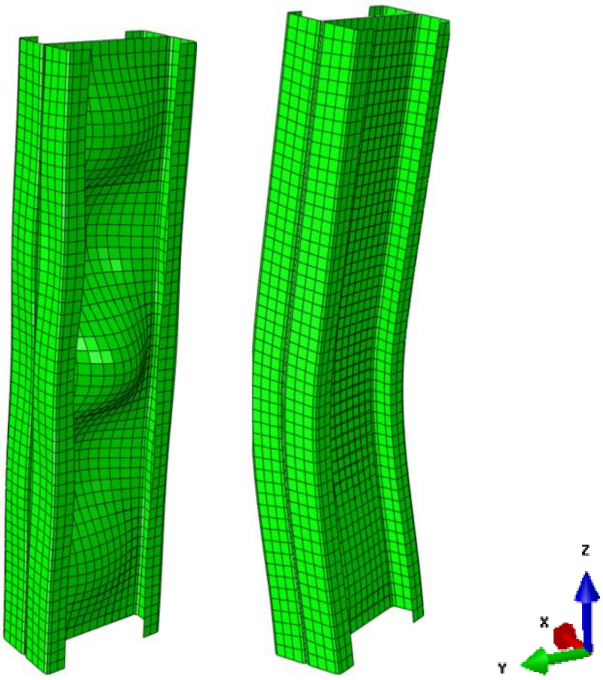
4.6 Modelling of corner strength enhancement

In the literature, Rossi *et al.* (2013), Afshan *et al.* (2013) and Ashraf *et al.* (2005) have presented recommendations for the corner strength enhancement of cold-formed stainless-steel channels. In a limited sensitivity study, the enhancements proposed by Ashraf *et al.* (2005) were modelled. However, it was found that the corner strength enhancement had negligible effect on the load-displacement curves. This is because the ultimate strength of the back-to-back built-up stainless-steel lipped channels is primarily influenced by the screw spacing.

4.7 FE model validation

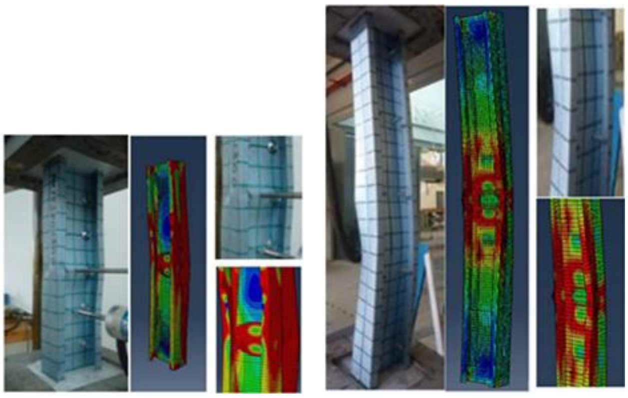
Test results from Ting *et al.* (2018) were used to validate the finite element model of built-up cold-formed carbon steel channels, connected back-to-back for stub, short, intermediate and slender columns (Fig. 9(a)). On the other hand, finite element model of back-to-back built-up cold-formed stainless-steel channels was validated against the experimental results of cold-formed stainless steel back-to-back built-up channels reported by Dobrić *et al.* (2018a) for specimen- (U92b-2) (Fig. 9(b)). The comparison of test and finite element strengths are shown in Fig. 10 for BU75-S50-L300-1 from Ting *et al.* (2018) for back-to-back built-up cold-formed carbon steel channels.

Tables 2(a) and 2(b) compare the failure load obtained from the experiments (Ting *et al.* 2018) and finite element analysis for back-to-back built-up carbon steel channels.

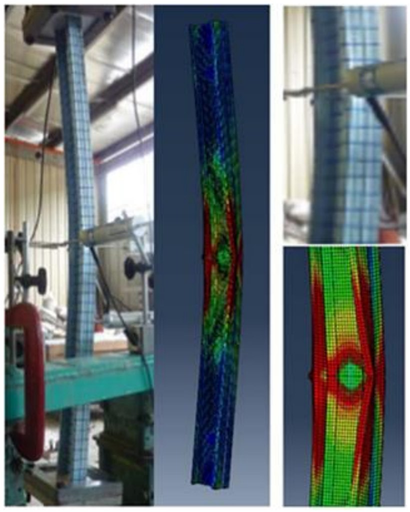


(a) Local buckling (b) Overall buckling

Fig. 8 Initial imperfection contours (BU75-S100-L500-1 (Duplex EN1.4462))

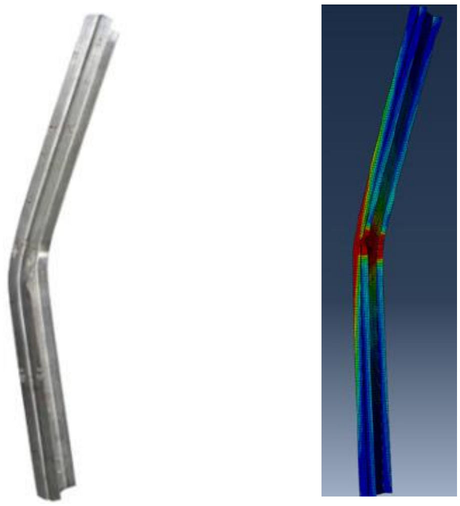


(i) Stub (BU75-S50-L300) (ii) Short column (BU75-S100-L500)



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

(a) Back-to-back built-up cold-formed carbon steel channels investigated by Ting *et al.* (2018)



(i) Experimental (Dobrić *et al.*2018a) (ii) FEA described in this paper

(Specimen id- U92b-2)

(b) Back-to-back built-up cold-formed stainless-steel channels investigated by Dobrić *et al.* (2018a)

Fig. 9 Back-to-back built-up cold-formed carbon and stainless-steel channels at failure

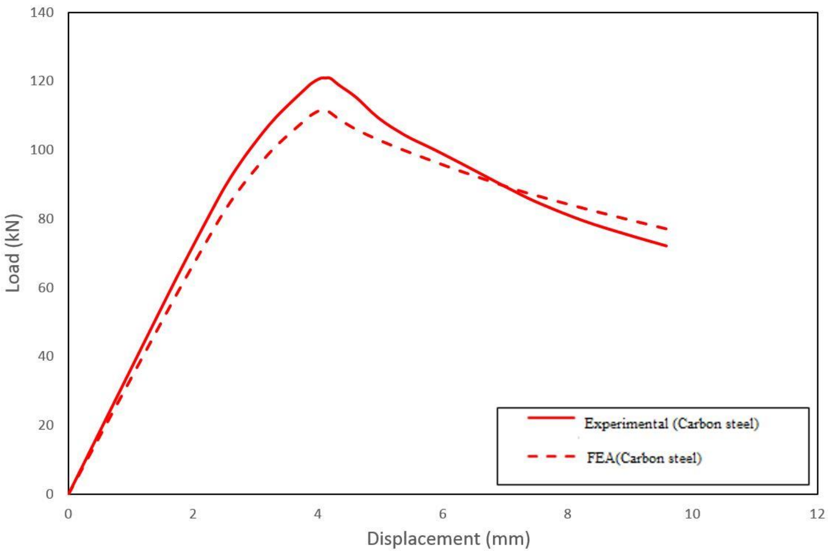


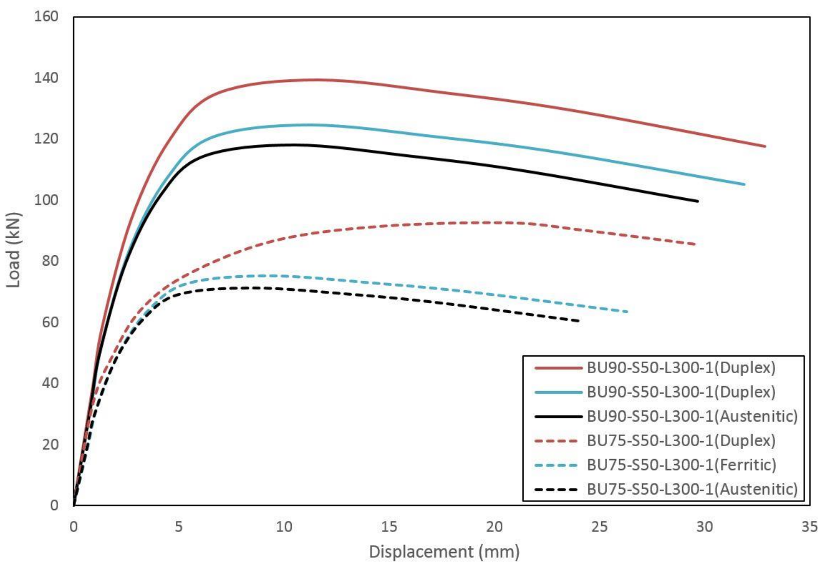
Fig. 10 Comparison of finite element results to tests results for back-to-back built-up cold-formed carbon steel channels investigated by Ting *et al.* (2018) (BU75-S50-L300-1)

It is shown that the mean value of P_{EXP}/P_{FEA} is 1.04, with a co-efficient of variation of 0.02 for stub column of BU75 series. Similarly, the mean value of P_{EXP}/P_{FEA} is 1.06, with a co-efficient of variation of 0.02 for stub column of BU90 series. Good correlation was obtained between FEA and test results, both in terms of axial capacity and failure modes.

5. Parametric study

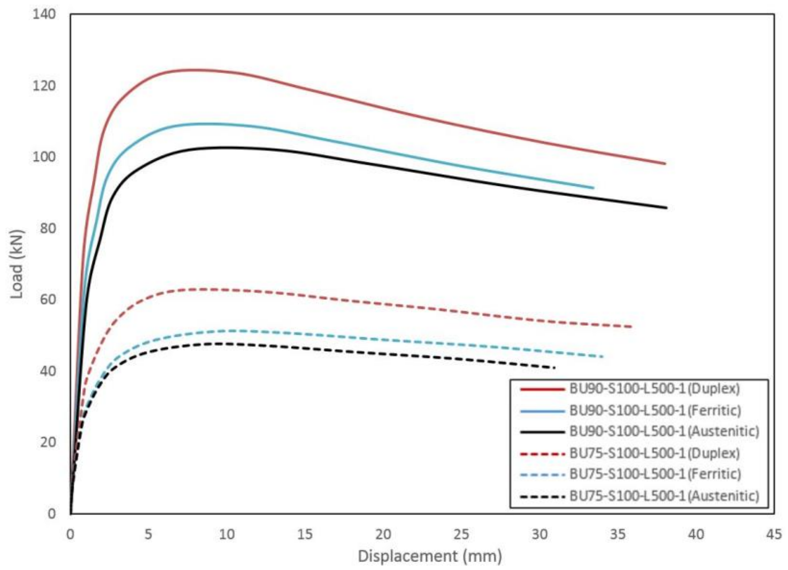
The validated finite element model was used to conduct an extensive parametric study to investigate the effect of screw spacing on axial strength of back-to-back built-up cold-formed stainless-steel lipped channels. In total, 647 finite element models were analyzed. Both BU75 and BU90 were considered (Fig. 1). Three most commonly used stainless steel grades were considered, i.e., duplex grade EN 1.4462, ferritic grade 1.4003 and austenitic grade 1.4404. Column lengths from 300 mm to 2000 mm were analysed. Tables 3(a,i) and 2(b,i) show the cross-sectional dimensions and the ultimate loads (P_{FEA}) for the duplex grade of built-up stainless-steel lipped channels. Similarly, the section dimensions and axial strengths of ferritic 1.4003 and austenitic 1.4404 grades of built-up stainless-steel lipped channels are shown in Tables 3(a,ii), 2(b,ii), 2(a,iii) and 2(b, iii), respectively.

Load-axial displacement curves for back-to-back built-up cold-formed stainless-steel lipped channels, covering stub to slender columns are shown in Fig. 11 for both BU75 and BU90 series. As can be seen, significant strength

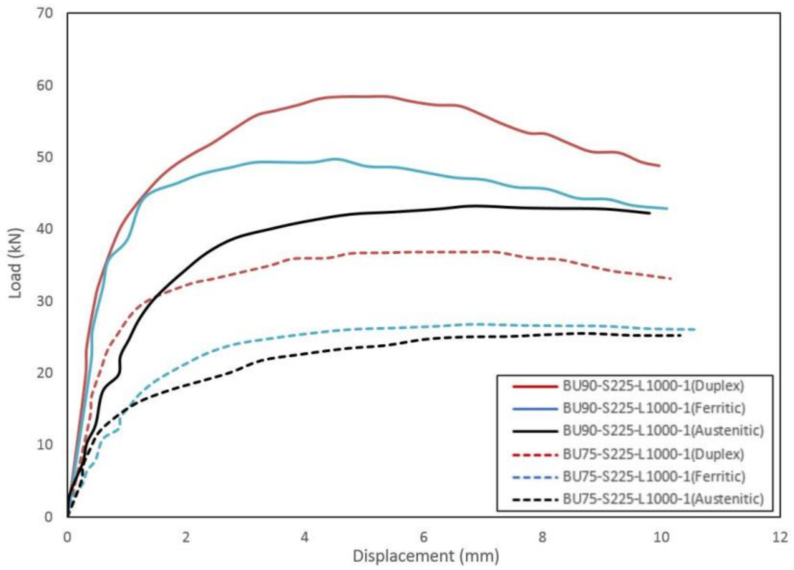


(a) Stub columns (300 mm length)

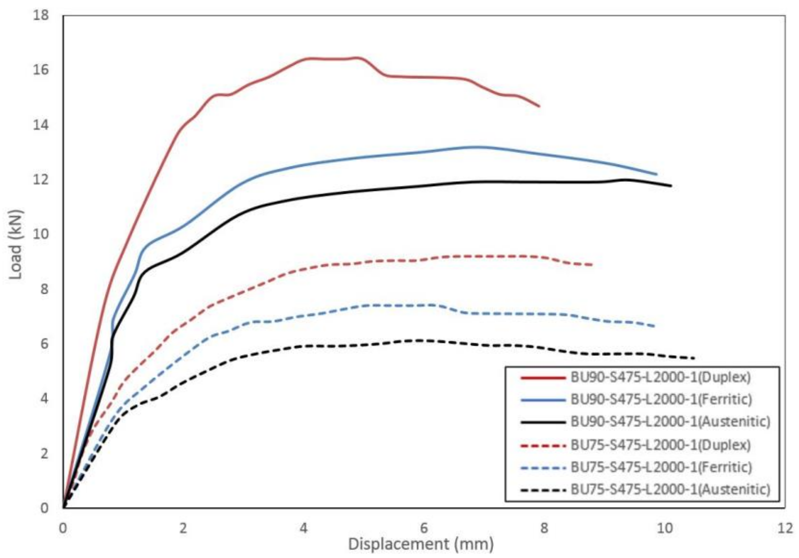
Fig. 11 Load versus axial displacement curves for back-to-back built-up stainless-steel lipped channels from the FE analysis



(b) Short columns (500 mm length)



(c) Intermediate columns (1000 mm length)



(d) Slender columns (2000 mm length)

Fig. 11 Continued

Table 3 Comparison of finite element strengths against design strengths (AISI&AS/NZS) for built-up stainless-steel channels
(a) BU75
(i) Duplex EN1.4462

Specimen	Web	Flange	Length	Thickness	Spacing	FEA results	AISI design strengths	
	A’	B’	L	t	S	P_{EXP}	P_{FEA}	P_{EXP}/P_{FEA}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	-
Stub								
BU75-S50-L300-1	73.1	19.8	273.0	1.20	50.0	92.4	99.5	0.93
BU75-S50-L300-2	73.1	19.8	280.0	1.21	50.0	90.1	100.8	0.89
BU75-S50-L300-3	72.7	19.5	270.0	1.19	50.9	91.2	97.4	0.94
BU75-S100-L300-1	73.1	19.8	267.0	1.20	99.7	89.0	98.7	0.90
BU75-S100-L300-2	73.1	19.9	273.0	1.20	100.2	94.8	99.1	0.96
BU75-S100-L300-3	73.6	19.7	273.0	1.21	99.5	87.6	96.9	0.90
BU75-S200-L300-1	73.7	19.8	266.5	1.22	200.0	86.0	89.0	0.97
BU75-S200-L300-2	73.6	19.9	266.0	1.20	199.5	86.4	89.2	0.96
BU75-S200-L300-3	72.9	20.0	268.0	1.21	200.0	85.8	89.4	0.96
Mean								0.93
COV								0.03
Short								
BU75-S100-L500-1	73.6	19.8	655.0	1.19	100.0	62.2	56.9	1.09
BU75-S100-L500-2	73.6	19.7	680.0	1.20	100.5	60.9	56.2	1.08
BU75-S200-L500-1	73.5	19.5	653.0	1.20	195.0	58.2	52.8	1.10
BU75-S200-L500-2	73.6	19.6	678.0	1.21	195.0	59.5	53.1	1.12
BU75-S200-L500-3	73.4	19.7	680.0	1.20	200.5	58.6	52.6	1.11
BU75-S400-L500-1	73.6	19.7	678.0	1.18	400.0	54.6	49.6	1.10
BU75-S400-L500-2	73.5	19.7	679.0	1.19	401.0	54.5	49.0	1.11
Mean								1.10
COV								0.01
Intermediate								
BU75-S225-L1000-1	75.3	20.2	1133	1.20	225.3	36.7	30.5	1.20
BU75-S225-L1000-2	75.7	19.9	1131	1.22	225.3	33.6	27.7	1.21
BU75-S450-L1000-1	75.8	19.9	1131	1.20	447.0	32.3	27.1	1.19
BU75-S450-L1000-2	75.6	19.9	1133	1.21	450.0	29.5	24.9	1.18
BU75-S450-L1000-3	75.9	19.8	1182	1.19	450.0	23.8	20.2	1.17
BU75-S900-L1000-1	76.0	19.9	1131	1.18	900.0	22.3	18.6	1.20
BU75-S900-L1000-2	76.3	19.8	1133	1.20	900.0	22.8	18.8	1.21
BU75-S900-L1000-3	75.9	19.8	1183	1.21	901.0	20.8	17.0	1.23
Mean								1.20
COV								0.03
Slender								
BU75-S475-L2000-1	73.9	20.3	2184	1.20	474.5	9.2	7.9	1.17
BU75-S475-L2000-2	73.9	20.2	2183	1.21	462.0	9.0	7.6	1.19
BU75-S950-L2000-1	73.9	20.3	2184	1.22	949.5	7.3	6.1	1.20
BU75-S950-L2000-2	73.9	20.2	2184	1.23	950.0	7.1	5.8	1.22
BU75-S1900-L2000-1	73.9	20.3	2183	1.20	1900.0	6.0	5.1	1.18
BU75-S1900-L2000-2	73.9	20.4	2184	1.18	1901.0	5.9	4.9	1.20
Mean								1.19
COV								0.02

Table 3 Continued
(a) BU75
(ii) Ferritic EN1.4003

Specimen	Web	Flange	Length	Thickness	Spacing	FEA results	AISI design strengths	
	A'	B'	L	t	S	P_{EXP}	P_{FEA}	P_{EXP}/P_{FEA}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	-
Stub								
BU75-S50-L300-1	73.1	19.8	273.0	1.20	50.0	75.7	78.3	0.97
BU75-S50-L300-2	73.1	19.8	280.0	1.21	50.0	73.9	79.4	0.93
BU75-S50-L300-3	72.7	19.5	270.0	1.19	50.9	74.8	76.7	0.97
BU75-S100-L300-1	73.1	19.8	267.0	1.20	99.7	73.0	77.7	0.94
BU75-S100-L300-2	73.1	19.9	273.0	1.20	100.2	77.7	78.0	1.00
BU75-S100-L300-3	73.6	19.7	273.0	1.21	99.5	71.8	76.3	0.94
BU75-S200-L300-1	73.7	19.8	266.5	1.22	200.0	70.5	73.0	0.97
BU75-S200-L300-2	73.6	19.9	266.0	1.20	199.5	70.8	72.5	0.98
BU75-S200-L300-3	72.9	20.0	268.0	1.21	200.0	70.3	72.4	0.97
Mean								0.96
COV								0.02
Short								
BU75-S100-L500-1	73.6	19.8	655.0	1.19	100.0	51.0	49.1	1.04
BU75-S100-L500-2	73.6	19.7	680.0	1.20	100.5	49.9	48.4	1.03
BU75-S200-L500-1	73.5	19.5	653.0	1.20	195.0	47.7	45.5	1.05
BU75-S200-L500-2	73.6	19.6	678.0	1.21	195.0	48.8	45.8	1.07
BU75-S200-L500-3	73.4	19.7	680.0	1.20	200.5	48.0	45.3	1.06
BU75-S400-L500-1	73.6	19.7	678.0	1.18	400.0	44.8	42.8	1.05
BU75-S400-L500-2	73.5	19.7	679.0	1.19	401.0	44.7	42.2	1.06
Mean								1.05
COV								0.01
Intermediate								
BU75-S225-L1000-1	75.3	20.2	1133	1.20	225.3	28.9	26.5	1.10
BU75-S225-L1000-2	75.7	19.9	1131	1.22	225.3	26.5	24.1	1.08
BU75-S450-L1000-1	75.8	19.9	1131	1.20	447.0	25.4	23.6	1.07
BU75-S450-L1000-2	75.6	19.9	1133	1.21	450.0	23.2	21.7	1.07
BU75-S450-L1000-3	75.9	19.8	1182	1.19	450.0	18.7	17.6	1.09
BU75-S900-L1000-1	76.0	19.9	1131	1.18	900.0	17.6	16.2	1.10
BU75-S900-L1000-2	76.3	19.8	1133	1.20	900.0	18.0	16.3	1.11
BU75-S900-L1000-3	75.9	19.8	1183	1.21	901.0	16.4	14.8	1.10
Mean								1.09
COV								0.01
Slender								
BU75-S475-L2000-1	73.9	20.3	2184	1.20	474.5	7.4	7.1	1.05
BU75-S475-L2000-2	73.9	20.2	2183	1.21	462.0	7.3	6.8	1.07
BU75-S950-L2000-1	73.9	20.3	2184	1.22	949.5	5.9	5.4	1.08
BU75-S950-L2000-2	73.9	20.2	2184	1.23	950.0	5.7	5.2	1.11
BU75-S1900-L2000-1	73.9	20.3	2183	1.20	1900.0	4.8	4.6	1.06
BU75-S1900-L2000-2	73.9	20.4	2184	1.18	1901.0	4.8	4.4	1.09
Mean								1.08
COV								0.02

Table 3 Continued
(a) BU75
(iii) Austenitic EN1.4404

Specimen	Web	Flange	Length	Thickness	Spacing	FEA results	AISI design strengths	
	A’	B’	L	t	S	P_{EXP}	P_{FEA}	P_{EXP}/P_{FEA}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	-
Stub								
BU75-S50-L300-1	73.1	19.8	273.0	1.20	50.0	71.2	75.2	0.95
BU75-S50-L300-2	73.1	19.8	280.0	1.21	50.0	69.5	76.2	0.91
BU75-S50-L300-3	72.7	19.5	270.0	1.19	50.9	70.3	73.6	0.95
BU75-S100-L300-1	73.1	19.8	267.0	1.20	99.7	68.6	74.6	0.92
BU75-S100-L300-2	73.1	19.9	273.0	1.20	100.2	73.0	74.9	0.98
BU75-S100-L300-3	73.6	19.7	273.0	1.21	99.5	67.5	73.2	0.92
BU75-S200-L300-1	73.7	19.8	266.5	1.22	200.0	66.3	70.1	0.95
BU75-S200-L300-2	73.6	19.9	266.0	1.20	199.5	66.6	69.6	0.96
BU75-S200-L300-3	72.9	20.0	268.0	1.21	200.0	66.1	69.5	0.95
Mean								0.94
COV								0.02
Short								
BU75-S100-L500-1	73.6	19.8	655.0	1.19	100.0	47.4	44.2	1.07
BU75-S100-L500-2	73.6	19.7	680.0	1.20	100.5	47.6	43.6	1.09
BU75-S200-L500-1	73.5	19.5	653.0	1.20	195.0	44.3	41.0	1.08
BU75-S200-L500-2	73.6	19.6	678.0	1.21	195.0	45.2	41.2	1.10
BU75-S200-L500-3	73.4	19.7	680.0	1.20	200.5	44.6	40.8	1.09
BU75-S400-L500-1	73.6	19.7	678.0	1.18	400.0	41.7	38.5	1.08
BU75-S400-L500-2	73.5	19.7	679.0	1.19	401.0	41.6	38.0	1.09
Mean								1.09
COV								0.01
Intermediate								
BU75-S225-L1000-1	75.3	20.2	1133	1.20	225.3	25.7	23.3	1.10
BU75-S225-L1000-2	75.7	19.9	1131	1.22	225.3	23.6	21.2	1.11
BU75-S450-L1000-1	75.8	19.9	1131	1.20	447.0	22.6	20.8	1.09
BU75-S450-L1000-2	75.6	19.9	1133	1.21	450.0	20.6	19.1	1.08
BU75-S450-L1000-3	75.9	19.8	1182	1.19	450.0	16.6	15.5	1.07
BU75-S900-L1000-1	76.0	19.9	1131	1.18	900.0	15.7	14.3	1.10
BU75-S900-L1000-2	76.3	19.8	1133	1.20	900.0	16.0	14.3	1.12
BU75-S900-L1000-3	75.9	19.8	1183	1.21	901.0	14.6	13.0	1.12
Mean								1.10
COV								0.02
Slender								
BU75-S475-L2000-1	73.9	20.3	2184	1.20	474.5	6.1	5.9	1.04
BU75-S475-L2000-2	73.9	20.2	2183	1.21	462.0	6.0	5.6	1.07
BU75-S950-L2000-1	73.9	20.3	2184	1.22	949.5	4.9	4.5	1.09
BU75-S950-L2000-2	73.9	20.2	2184	1.23	950.0	4.7	4.3	1.10
BU75-S1900-L2000-1	73.9	20.3	2183	1.20	1900.0	4.1	3.8	1.08
BU75-S1900-L2000-2	73.9	20.4	2184	1.18	1901.0	4.0	3.6	1.09
Mean								1.08
COV								0.02

Table 3 Continued

(b) BU90

(i) Duplex EN1.4462

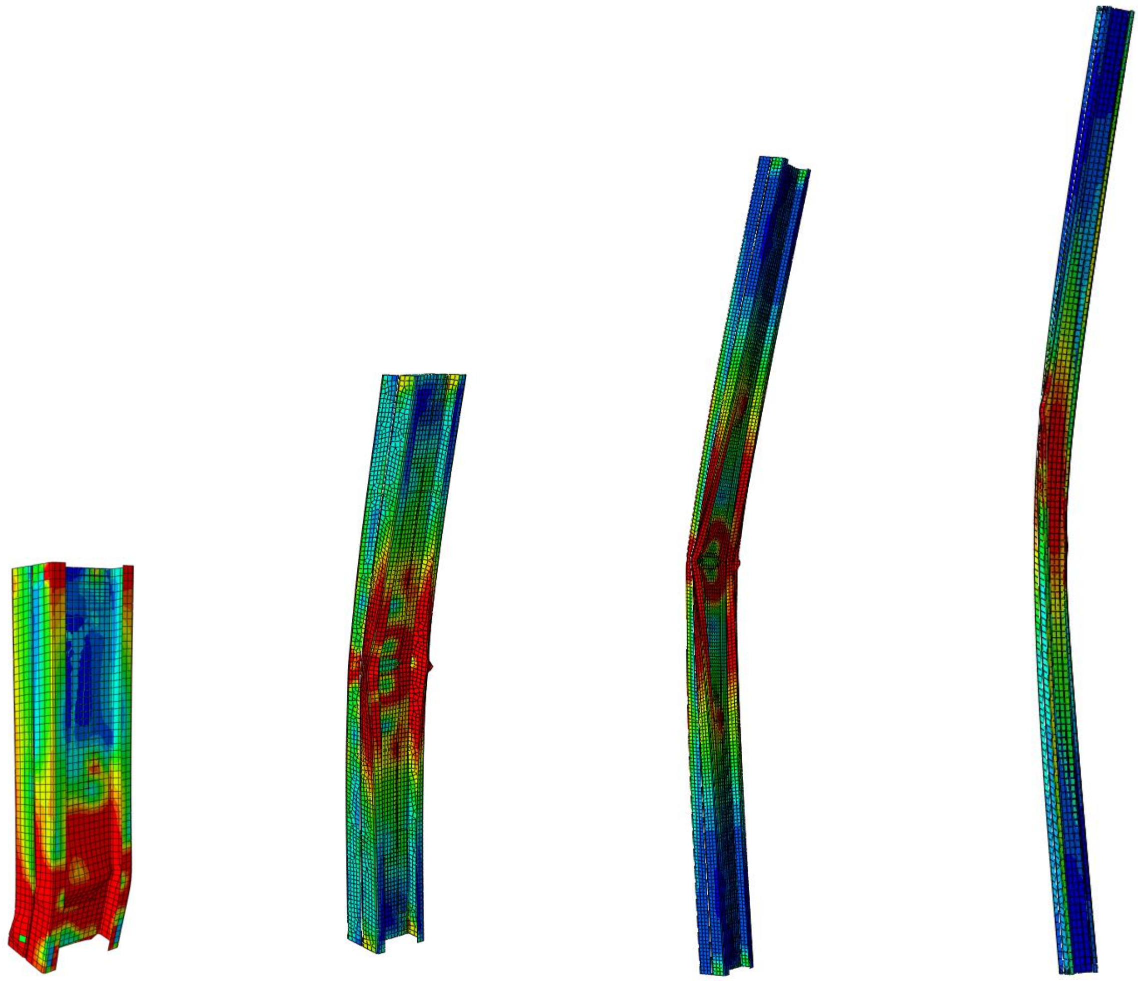
Specimen	Web	Flange	Length	Thickness	Spacing	FEA results	AISI design strengths	
	A'	B'	L	t	S	P_{EXP}	P_{FEA}	P_{EXP}/P_{FEA}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	-
Stub								
BU90-S50-L300-1	91.3	49.8	277.0	1.20	50.0	139.7	148.1	0.94
BU90-S50-L300-2	91.8	49.7	272.0	1.19	49.8	139.0	146.0	0.95
BU90-S50-L300-3	92.9	49.4	261.0	1.21	50.0	138.2	146.4	0.94
BU90-S100-L300-1	90.8	49.7	262.0	1.20	99.9	134.6	138.8	0.97
BU90-S100-L300-2	90.6	49.5	268.0	1.18	100.0	134.3	142.3	0.94
BU90-S200-L300-1	90.7	49.4	273.5	1.18	201.0	132.3	142.9	0.93
BU90-S200-L300-2	90.7	49.4	269.5	1.20	199.0	132.4	141.7	0.93
BU90-S200-L300-3	89.5	48.3	280.5	1.20	199.0	131.9	144.0	0.92
Mean								0.94
COV								0.02
Short								
BU75-S100-L500-1	90.6	49.5	656.0	1.21	100.5	123.5	116.1	1.06
BU75-S100-L500-2	90.6	49.4	678.0	1.20	100.5	121.7	116.7	1.04
BU75-S200-L500-1	90.4	49.3	653.0	1.18	199.5	117.2	108.1	1.08
BU75-S200-L500-2	90.4	49.3	678.0	1.19	199.5	116.2	108.2	1.07
BU75-S200-L500-3	90.4	49.3	680.0	1.21	200.5	114.9	109.1	1.05
BU75-S400-L500-1	90.6	49.4	678.0	1.18	400.0	101.9	96.7	1.05
BU75-S400-L500-2	90.4	49.4	678.0	1.20	399.0	103.6	97.4	1.06
Mean								1.06
COV								0.01
Intermediate								
BU75-S225-L1000-1	90.8	49.6	1182	1.21	225.0	58.5	50.3	1.16
BU75-S225-L1000-2	90.6	49.6	1132	1.20	225.0	58.1	49.5	1.17
BU75-S450-L1000-1	90.6	49.7	1130	1.21	450.0	55.0	45.1	1.22
BU75-S450-L1000-2	90.4	49.7	1182	1.18	448.0	53.8	44.5	1.21
BU75-S450-L1000-3	90.5	49.8	1180	1.19	452.0	53.2	43.6	1.22
BU75-S900-L1000-1	90.5	49.6	1131	1.20	897.0	51.0	42.6	1.20
BU75-S900-L1000-2	91.0	49.3	1182	1.21	899.0	49.9	41.3	1.21
BU75-S900-L1000-3	90.1	49.2	1129	1.22	896.0	49.9	42.1	1.19
Mean								1.20
COV								0.02
Slender								
BU75-S475-L2000-1	90.6	49.5	2164	1.20	474.2	16.4	13.2	1.24
BU75-S475-L2000-2	90.7	49.4	2172	1.20	466.6	16.5	13.8	1.19
BU75-S950-L2000-1	90.5	49.5	2169	1.18	960.4	13.5	11.5	1.17
BU75-S950-L2000-2	90.4	49.2	2148	1.17	949.3	11.4	9.8	1.16
BU75-S1900-L2000-1	90.5	49.3	2158	1.18	1902.4	12.0	10.7	1.12
BU75-S1900-L2000-2	90.9	49.7	2152	1.19	1906.7	10.8	9.5	1.14
Mean								1.17
COV								0.04

Table 3 Continued
(b) BU90
(ii) Ferritic EN1.4003

Specimen	Web	Flange	Length	Thickness	Spacing	FEA results	AISI design strengths	
	A’	B’	L	t	S	P_{EXP}	P_{FEA}	P_{EXP}/P_{FEA}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	-
Stub								
BU90-S50-L300-1	91.3	49.8	277.0	1.20	50.0	124.3	130.3	0.95
BU90-S50-L300-2	91.8	49.7	272.0	1.19	49.8	123.7	128.5	0.96
BU90-S50-L300-3	92.9	49.4	261.0	1.21	50.0	123.0	128.8	0.95
BU90-S100-L300-1	90.8	49.7	262.0	1.20	99.9	119.8	122.1	0.98
BU90-S100-L300-2	90.6	49.5	268.0	1.18	100.0	119.5	125.2	0.95
BU90-S200-L300-1	90.7	49.4	273.5	1.18	201.0	117.7	125.8	0.94
BU90-S200-L300-2	90.7	49.4	269.5	1.20	199.0	117.8	124.7	0.94
BU90-S200-L300-3	89.5	48.3	280.5	1.20	199.0	117.4	126.7	0.93
Mean								0.95
COV								0.02
Short								
BU75-S100-L500-1	90.6	49.5	656.0	1.21	100.5	108.7	101.0	1.08
BU75-S100-L500-2	90.6	49.4	678.0	1.20	100.5	107.1	101.5	1.05
BU75-S200-L500-1	90.4	49.3	653.0	1.18	199.5	103.1	94.0	1.10
BU75-S200-L500-2	90.4	49.3	678.0	1.19	199.5	102.3	94.1	1.09
BU75-S200-L500-3	90.4	49.3	680.0	1.21	200.5	101.1	94.9	1.07
BU75-S400-L500-1	90.6	49.4	678.0	1.18	400.0	93.5	84.1	1.11
BU75-S400-L500-2	90.4	49.4	678.0	1.20	399.0	94.5	85.0	1.11
Mean								1.09
COV								0.02
Intermediate								
BU75-S225-L1000-1	90.8	49.6	1182	1.21	225.0	49.7	46.3	1.07
BU75-S225-L1000-2	90.6	49.6	1132	1.20	225.0	49.4	45.6	1.08
BU75-S450-L1000-1	90.6	49.7	1130	1.21	450.0	46.8	43.6	1.07
BU75-S450-L1000-2	90.4	49.7	1182	1.18	448.0	45.7	42.3	1.08
BU75-S450-L1000-3	90.5	49.8	1180	1.19	452.0	45.2	42.1	1.07
BU75-S900-L1000-1	90.5	49.6	1131	1.20	897.0	43.4	39.2	1.11
BU75-S900-L1000-2	91.0	49.3	1182	1.21	899.0	40.4	38.0	1.06
BU75-S900-L1000-3	90.1	49.2	1129	1.22	896.0	40.4	38.7	1.04
Mean								1.08
COV								0.02
Slender								
BU75-S475-L2000-1	90.6	49.5	2164	1.20	474.2	13.3	12.4	1.07
BU75-S475-L2000-2	90.7	49.4	2172	1.20	466.6	13.0	11.9	1.10
BU75-S950-L2000-1	90.5	49.5	2169	1.18	960.4	10.7	10.1	1.06
BU75-S950-L2000-2	90.4	49.2	2148	1.17	949.3	10.1	9.7	1.04
BU75-S1900-L2000-1	90.5	49.3	2158	1.18	1902.4	9.5	8.9	1.07
BU75-S1900-L2000-2	90.9	49.7	2152	1.19	1906.7	9.4	8.7	1.08
Mean								1.07
COV								0.02

Table 3 Continued
(b) BU90
(iii) Austenitic EN1.4404

Specimen	Web	Flange	Length	Thickness	Spacing	FEA results	AISI design strengths	
	A’	B’	L	t	S	P_{EXP}	P_{FEA}	P_{EXP}/P_{FEA}
	(mm)	(mm)	(mm)	(mm)	(mm)	(kN)	(kN)	-
Stub								
BU90-S50-L300-1	91.3	49.8	277.0	1.20	50.0	118.1	122.5	0.96
BU90-S50-L300-2	91.8	49.7	272.0	1.19	49.8	117.5	120.8	0.97
BU90-S50-L300-3	92.9	49.4	261.0	1.21	50.0	116.9	121.1	0.97
BU90-S100-L300-1	90.8	49.7	262.0	1.20	99.9	113.8	114.8	0.99
BU90-S100-L300-2	90.6	49.5	268.0	1.18	100.0	113.5	117.7	0.96
BU90-S200-L300-1	90.7	49.4	273.5	1.18	201.0	111.8	118.3	0.95
BU90-S200-L300-2	90.7	49.4	269.5	1.20	199.0	111.9	117.2	0.95
BU90-S200-L300-3	89.5	48.3	280.5	1.20	199.0	111.5	119.1	0.94
Mean								0.96
COV								0.02
Short								
BU75-S100-L500-1	90.6	49.5	656.0	1.21	100.5	102.2	96.0	1.06
BU75-S100-L500-2	90.6	49.4	678.0	1.20	100.5	100.7	96.4	1.04
BU75-S200-L500-1	90.4	49.3	653.0	1.18	199.5	96.9	89.3	1.09
BU75-S200-L500-2	90.4	49.3	678.0	1.19	199.5	96.2	89.4	1.08
BU75-S200-L500-3	90.4	49.3	680.0	1.21	200.5	95.0	90.2	1.05
BU75-S400-L500-1	90.6	49.4	678.0	1.18	400.0	87.9	79.9	1.10
BU75-S400-L500-2	90.4	49.4	678.0	1.20	399.0	88.8	80.8	1.10
Mean								1.07
COV								0.02
Intermediate								
BU75-S225-L1000-1	90.8	49.6	1182	1.21	225.0	46.2	42.6	1.09
BU75-S225-L1000-2	90.6	49.6	1132	1.20	225.0	45.9	42.0	1.10
BU75-S450-L1000-1	90.6	49.7	1130	1.21	450.0	43.5	40.1	1.09
BU75-S450-L1000-2	90.4	49.7	1182	1.18	448.0	42.5	38.9	1.09
BU75-S450-L1000-3	90.5	49.8	1180	1.19	452.0	42.0	38.7	1.09
BU75-S900-L1000-1	90.5	49.6	1131	1.20	897.0	38.6	36.1	1.07
BU75-S900-L1000-2	91.0	49.3	1182	1.21	899.0	37.6	35.0	1.07
BU75-S900-L1000-3	90.1	49.2	1129	1.22	896.0	37.6	35.6	1.06
Mean								1.08
COV								0.01
Slender								
BU75-S475-L2000-1	90.6	49.5	2164	1.20	474.2	12.0	11.0	1.08
BU75-S475-L2000-2	90.7	49.4	2172	1.20	466.6	11.7	10.6	1.10
BU75-S950-L2000-1	90.5	49.5	2169	1.18	960.4	9.6	9.0	1.07
BU75-S950-L2000-2	90.4	49.2	2148	1.17	949.3	9.1	8.6	1.05
BU75-S1900-L2000-1	90.5	49.3	2158	1.18	1902.4	8.6	7.9	1.08
BU75-S1900-L2000-2	90.9	49.7	2152	1.19	1906.7	8.5	7.7	1.09
Mean								1.08
COV								0.02



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

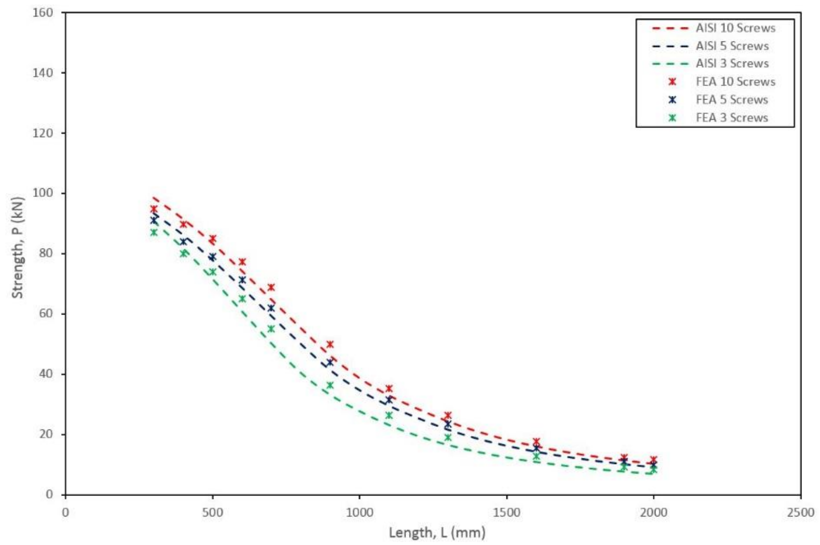
Fig. 12 Back-to-back built-up cold-formed stainless-steel lipped channels at failure (Duplex EN1.4462)

reduction occurred for all columns beyond 1000 mm length. The failure modes of duplex grade of built-up stainless-steel lipped channels are shown in Fig. 12.

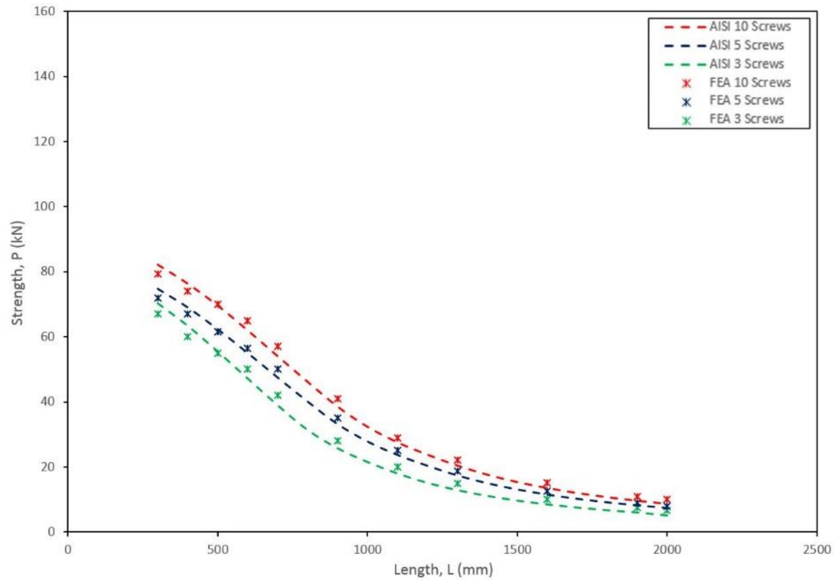
The effect of screw spacing was investigated. As can be seen, three different numbers of screws were considered: ten, five and three number of screws. The lengths of the built-up columns were varied from 300 mm to 2000 mm. The axial capacities obtained from the FEA were compared against the design strengths of the built-up stainless-steel columns and presented in Tables 4(a) and 4(b) for BU75 and BU90, respectively for all three grades of stainless-steel built-up channels. In case of stub columns, increasing the number of screws had negligible effect on the axial strength of built-up channels for all three grades of stainless-steel columns. While for the case of short and intermediate columns, the axial strength of the built-up columns was significantly dependent on the number of screws connecting the back-to-back built-up cold-formed stainless-steel lipped channels for all three grades of stainless-steel. In the case of short columns, when the spacing of the screws was doubled, the axial strength of the duplex built-up columns were reduced by around 7 to 13%, whereas for ferritic and austenitic grades of stainless-steel built-up channels, a strength reduction of 10-16% occurred, when the screw spacing was doubled. The axial strength of intermediate columns was decreased by around 12 to 17% when the screw spacing was doubled for duplex grade, while a strength reduction of 14 to 19% was observed, when the screw spacing was doubled for ferritic and austenitic grades of stainless-steel built-up lipped channels. On the other hand, there was little effect of screw spacing on the axial strength of slender columns as they failed primarily in global buckling mode.

6. Comparison against the current design guidelines

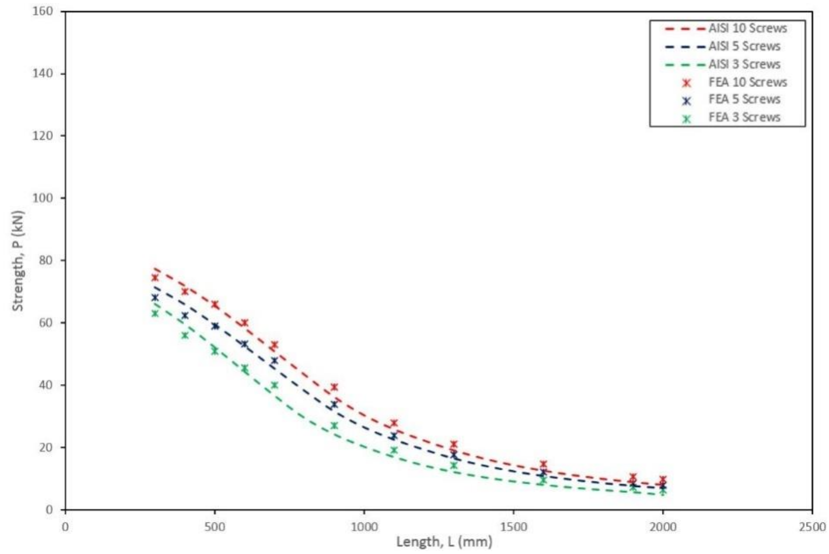
Tables 3(a) and 3(b) show the comparison of axial strength calculated from the AISI (2016) and AS/NZS (2018) and finite element analysis for all three grades of BU75 and BU90, respectively. As can be seen, the AISI (2016) and AS/NZS (2018) are safe while predicting the axial strength of back-to-back built-up cold-formed stainless-steel lipped channels for all three grades of short, intermediate and slender columns. However, for stub



(i) Duplex EN1.4462



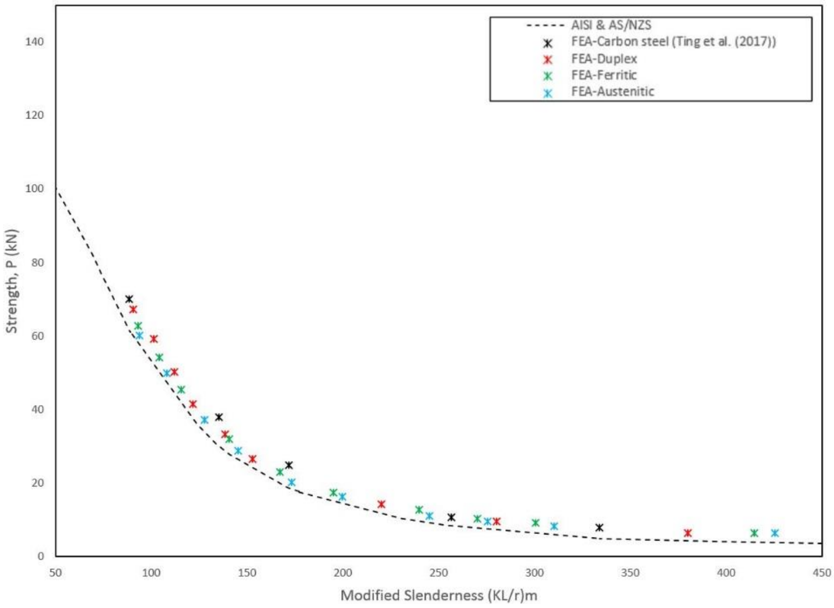
(ii) Ferritic EN1.4003



(iii) Austenitic EN1.4404

(a) Variation of strength against length

Fig. 13 Effect of varying number of screws and slenderness for BU75



(b) Variation of strength against modified slenderness

Fig. 13 Continued

columns which were mainly failed by local buckling, the AISI (2016) and AS/NZS (2018) are un-conservative by approximately 6% for all three grades of stainless-steel built-up channels.

Fig. 13(a) shows the variation of strength against the length for all three grades of stainless steel for BU75 series.

Table 4 Finite element and AISI strength with varying length of the section for 3, 5 and 10 number of screw

(a) BU75

(i) Duplex EN1.4462

Specimen	Web	Flange	Lip	Length	Spacing(s) For			Failure mode(s)	$P_{AISI/AS/NZ}$ for			P_{FEA} for		
	A'	B'	C'	L	3 screws	5 screws	10 screws		3 screws	5 screws	10 screws	3 screws	5 screws	10 screws
	mm	mm	mm	mm	mm	mm	mm		kN	kN	kN	kN	kN	kN
BU75-L300	73.6	19.8	11.2	300	75.00	50.00	27.27	Local	90.70	93.54	98.62	87.11	91.20	94.81
BU75-L400	73.6	19.8	11.2	400	100.00	66.67	36.36	Local	81.78	86.37	91.63	80.33	84.12	89.70
BU75-L500	73.6	19.8	11.2	500	125.00	83.33	45.45	Local	71.61	77.97	83.52	74.41	79.22	85.23
BU75-L600	73.6	19.8	11.2	600	150.00	100.00	54.55	Local + Distortional	60.90	68.83	74.37	65.22	71.41	77.48
BU75-L700	73.6	19.8	11.2	700	175.00	116.67	63.64	Local + Distortional	50.29	59.40	64.85	55.40	62.30	68.81
BU75-L800	73.6	19.8	11.2	800	200.00	133.33	72.73	Local + Overall	40.50	50.12	55.37	45.01	53.14	59.42
BU75-L900	73.6	19.8	11.2	900	225.00	150.00	81.82	Local + Overall	33.24	41.42	46.21	36.43	44.21	50.11
BU75-L1000	73.6	19.8	11.2	1000	250.00	166.67	90.91	Overall	27.79	34.72	38.75	31.12	37.25	41.62
BU75-L1100	73.6	19.8	11.2	1100	275.00	183.33	100.00	Local + Overall	23.24	29.55	33.00	26.47	31.53	35.43
BU75-L1200	73.6	19.8	11.2	1200	300.00	200.00	109.09	Overall	19.52	25.38	28.45	22.52	26.91	30.63
BU75-L1300	73.6	19.8	11.2	1300	325.00	216.67	118.18	Local + Overall	16.64	21.63	24.42	19.14	23.44	26.49
BU75-L1400	73.6	19.8	11.2	1400	350.00	233.33	127.27	Overall	14.34	18.65	21.06	16.84	20.48	23.47
BU75-L1500	73.6	19.8	11.2	1500	375.00	250.00	136.36	Local + Overall	12.50	16.24	18.35	14.85	17.64	20.48
BU75-L1600	73.6	19.8	11.2	1600	400.00	266.67	145.45	Overall	10.98	14.28	16.12	12.80	15.47	17.80
BU75-L1700	73.6	19.8	11.2	1700	425.00	283.33	154.55	Overall	9.73	12.65	14.28	11.82	13.62	16.27
BU75-L1800	73.6	19.8	11.2	1800	450.00	300.00	163.64	Overall	8.68	11.28	12.74	10.41	12.40	14.21
BU75-L1900	73.6	19.8	11.2	1900	475.00	316.67	172.73	Overall	7.79	10.12	11.43	9.23	11.13	12.43
BU75-L2000	73.6	19.8	11.2	2000	500.00	333.33	181.82	Overall	7.03	9.14	10.32	8.41	10.12	11.86

Table 4 Continued
(a) BU75
(ii) Ferritic EN1.4003

Specimen	Web	Flange	Lip	Length	Spacing(s) For			Failure mode(s)	$P_{AISI/AS/NZ}$ for			P_{FEA} for		
	A’	B’	C’	L	3 screws	5 screws	10 screws		3 screws	5 screws	10 screws	3 screws	5 screws	10 screws
	mm	mm	mm	mm	mm	mm	mm		kN	kN	kN	kN	kN	kN
BU75-L300	73.6	19.8	11.2	300	75.00	50.00	27.27	Local	70.29	74.83	81.01	67.12	72.04	79.41
BU75-L400	73.6	19.8	11.2	400	100.00	66.67	36.36	Local	63.38	69.10	75.26	60.14	67.11	74.30
BU75-L500	73.6	19.8	11.2	500	125.00	83.33	45.45	Local + Distortional	55.50	62.38	68.60	55.23	61.50	70.05
BU75-L600	73.6	19.8	11.2	600	150.00	100.00	54.55	Local	47.20	55.06	61.09	50.05	56.42	65.12
BU75-L700	73.6	19.8	11.2	700	175.00	116.67	63.64	Local + Distortional	38.97	47.52	54.04	42.45	50.62	57.17
BU75-L800	73.6	19.8	11.2	800	200.00	133.33	72.73	Local + Overall	31.39	40.09	46.15	34.20	41.81	48.41
BU75-L900	73.6	19.8	11.2	900	225.00	150.00	81.82	Overall	25.76	33.14	38.51	28.19	35.18	41.20
BU75-L1000	73.6	19.8	11.2	1000	250.00	166.67	90.91	Overall	21.54	27.77	32.29	24.28	29.63	34.52
BU75-L1100	73.6	19.8	11.2	1100	275.00	183.33	100.00	Local + Overall	18.01	23.64	27.50	20.50	25.60	29.39
BU75-L1200	73.6	19.8	11.2	1200	300.00	200.00	109.09	Local + Overall	15.13	20.31	23.71	17.46	21.84	24.98
BU75-L1300	73.6	19.8	11.2	1300	325.00	216.67	118.18	Local + Overall	12.89	17.30	20.35	15.60	18.70	22.16
BU75-L1400	73.6	19.8	11.2	1400	350.00	233.33	127.27	Overall	11.12	14.92	17.55	13.13	16.45	19.22
BU75-L1500	73.6	19.8	11.2	1500	375.00	250.00	136.36	Overall	9.68	13.00	15.29	11.44	14.40	16.89
BU75-L1600	73.6	19.8	11.2	1600	400.00	266.67	145.45	Overall	8.51	11.42	13.44	10.20	12.51	15.24
BU75-L1700	73.6	19.8	11.2	1700	425.00	283.33	154.55	Overall	7.54	10.12	11.90	8.61	11.48	13.42
BU75-L1800	73.6	19.8	11.2	1800	450.00	300.00	163.64	Overall	6.73	9.02	10.62	8.42	10.43	12.46
BU75-L1900	73.6	19.8	11.2	1900	475.00	316.67	172.73	Overall	6.04	8.10	9.53	7.50	9.12	11.12
BU75-L2000	73.6	19.8	11.2	2000	500.00	333.33	181.82	Overall	5.10	7.31	8.60	6.71	8.27	10.08

(iii) Austenitic EN1.4404

Specimen	Web	Flange	Lip	Length	Spacing(s) For			Failure mode(s)	$P_{AISI/AS/NZ}$ for			P_{FEA} for		
	A’	B’	C’	L	3 screws	5 screws	10 screws		3 screws	5 screws	10 screws	3 screws	5 screws	10 screws
	mm	mm	mm	mm	mm	mm	mm		kN	kN	kN	kN	kN	kN
BU75-L300	73.6	19.8	11.2	300	75.00	50.00	27.27	Local	66.08	71.54	77.41	63.03	68.11	74.60
BU75-L400	73.6	19.8	11.2	400	100.00	66.67	36.36	Local	59.58	66.05	71.93	56.14	62.52	70.12
BU75-L500	73.6	19.8	11.2	500	125.00	83.33	45.45	Local + Distortional	52.17	59.63	65.56	51.18	59.20	66.20
BU75-L600	73.6	19.8	11.2	600	150.00	100.00	54.55	Local + Distortional	44.37	52.64	58.38	45.62	53.35	60.15
BU75-L700	73.6	19.8	11.2	700	175.00	116.67	63.64	Local + Overall	36.63	45.43	50.91	38.44	48.08	53.14
BU75-L800	73.6	19.8	11.2	800	200.00	133.33	72.73	Local + Overall	29.51	38.33	43.47	32.39	40.32	45.88
BU75-L900	73.6	19.8	11.2	900	225.00	150.00	81.82	Local + Overall	24.21	31.68	36.28	26.45	34.18	39.36
BU75-L1000	73.6	19.8	11.2	1000	250.00	166.67	90.91	Overall	20.25	26.55	30.42	21.92	28.09	32.67
BU75-L1100	73.6	19.8	11.2	1100	275.00	183.33	100.00	Local + Overall	16.93	22.60	25.91	18.57	24.20	27.98
BU75-L1200	73.6	19.8	11.2	1200	300.00	200.00	109.09	Local + Overall	14.22	19.41	22.34	15.88	21.35	25.05
BU75-L1300	73.6	19.8	11.2	1300	325.00	216.67	118.18	Local + Overall	12.12	16.54	19.17	13.81	17.69	21.22
BU75-L1400	73.6	19.8	11.2	1400	350.00	233.33	127.27	Overall	10.45	14.26	16.53	11.99	15.61	18.15
BU75-L1500	73.6	19.8	11.2	1500	375.00	250.00	136.36	Overall	9.10	12.42	14.40	10.40	13.69	16.21
BU75-L1600	73.6	19.8	11.2	1600	400.00	266.67	145.45	Overall	8.00	10.92	12.66	9.41	12.28	14.67
BU75-L1700	73.6	19.8	11.2	1700	425.00	283.33	154.55	Overall	7.09	9.67	11.21	8.23	10.70	12.83
BU75-L1800	73.6	19.8	11.2	1800	450.00	300.00	163.64	Overall	6.32	8.63	10.00	7.60	9.82	11.77
BU75-L1900	73.6	19.8	11.2	1900	475.00	316.67	172.73	Overall	5.67	7.74	8.98	7.21	8.64	10.69
BU75-L2000	73.6	19.8	11.2	2000	500.00	333.33	181.82	Overall	4.79	6.99	8.10	6.50	7.97	9.93

Table 4 Continued
(b) BU90
(i) Duplex EN1.4462

Specimen	Web	Flange	Lip	Length	Spacing(s) For			Failure mode(s)	$P_{AISI/AS/NZ}$ for			P_{FEA} for		
	A’	B’	C’	L	3 screws	5 screws	10 screws		3 screws	5 screws	10 screws	3 screws	5 screws	10 screws
	mm	mm	mm	mm	mm	mm	mm		kN	kN	kN	kN	kN	kN
BU75-L300	90.4	49.4	14.6	300	75.00	50.00	27.27	Local	143.99	146.69	150.88	138.41	143.90	147.51
BU75-L400	90.4	49.4	14.6	400	100.00	66.67	36.36	Local	129.82	135.45	140.19	126.40	131.98	137.22
BU75-L500	90.4	49.4	14.6	500	125.00	83.33	45.45	Local+ Distortional	113.67	122.28	127.78	118.25	124.33	129.60
BU75-L600	90.4	49.4	14.6	600	150.00	100.00	54.55	Local+ Distortional	96.68	107.93	113.78	101.42	120.14	116.54
BU75-L700	90.4	49.4	14.6	700	175.00	116.67	63.64	Local + Distortional	79.83	93.13	99.22	89.89	98.42	104.61
BU75-L800	90.4	49.4	14.6	800	200.00	133.33	72.73	Local	64.30	78.60	84.72	72.41	84.98	88.64
BU75-L900	90.4	49.4	14.6	900	225.00	150.00	81.82	Local + Distortional	52.76	64.96	70.70	60.48	70.90	77.31
BU75-L1000	90.4	49.4	14.6	1000	250.00	166.67	90.91	Local + Overall	44.11	54.45	59.29	49.68	58.38	64.45
BU75-L1100	90.4	49.4	14.6	1100	275.00	183.33	100.00	Local + Overall	36.89	46.33	50.49	41.53	49.69	54.89
BU75-L1200	90.4	49.4	14.6	1200	300.00	200.00	109.09	Overall	30.99	39.81	43.53	36.46	43.87	47.89
BU75-L1300	90.4	49.4	14.6	1300	325.00	216.67	118.18	Overall	26.41	33.92	37.37	32.66	38.11	42.06
BU75-L1400	90.4	49.4	14.6	1400	350.00	233.33	127.27	Local+ Overall	22.77	29.24	32.22	23.13	33.18	38.70
BU75-L1500	90.4	49.4	14.6	1500	375.00	250.00	136.36	Local+ Overall	19.84	25.48	28.07	22.07	28.29	31.61
BU75-L1600	90.4	49.4	14.6	1600	400.00	266.67	145.45	Overall	17.43	22.40	24.67	20.89	25.19	28.91
BU75-L1700	90.4	49.4	14.6	1700	425.00	283.33	154.55	Overall	15.44	19.83	21.86	19.09	23.36	26.09
BU75-L1800	90.4	49.4	14.6	1800	450.00	300.00	163.64	Overall	13.78	17.69	19.49	17.54	21.48	23.64
BU75-L1900	90.4	49.4	14.6	1900	475.00	316.67	172.73	Overall	12.36	15.88	17.49	15.48	19.54	20.88
BU75-L2000	90.4	49.4	14.6	2000	500.00	333.33	181.82	Overall	11.16	14.32	15.79	13.13	17.29	17.93

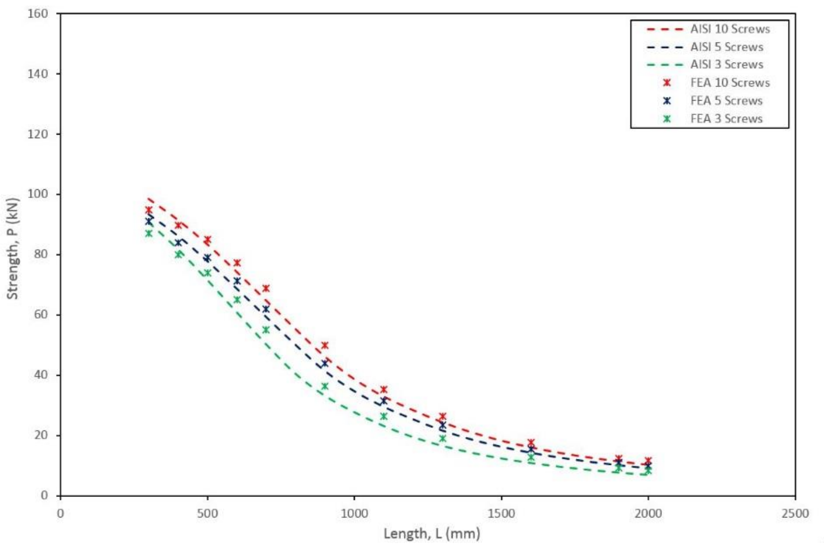
(ii) Ferritic EN1.4003

Specimen	Web	Flange	Lip	Length	Spacing(s) For			Failure mode(s)	$P_{AISI/AS/NZ}$ for			P_{FEA} for		
	A’	B’	C’	L	3 screws	5 screws	10 screws		3 screws	5 screws	10 screws	3 screws	5 screws	10 screws
	mm	mm	mm	mm	mm	mm	mm		kN	kN	kN	kN	kN	kN
BU75-L300	90.4	49.4	14.6	300	75.00	50.00	27.27	Local	121.43	127.01	132.92	118.41	124.60	130.41
BU75-L400	90.4	49.4	14.6	400	100.00	66.67	36.36	Local	109.48	117.28	123.50	109.23	118.44	123.54
BU75-L500	90.4	49.4	14.6	500	125.00	83.33	45.45	Local	95.87	105.88	112.57	101.52	107.91	115.48
BU75-L600	90.4	49.4	14.6	600	150.00	100.00	54.55	Local+ Distortional	81.53	93.46	100.24	87.94	95.48	104.65
BU75-L700	90.4	49.4	14.6	700	175.00	116.67	63.64	Local + Distortional	67.32	80.66	87.41	73.95	84.27	90.25
BU75-L800	90.4	49.4	14.6	800	200.00	133.33	72.73	Local	54.22	68.05	75.65	63.47	72.45	78.48
BU75-L900	90.4	49.4	14.6	900	225.00	150.00	81.82	Local + Distortional	44.50	56.24	63.13	49.82	59.48	67.24
BU75-L1000	90.4	49.4	14.6	1000	250.00	166.67	90.91	Local + Overall	37.20	47.14	52.94	41.46	50.21	56.89
BU75-L1100	90.4	49.4	14.6	1100	275.00	183.33	100.00	Local + Overall	31.11	40.12	45.08	34.51	42.50	48.21
BU75-L1200	90.4	49.4	14.6	1200	300.00	200.00	109.09	Local+ Overall	26.14	34.17	38.87	29.78	37.85	41.25
BU75-L1300	90.4	49.4	14.6	1300	325.00	216.67	118.18	Overall	22.27	29.37	33.37	25.42	32.48	36.26
BU75-L1400	90.4	49.4	14.6	1400	350.00	233.33	127.27	Local+ Overall	19.20	25.32	28.77	22.45	27.42	31.87
BU75-L1500	90.4	49.4	14.6	1500	375.00	250.00	136.36	Local+ Overall	16.73	22.06	25.06	19.62	23.74	26.87
BU75-L1600	90.4	49.4	14.6	1600	400.00	266.67	145.45	Overall	14.70	19.39	22.32	17.87	21.48	24.58
BU75-L1700	90.4	49.4	14.6	1700	425.00	283.33	154.55	Overall	13.02	17.17	19.77	15.42	18.71	21.84
BU75-L1800	90.4	49.4	14.6	1800	450.00	300.00	163.64	Overall	11.62	15.32	17.64	13.45	16.45	23.09
BU75-L1900	90.4	49.4	14.6	1900	475.00	316.67	172.73	Overall	10.43	13.75	15.83	12.48	14.98	20.48
BU75-L2000	90.4	49.4	14.6	2000	500.00	333.33	181.82	Overall	9.41	12.40	14.29	11.23	14.21	16.48

Table 4 Continued
(b) BU90
(iii) Austenitic EN1.4404

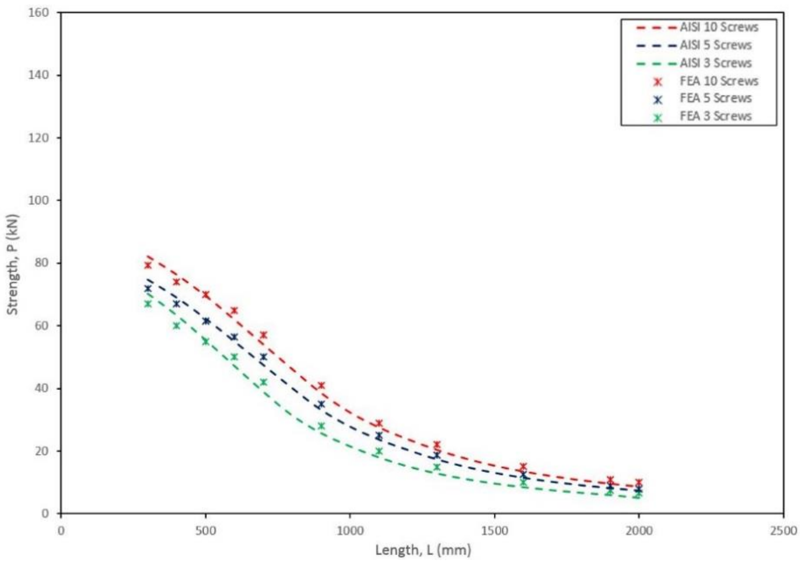
Specimen	Web	Flange	Lip	Length	Spacing(s) For			Failure mode(s)	$P_{AISI/AS/NZ}$ for			P_{FEA} for		
	A’	B’	C’	L	3 screws	5 screws	10 screws		3 screws	5 screws	10 screws	3 screws	5 screws	10 screws
	mm	mm	mm	mm	mm	mm	mm		kN	kN	kN	kN	kN	kN
BU75-L300	90.4	49.4	14.6	300	75.00	50.00	27.27	Local	115.36	121.93	126.27	111.29	118.37	123.23
BU75-L400	90.4	49.4	14.6	400	100.00	66.67	36.36	Local	104.01	112.59	117.33	101.41	112.48	116.65
BU75-L500	90.4	49.4	14.6	500	125.00	83.33	45.45	Local	91.08	101.64	106.94	95.42	102.51	109.63
BU75-L600	90.4	49.4	14.6	600	150.00	100.00	54.55	Local + Distortional	77.45	89.72	95.23	82.47	91.45	97.86
BU75-L700	90.4	49.4	14.6	700	175.00	116.67	63.64	Local + Distortional	63.96	77.43	83.04	69.47	80.83	86.14
BU75-L800	90.4	49.4	14.6	800	200.00	133.33	72.73	Local + Distortional	51.51	65.33	71.86	59.45	67.87	74.50
BU75-L900	90.4	49.4	14.6	900	225.00	150.00	81.82	Local + Distortional	42.27	53.99	59.97	46.81	57.02	64.18
BU75-L1000	90.4	49.4	14.6	1000	250.00	166.67	90.91	Local + Overall	35.37	45.26	50.29	38.92	48.19	54.24
BU75-L1100	90.4	49.4	14.6	1100	275.00	183.33	100.00	Local + Overall	29.55	38.51	42.83	32.43	40.84	46.03
BU75-L1200	90.4	49.4	14.6	1200	300.00	200.00	109.09	Overall	24.83	33.09	36.93	27.04	35.88	40.09
BU75-L1300	90.4	49.4	14.6	1300	325.00	216.67	118.18	Overall	21.16	28.19	31.70	23.88	31.10	34.21
BU75-L1400	90.4	49.4	14.6	1400	350.00	233.33	127.27	Local+ Overall	18.24	24.31	27.33	20.89	26.48	30.48
BU75-L1500	90.4	49.4	14.6	1500	375.00	250.00	136.36	Local+ Overall	15.89	21.18	23.81	18.42	22.75	25.59
BU75-L1600	90.4	49.4	14.6	1600	400.00	266.67	145.45	Local+ Overall	13.97	18.61	21.20	15.19	20.27	23.77
BU75-L1700	90.4	49.4	14.6	1700	425.00	283.33	154.55	Overall	12.37	16.49	18.78	14.47	17.95	20.82
BU75-L1800	90.4	49.4	14.6	1800	450.00	300.00	163.64	Overall	11.04	14.71	16.75	12.84	15.89	18.97
BU75-L1900	90.4	49.4	14.6	1900	475.00	316.67	172.73	Overall	9.91	13.20	15.04	11.42	14.31	17.85
BU75-L2000	90.4	49.4	14.6	2000	500.00	333.33	181.82	Overall	8.94	11.91	13.57	10.53	13.63	15.66

Fig. 13 also shows the strengths predicted by the AISI (2016) and AS/NZS (2018). As can be seen from Table 4, the AISI (2016) and AS/NZS (2018) are un-conservative for the stub column but conservative for short, intermediate and slender columns for all three grades of stainless-steel built-up lipped channels considered in this paper. The mean value of P_{EXP}/P_{AISI} for stub columns of duplex grade built-up column is 0.93 with a corresponding coefficient of variation (COV) of 0.03 for BU75 series. The corresponding mean values of P_{EXP}/P_{AISI} for short, intermediate and slender columns of duplex grade built-up channels are 1.10, 1.20 and 1.19, respectively, with coefficients of

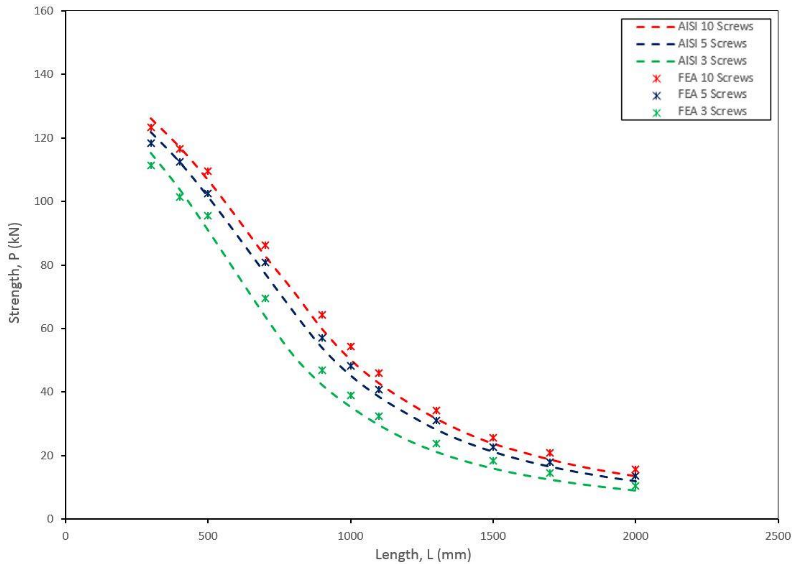


(i) Duplex EN1.4462

Fig. 14 Effect of varying number of screws and slenderness for BU90

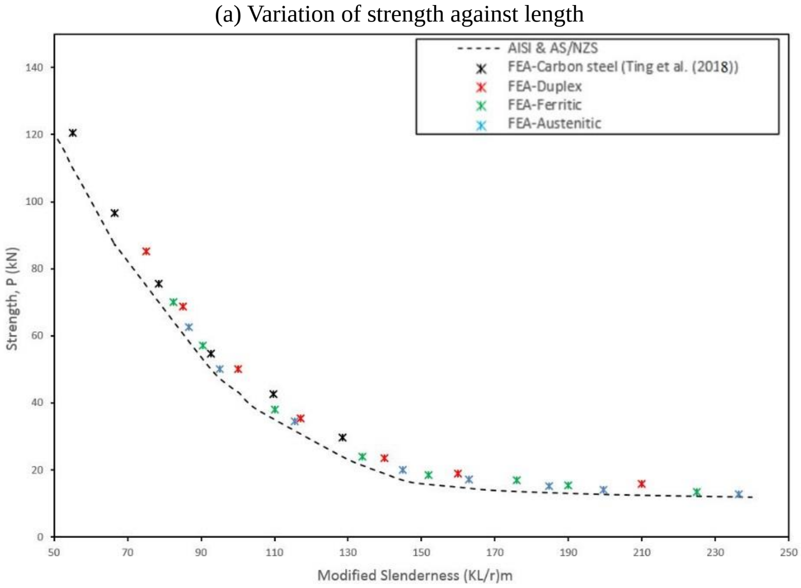


(ii) Ferritic EN1.4003



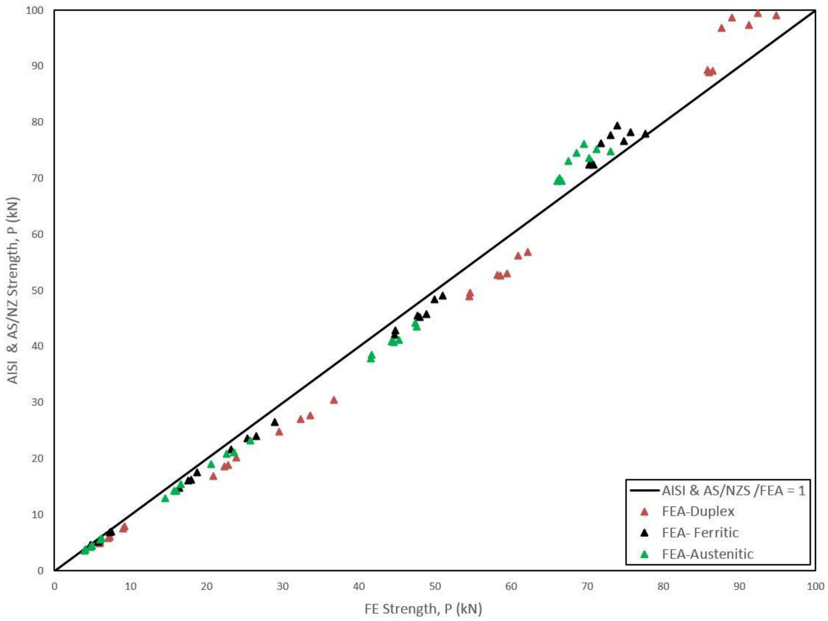
(iii) Austenitic EN1.4404

(a) Variation of strength against length

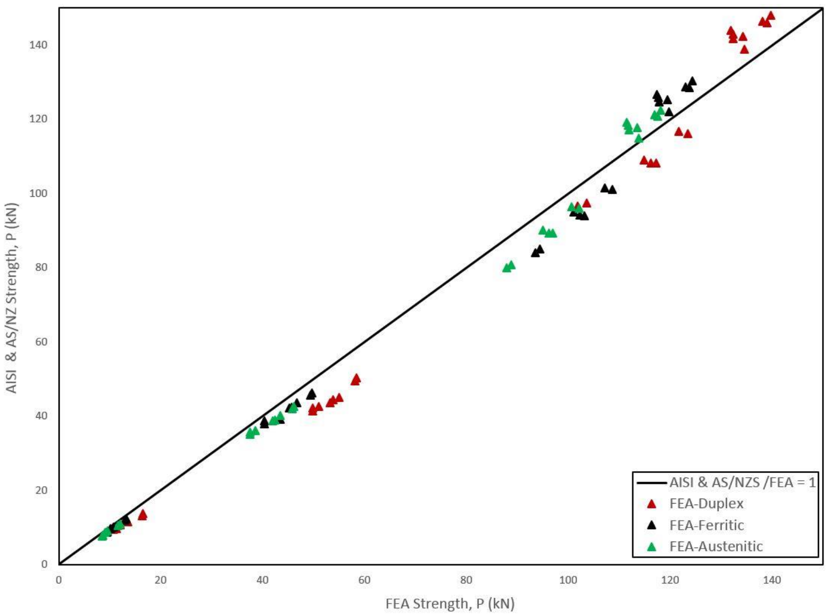


(b) Variation of strength against modified slenderness

Fig. 14 Continued



(a) BU75



(b) BU90

Fig. 15 Comparison of FEA strength and design strength (AISI & AS/NZ standards) for stainless steel built-up ipped channels

variation (COVs) of 0.01, 0.03 and 0.02, respectively for BU75series. The same information is provided in Tables 3(a) and (b) for ferritic EN1.4003 and austenitic EN1.4404 grades of stainless-steel built-up lipped channels for BU75 and BU90. From Figs. 13(a) and (b), the columns having modified slenderness's less than 34 failed mainly by local buckling, while the columns having modified slenderness's greater than 61.4 failed through overall buckling.

Fig. 14 shows the axial strength of BU90 sections with varying length and modified slenderness's for all three grades of stainless-steel built-up lipped channels. As mentioned previously, for both BU75 and BU90 sections, stub column strengths were overestimated by the AISI (2016) and AS/NZS (2018). However, for other length of the columns; axial strengths are over-conservative as per the AISI (2016) and AS/NZS (2018) (Fig. 15).

7. Conclusions

This paper presents a finite element investigation into the behavior of cold-formed stainless-steel built-up lipped channels, connected back-to-back. A non-linear FE model was developed which includes material non-linearity, initial imperfections, modeling of intermediate fasteners and corner strength enhancements of the stainless-steel sections. Also, significant strain hardening of the stainless-steel channels in tension and compression was considered. The finite element model was validated against the experimental test results available in the literature on back-to-back built-up cold-formed stainless-steel channels.

This validated finite element model was used to perform an extensive parametric study to investigate the effect of screw spacing on the axial strength of such back-to-back built-up cold-formed stainless-steel lipped channels under compression. Three different grades of stainless steel i.e., duplex EN1.4462, ferritic EN1.4003 and austenitic EN1.4404 were considered in the parametric study. From the results of the parametric study, it was found that for stub and slender columns of all three grades of stainless-steel, the screw spacing had negligible effect on the axial strength. However, for short and intermediate stainless-steel columns, axial capacity was reduced approximately by (7-16)% and (12-19)%, respectively when the screw spacing was doubled as they acted less integrally. The axial strength of stainless-steel built-up columns determined from the finite element analysis was compared against the design strengths calculated in accordance with the current AISI &AS/NZS. The obtained comparison showed that that the current design guidelines by AISI & AS/NZS can be conservative by around (10-20)% for all three grades of stainless-steel built-up lipped channels, which were failed through either overall buckling or a combination of local and overall buckling.

References

ABAQUS (2018), Version 6.14-2, USA: SIMULIA, Providence, RI, USA.

Afshan, S., Rossi, B. and Gardner, L. (2013), "Strength enhancements in cold-formed structural sections — Part I: Material testing", *J. Constr. Steel Res.*, **83**, 177-188. https://doi.org/10.1016/j.jcsr.2012.12.008

American Iron and Steel Institute (2012), North American specification for the design of cold-formed Steel Structural Members; NAS S100.

American Society of Civil Engineers (2002), Specification for the design of cold-formed stainless steel structural members; SEI/ASCE 8-02.

Ananthi, G., Roy, K. and Lim, J.B. (2019), "Experimental and numerical investigations on axial strength of back-to-back built-up cold-formed steel angle columns", *Steel Compos. Struct.*, *Int. J.*, **31**(6), 601-615. https://doi.org/10.12989/scs.2019.31.6.601

Anbarasu, M., Kanagarasu, K. and Sukumar, S. (2015), "Investigation on the behaviour and strength of cold-formed steel web stiffened built-up battened columns", *Mater. Struct.*, **48**(12),4029-4038. https://doi.org/10.1617/s11527-014-0463-8

Arrayago, I., Real, E. and Gardner, L. (2015), "Description of stress–strain curves for stainless steel alloys", *Mater. Des.*, **87**, 540-552. https://doi.org/10.1016/j.matdes.2015.08.001

Ashraf, M., Gardner, L. and Nethercot, D.A. (2005), "Strength enhancement of the corner regions of stainless steel cross-sections", *J. Constr. Steel Res.*, **61**(1), 37-52. https://doi.org/10.1016/j.jcsr.2004.06.001

Aslani, F. and Goel, S.C. (1991), "An analytical criterion for buckling strength of built-up compression members", *J. Struct. Eng. Am. Soc. Civil Engr.*,**28**(4), 159-168.

Baddoo, N.R. (2008), "Stainless steel in construction: a review of research, applications, challenges and opportunities", *J. Constr. Steel Res.*, **64**(11), 1199-1206. https://doi.org/10.1016/j.jcsr.2008.07.011

Becque, J. and Rasmussen, K.J. (2009), "Experimental investigation of the interaction of local and overall buckling of stainless steel I-columns", *J. Struct. Eng. Am. Soc. Civil Engr.*, **135**(11), 1340-1348. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000051

Biggs, K.A., Ramseyer, C., Ree, S. and Kang, T.H.K. (2015), "Experimental testing of cold-formed built-up members in pure compression", *Steel Compos. Struct.*, *Int. J.*, **18**(6), 1331-1351. https://doi.org/10.12989/scs.2015.18.6.1331

BS EN (2001), Tensile testing of metallic materials method of test at ambient temperature; British Standards Institution.

Chen, J. and Young, B. (2006), "Stress–strain curves for stainless steel at elevated temperatures", *Eng. Struct.*, **28**, 229-239. https://doi.org/10.1016/j.engstruct.2005.07.005

Chen, B., Roy, K., Uzzaman, A., Raftery, G.M., Nash, D., Clifton, G.C., Pouladi, P. and Lim, J.B. (2019), "Effects of edge-stiffened web openings on the behaviour of cold-formed steel channel sections under compression", *Thin-Wall. Struct.*, **144**, 106307. https://doi.org/10.1016/j.tws.2019.106307

Dabaon, M., Ellobody, E. and Ramzy, K. (2015), "Nonlinear behavior of built-up cold-formed steel section battened columns", *J. Constr. Steel Res.*, **110**, 16-28. https://doi.org/10.1016/j.jcsr.2015.03.007

Dai, X. and Lam, D. (2010), "Axial compressive behaviour of stub concrete-filled columns with elliptical stainless steel hollow sections", *Steel Compos. Struct.*, *Int. J.*, **10**(6), 517-539. https://doi.org/10.12989/scs.2010.10.6.517

Dar, M.A., Sahoo, D.R., Pulikkal, S. and Jain, A.K. (2018a), "Behaviour of laced built-up cold-formed steel columns: Experimental investigation and numerical validation", *Thin-Wall. Struct.*, **132**, 398-409. https://doi.org/10.1016/j.tws.2018.09.012

Dar, M.A., Subramanian, N., Anbarasu, M., Dar, A.R. and Lim, J.B. (2018b), "Structural performance of cold-formed steel composite beams", *Steel Compos. Struct.*, *Int. J.*, **27**(5), 545-554. https://doi.org/10.12989/scs.2018.27.5.545

Dar, M.A., Subramanian, N., Dar, A.R., Anbarasu, M., Lim, J.B. and Atif, M. (2019), "Behaviour of partly stiffened cold-formed steel built-up beams: Experimental investigation and numerical validation", *Adv. Struct. Eng.*, **22**(1), 172-186. https://doi.org/10.1177/1369433218782767

Darcy, G. and Mahendran, M. (2008), "Development of a new cold-formed steel building system", *Adv. Struct. Eng.*, **11**(6), 661-677. https://doi.org/10.1260/136943308787543621

Dobrić, J., Marković, Z., Buđevac, D., Spremić, M. and Fric, N. (2018a), "Resistance of cold-formed built-up stainless steel columns – Part I: Experiment", *J. Constr. Steel Res.*, **145**, 552-572. https://doi.org/10.1016/j.jcsr.2018.02.026

Dobrić, J., Pavlović, M., Marković, Z., Buđevac, D. and Spremić, M. (2018b), "Resistance of cold-formed built-up stainless steel columns – Part II: Numerical simulation", *J. Constr. Steel Res.*, **140**, 247-260. https://doi.org/10.1016/j.jcsr.2017.10.032

Fan, S., Liu, F., Zheng, B., Shu, G. and Tao, Y. (2014), "Experimental study on bearing capacity of stainless steel lipped C section stub columns", *Thin-Wall. Struct.*, **83**, 70-84. https://doi.org/10.1016/j.tws.2014.02.002

Fratamico, D.C., Torabian, S., Zhao, X., Rasmussen, K.J. and Schafer, B.W. (2018), "Experiments on the global buckling and collapse of built-up cold-formed steel columns", *J. Constr. Steel Res.*, **144**, 65-80. https://doi.org/10.1016/j.jcsr.2018.01.007

Gardner, L. and Nethercot, D.A. (2004a), "Experiments on stainless steel hollow sections – Part 2: Member behaviour of columns and beams", *J. Constr. Steel Res.*, **60**(9), 1319-1332. https://doi.org/10.1016/j.jcsr.2003.11.007

Gardner, L. and Nethercot, D.A. (2004b), "Numerical modeling of stainless steel structural components—a consistent approach", *J. Struct. Eng. Am. Soc. Civil Engr.*, **130**(10), 1586-1601.

https://doi.org/10.1061/(ASCE)0733-9445(2004)130:10(1586)

Gardner, L., Talja, A. and Baddoo, N.R. (2006), "Structural design of high-strength austenitic stainless steel", *Thin-Wall. Struct.*, **44**(5), 517-528. https://doi.org/10.1016/j.tws.2006.04.014

Hasan, M.J., Ashraf, M. and Uy, B. (2017), "Moment-rotation behaviour of top-seat angle bolted connections produced from austenitic stainless", *J. Constr. Steel Res.*, **136**, 149-161. https://doi.org/10.1016/j.jcsr.2017.05.014

Jiang, L., Feng, Y., Zhou, W. and He, B. (2018), "Analysis on natural vibration characteristics of steel-concrete composite truss beam", *Steel Compos. Struct.*, *Int. J.*, **26**(1), 79-87. https://doi.org/10.12989/scs.2018.26.1.079

Kanishchev, R. and Kvočák, V. (2019), "Local buckling of rectangular steel tubes filled with concrete", *Steel Compos. Struct.*, *Int. J.*, **31**(2), 201-216. https://doi.org/10.12989/scs.2019.31.2.201

Kiymaz, G. and Seckin, E. (2014), "Behavior and design of stainless steel tubular member welded end connections", *Steel Compos. Struct.*, *Int. J.*, **17**(3), 253-269. https://doi.org/10.12989/scs.2014.17.3.253

Lawson, R.M., Way, A.G., Heywood, M., Lim, J.B., Johnston, R. and Roy, K. (2019), "Stability of light steel walls in compression with plasterboards on one or both sides", *Proceedings of the Institution of Civil Engineers – Structures and Building*, https://doi.org/10.1680/jstbu.18.00118

Macdonald, M., Rhodes, J. and Kotelko, M. (2007), "Stainless steel stub columns subject to combined bending and axial loading", *Thin-Wall. Struct.*, **45**(10-11), 893-897. https://doi.org/10.1016/j.tws.2007.08.044

Mathison, C., Roy, K., Clifton, G.C., Ahmadi, A., Masood, R. and Lim, J.B. (2019), "Novel pin jointed moment connection for cold-formed steel trusses", *Steel Compos. Struct., Int. J.*, **31**(5), 453-467. https://doi.org/10.12989/scs.2019.31.5.453

Rasmussen, K.J.R. and Hancock, G.J. (1993), "Design of cold-formed stainless steel tubular members. I: columns", *J. Struct. Eng.Am. Soc. Civil Engr.*, **119**(8), 2349-2367. https://doi.org/10.1061/(ASCE)0733-9445(1993)119:8(2368)

Reyes, W. and Guzmán, A. (2011), "Evaluation of the slenderness ratio in built-up cold formed box sections", *J. Constr. Steel Res.*, **67**(6), 929-935. https://doi.org/10.1016/j.jcsr.2011.02.003

Rossi, B., Afshan, S. and Gardner, L. (2013), "Strength enhancements in cold-formed structural sections — Part II: Predictive models", *J. Constr. Steel Res.*, **83**, 189-196. https://doi.org/10.1016/j.jcsr.2012.12.007

Roy, K. and Lim, J.B. (2019), "Numerical investigation into the buckling behaviour of face-to-face built-up cold-formed stainless steel channel sections under axial compression", *Structures*, **20**, 42-73. https://doi.org/10.1016/j.istruc.2019.02.019

Roy, K., Lau, H.H. and Lim, J.B. (2018a), "Numerical investigations on the axial capacity of back-to-back gapped built-up cold-formed stainless steel channels", *Adv. Struct. Eng.*, **22**(10), 2289-2310. https://doi.org/10.1177/1369433219837390

Roy, K., Ting, T.C.H., Lau, H.H. and Lim, J.B. (2018b), "Nonlinear behavior of axially loaded back-to-back built-up cold-formed steel un-lipped channel sections", *Steel Compos. Struct., Int. J.*, **28**(2), 233-250. https://doi.org/10.12989/scs.2018.28.2.233

Roy, K., Ting, T.C.H., Lau, H.H. and Lim, J.B. (2018c), "Effect of thickness on the behaviour of axially loaded back-to-back cold-formed steel built-up channel sections - Experimental and numerical investigation", *Structures*, **16**, 327-346. https://doi.org/10.1016/j.istruc.2018.09.009

Roy, K., Ting, T.C., Lau, H.H. and Lim, J.B. (2018d), "Effect of screw spacing into the behaviour of back-to-back cold-formed duplex stainless steel built-up channel sections under compression", *Proceedings of the International Conference on Engineering Research and Practice for Steel Construction 2018* (*ICSC2018*), Hong Kong, China, September.

Roy, K., Ting, T.C.H., Lau, H.H. and Lim, J.B. (2018e), "Nonlinear behaviour of back-to-back gapped built-up cold-formed steel channel sections under compression", *J. Constr. Steel Res.*, **147**, 257-276. https://doi.org/10.1016/j.jcsr.2018.04.007

Roy, K., Mohammadjani, C. and Lim, J.B. (2019a), "Experimental and numerical investigation into the behaviour of face-to-face built-up cold-formed steel channel sections under compression", *Thin-Wall. Struct.*, **134**, 291-309. https://doi.org/10.1016/j.tws.2018.09.045

Roy, K., Ting, T.C.H., Lau, H.H. and Lim, J.B. (2019b), "Experimental and numerical investigations on the axial capacity of cold-formed steel built-up box sections", *J. Constr. Steel Res.*, **160**, 411-427. https://doi.org/10.1016/j.jcsr.2019.05.038

Roy, K., Lim, J.B., Lau, H.H., Yong, P.M., Clifton, G.C., Wrzesien, A. and Mei, C.C. (2019c), "Collapse behaviour of a fire engineering designed single-storey cold- formed steel building in severe fires", *Thin-Wall. Struct.*, **140**, 340-357. https://doi.org/10.1016/j.tws.2019.04.046

Schafer, B.W. (2002), "Local, distortional and euler buckling of thin-walled columns", *J. Struct. Eng. Am. Soc. Civil Engr.*, **128**(3), 289-299. https://doi.org/10.1061/(ASCE)0733-9445(2002)128:3(289)

Standards Australia (2005), Cold-Formed Steel Structures; AS/NZS 4600:2005, Standards Australia/ Standards New Zealand.

Stone, T.A. and LaBoube, R.A. (2005), "Behaviour of cold-formed steel built-up I-sections", *Thin-Wall. Struct.*, **43**(12), 1805-1817. https://doi.org/10.1016/j.tws.2005.09.001

Theofanous, M., Chan, T.M. and Gardner, L. (2009), "Structural response of stainless steel oval hollow section compression members", *Eng. Struct.*, **31**(4), 922-934. https://doi.org/10.1016/j.engstruct.2008.12.002

Ting, T.C.H., Roy, K., Lau, H.H. and Lim, J.B. (2018), "Effect of screw spacing on behavior of axialy loaded back-to-back cold-formed steel built-up channel sections", *Adv. Struct. Eng.*, **21**(3), 474-487. https://doi.org/10.1177/1369433217719986

Whittle, J. and Ramseyer, C. (2009), "Buckling capacities of axially loaded, cold-formed, built-up channels", *Thin-Wall. Struct.*, **47**(2), 190-201. https://doi.org/10.1016/j.tws.2008.05.014

Yang, L., Zhao, M., Chan, T.M., Shang, F. and Xu, D. (2016), "Flexural buckling of welded austenitic and duplex stainless steel I-section columns", *J. Constr. Steel Res.*, **122**, 339-353. https://doi.org/10.1016/j.jcsr.2016.04.007

Young, B. and Chen, J. (2008), "Design of cold-formed steel built-up closed sections with intermediate stiffeners", *J. Struct. Eng.Am. Soc. Civil Engr.*, **134**(5), 727-737. https://doi.org/10.1061/(ASCE)0733-9445(2008)134:5(727)

Young, B. and Liu, Y. (2003), "Experimental investigation of cold-formed stainless steel columns", *J. Struct. Eng.Am. Soc. Civil Engr.*, **129**(2), 169-176. https://doi.org/10.1061/(ASCE)0733-9445(2003)129:2(169)

Yuan, H.X., Wang, Y.Q., Shi, Y.J. and Gardner, L. (2014), "Stub column tests on stainless steel built-up sections", *Thin-Wall. Struct.*, **83**, 103-114. https://doi.org/10.1016/j.tws.2014.01.007

Zhang, J.H. and Young, B. (2012), "Compression tests of cold-formed steel I-shaped open sections with edge and web stiffeners", *Thin-Wall. Struct.*, **52**, 1-11. https://doi.org/10.1016/j.tws.2011.11.006

Zhou, F., Chen, Y. and Young, B. (2013), "Cold-formed high strength stainless steel cross-sections in compression considering interaction effects of constituent plate elements", *J. Constr. Steel*

Res., **80**, 32-41.
https://doi.org/10.1016/j.jcsr.2012.09.004

DL

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_y	Yield stress of the steel;
F_n	Critical buckling stress;
K	Effective length factor;
L	Overall length of the built-up columns;
$(KL/r)_{ms}$	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;
r_{yc}	Radius of gyration;