Steel and Composite Structures, *Vol. 18*, *No. 6* (*2015*) *1331-1351*
DOI: http://dx.doi.org/10.12989/scs.2015.18.6.1331

Experimental testing of cold-formed built-up members in pure compression

Kenneth A. Biggs [1a], Chris Ramseyer [1b],
Suhyun Ree [2c] and Thomas H.-K. Kang [*2]

[1] *School of Civil Engineering and Environmental Science, The University of Oklahoma, Norman, OK 73019, USA*
[2] *Department of Architecture and Architectural Engineering, Seoul National University, Seoul 151-744, Korea*

(*Received June 03, 2014, Revised November 16, 2014, Accepted November 24, 2014*)

Abstract. Cold-formed built-up members are compression members that are common in multiple areas of steel construction, which include cold-formed steel joints and stud walls. These members are vulnerable to unique buckling behaviors; however, limited experimental research has been done in this area. Give this gap, experimental testing of 71 built-up members was conducted in this study. The variations of the test specimens include multiple lengths, intermediate welds, orientations, and thicknesses. The experimental testing was devised to observe the different buckling modes of the built-up C-channels and the effects of the geometrical properties; to check for applicability of multiple intermediate welding patterns; and to evaluate both the 2001 and 2007 editions of the American Iron and Steel Institute (AISI) Specification for 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.

Keywords: cold-formed steel, axial compression, column, buckling, built-up steel sections

1. Introduction

For all of the uses of cold-formed steel elements, the ability to design an efficient and accurate member is vital (Kang *et al*. 2011, Anbarasu *et al*. 2013, Heva and Mahendran 2013, Phan *et al*. 2013, Piyawat *et al*. 2011, 2013, Valsa Ipe *et al*. 2013, Wehbe *et al*. 2013). A frequent use of cold-formed steel member is a built-up member, which is a member formed by connecting multiple steel members. Depending on how the members are connected, the built-up member can fail as individual members or as one single member. The analysis of these members comes from Sections C4 and D1.2 of the 2007 edition of the American Iron and Steel Institute (AISI) *North American Specification for the Design of Cold-Formed Steel Structural Members*. It is the purpose

*Corresponding author, Associate Professor, E-mail: tkang@snu.ac.kr
[a] Former Graduate Student
[b] Associate Professor
[c] Graduate Student

http://www.techno-press.org/?journal=scs&subpage=8 ISSN: 1229-9367 (Print), 1598-6233 (Online)

of this research to evaluate the current AISI-2007 Specification (AISI 2007) and previous AISI-2001 Specification (AISI 2001a) for various built-up members in pure axial compression.

Limited experimental research has been done in the area of cold-formed built-up members. According to the AISI-2001 Commentary (AISI 2001b), the built-up design section has been "substantially taken from research in hot-rolled built-up members connected with bolts or welds." However, the behavior of hot-rolled and cold-formed built-up members may be a lot different. Given this gap, an experimental program is carried out by performing axial load tests of 71 specimens of the cold-formed built-up members. The variations of the test specimens include multiple lengths, intermediate welds, orientations, and thicknesses. The testing is devised to observe the different buckling modes of the built-up C-channels and the effects of the geometrical properties such as thickness and width of the member. All of the built-up members have welds at each end of the specimen that are longer than the width of the C-channel, in accordance with the AISI-2001 or AISI-2007 Specification. The C-channels are welded together using 8 different welding patterns to check for applicability of multiple intermediate welding patterns.

2. AISI specification

2.1 AISI-2001 specification

The AISI 2001 *North American Specification for the Design of Cold Formed Steel Structural Members* includes Section C4.5 as a provision for the design of built-up members. Section C4.5 *Built-Up Members* is the only change in the design process between a built-up member and a single member according to AISI Specifications. Local, distortional, and global (flexural and flexural-torsional) buckling should be considered in the design of cold-formed steel columns of built-up sections; however, it is stated within the AISI 2001 Commentary (AISI 2001a) that "the modified slenderness ratio, $(KL/r)_m$, replaces KL/r in the *Specification* C4 for both flexural and torsional-flexural buckling." There was no modification factor in the AISI-2001 specification for any of the other forms of buckling that needs to be considered in the failure of cold-formed members.

According to the AISI-2001 Specification, it states that if a built-up member undergoes buckling that "involves relative deformations that produce shear forces in the connectors between individual shapes," the modification should be applied to determine the ultimate buckling capacity of the member (AISI 2001b). This means that the modification is required only when the two elements of the built-up member globally buckle separately from each other. The slenderness modification ratio, which is based on the effective length and the radius of gyration of the specimen, incorporates Euler buckling instabilities when two members are connected at discrete points (AISI 2001a).

The slenderness modification in Section C4.5 is used to decrease the ultimate buckling capacity of the built-up member, which is based on the slenderness ratio, intermediate attachment spacing, and the least radius of gyration of the individual member (AISI 2001b). According to the AISI-2001 Commentary, the built-up design section has been "substantially taken from research in hot-rolled built-up members connected with bolts or welds." However, the behavior of hot-rolled and cold-formed built-up members is drastically different since hot-rolled members nearly always buckle due to global or Euler buckling. Another highly contested issue with the AISI-2001 Specification was the uncertainty of the writing. The language infers that the slenderness modification is not a requirement unless the member "undergoes deformations that produce shear forces in the connectors" (AISI 2001a). However, with the complexities of thin-walled column buckling, it is difficult to determine the buckling modes that the member will experience during loading and if shear forces will be present in the connectors. The slenderness modification equation is shown in AISI-2001 C4.5 (Eq. C4.5-1) (AISI, 2001a) or in Eq. (1) of this paper as

$$\left(\frac{kL}{r}\right)_m = \sqrt{\left(\frac{kL}{r}\right)_o^2 + \left(\frac{a}{r_i}\right)^2} \tag{1}$$

where L is the length of the member; k is the effective length factor, r is the radius of gyration; (kL/r) is the overall slenderness ratio of the entire section about the built-up member axis; E is the modulus of elasticity of steel; $(kL/r)_m$ is the modified slenderness ratio for built-up sections; $(kL/r)_o$ is the overall (unmodified) slenderness ratio of the entire section about the built-up member axis; a is the intermediate fastener or spot weld spacing; r_i is the minimum radius of gyration of the full unreduced cross-sectional area of an individual shape in a built-up member.

The second provision of Section C4.5 limits the minimum strength and spacing (a) of intermediate attachments. The purpose of the spacing requirement is to "prevent the flexural buckling of the individual shape between intermediate connectors" (AISI 2001b). The ratio of the intermediate fastener spacing is not to exceed one-half of the built-up member's slenderness ratio, and the factor of one-half accounts for the possibility of a failed or ineffective attachment (AISI 2001a). Section C4.5(1) of AISI-2001 or Eq. (2) of this paper gives the fastener spacing provision as

$$\frac{a}{r_i} \le 0.5\left(\frac{kL}{r}\right)_o \tag{2}$$

In addition, the members end weld lengths are required to be at least the width of the member to prevent shear slip in the connections, and the intermediate fastener attachments are required to be able to carry a shear force of at least 2.5% of the total factored LRFD force (AISI 2001a).

2.2 AISI-2007 specification

Section C4.5 of AISI-2001 has been moved to D1.2 *Compression Members Composed to Two Sections in Contact* in the AISI-2007 Specification, that is, Eqs. (1) and (2) also apply to all built-up sections. Section C4 of the AISI-2007 Specification (AISI 2007) has been updated to address the issue of estimating the distortional, torsional and flexural-torsional buckling failure modes and capacities of cold-formed sections; however, the consideration of such buckling modes has made the AISI-2007 Specification quite complicated than the AISI-2001 Specification as shown in the following paragraphs.

The nominal axial strength (P_n) and nominal buckling stress (F_n) of the built-up cold-formed sections are given as

$$P_n = \text{smaller of } (A_e F_n \text{ and } P_{n\_distortional}) \tag{3}$$

$$F_n = \begin{cases} \left(0.658^{\lambda_c^2}\right) F_y : & \lambda_c \le 1.5 \\ \left(\dfrac{0.877}{\lambda_c^2}\right) F_y : & \lambda_c > 1.5 \end{cases} \tag{4}$$

$$\lambda_c^2 = \sqrt{\frac{F_y}{F_e}} \tag{5}$$

where A_e is the effective area; $P_{n\_distortional}$ is the distortional buckling strength; λ_c is the slenderness factor defining the transition from inelastic to elastic buckling, as calculated using Eq. (5); F_y is the yield stress; and F_e is the least of the applicable elastic flexural, torsional and flexural-torsional buckling stress. The flexural buckling stress is determined using Eq. (6), while the torsional or flexural-torsional buckling stress of doubly-symmetric sections is determined using Eq. (8). Note that although pure torsional buckling rarely controls, σ_t typically governs in Eq. (7), where σ_t is the torsional buckling stress as defined in Section C3.1.2.1 or C4.1.5 of AISI-2007 or in Eq. (8) of this paper.

$$F_e = \frac{\pi^2 E}{(kL/r)_m^2} \tag{6}$$

$$F_e = \text{smaller of } (\text{Eq. (6) and } \sigma_t) \tag{7}$$

$$\sigma_t = \frac{1}{Ar_o^2}\left[GJ + \frac{\pi^2 EC_w}{(K_t L_t)^2}\right] \tag{8}$$

where A is the full unreduced cross-sectional area; r_o is the polar radius of gyration of the cross-section about the shear center; G is the shear modulus; I is the Saint-Venant torsion constant; C_w is the torsional warping constant; K_t is the effective length factors for twisting; and L_t is the unbraced length of member for twisting.

The distortional buckling strength ($P_{n\_distortional}$) in Eq. (3) is calculated as follows

$$P_{n\_distortional} = \begin{cases} P_y(= A_g F_y) & : \ \lambda_d \le 0.561 \\ \left[1 - 0.25\left(\frac{P_{crd}}{P_y}\right)^{0.6}\right]\left(\frac{P_{crd}}{P_y}\right)^{0.6} P_y & : \ \lambda_d > 0.561 \end{cases} \tag{9}$$

$$\lambda_d = \sqrt{\frac{P_y}{P_{crd}}} \tag{10}$$

where A_g is the gross area of the cross-section; F_y is the yield stress; P_y (= $A_g F_y$) is the member yield strength; P_{crd} (= $A_g F_d$) is the distortional buckling load; and F_d is the elastic distortional buckling stress calculated in accordance with Section 4.2(b) of AISI-2007 for built-up sections as follows

$$F_d = \frac{k_{\varphi fe} + k_{\varphi we} + k_\varphi}{\tilde{k}_{\varphi fg} + \tilde{k}_{\varphi fe}} \tag{11}$$

where $k_{\varphi fe}$ is the elastic rotational stiffness provided by the flange to the flange/web junction in accordance with Eq. C3.1.4-13 of AISI-2007; $k_{\varphi we}$ (= $Et^3/[6h_o(1-\mu^2)]$) is the elastic rotational stiffness provided by the web to the flange/web juncture; h_o is the out-to-out web depth; μ is the Poisson's ratio; k_φ is the rotational stiffness provided by restraining elements to the flange/web junction of a member (zero if the flange is unrestrained); $\tilde{k}_{\varphi fe}$ is the geometric rotational stiffness (divided by F_d) demanded by the flange from the flange/web juncture in accordance with Eq. C3.1.4-15 of AISI-2007; and $\tilde{k}_{\varphi fg}$ is the geometric rotational stiffness (divided by F_d) demanded by the flange from the flange/web juncture in accordance with Eq. C4.2-12 of AISI-2007.

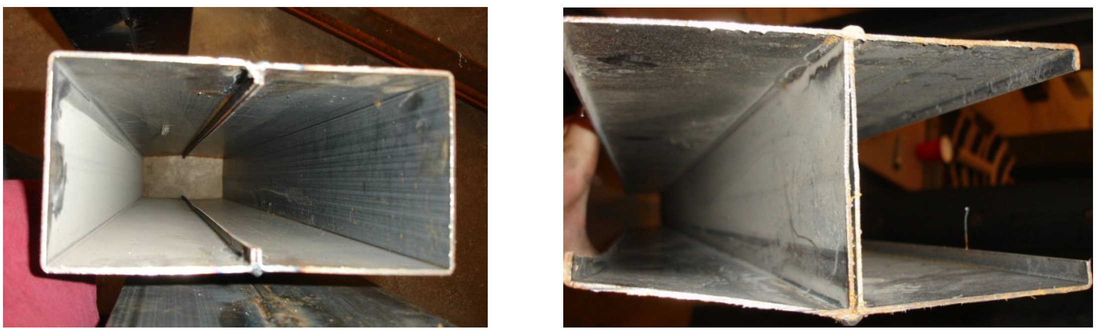
It is worth mentioning that the first equation in Eq. (4) does not govern the nominal axial strength for most of the "doubly-symmetric built-up" sections. Also, the distortional buckling equations (Eqs. (9) to (11)) govern only for the cases with relatively small effective length or slenderness ratio; however, the distortional buckling strength should always be calculated to be compared with other failure modes' equations (Eqs. (1) to (8)) according to Section C4 of AISI-2007. This may be quite cumbersome to the designers.

3. Experimental testing

3.1 Test description

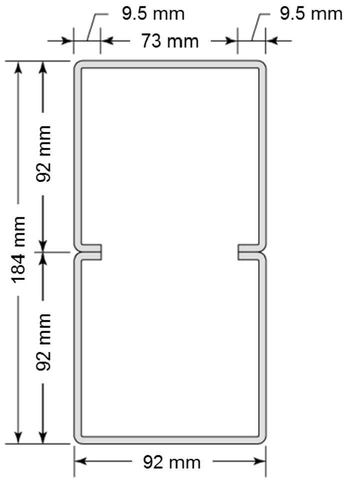
This research is a continuation of research started at the University of Oklahoma (Brueggen and Ramseyer 2005, Whittle and Ramseyer 2009), where 1.4 m long built-up sections and 1.8m long built-up sections with 67 mm width were tested. Therefore, in this study, 1 m long built-up sections and 1.8 m long built-up sections with 92 mm width were tested to cover the common range of design parameters. All built-up members were loaded in axial compression with pinned end connections. The members were tested in two different orientations, one with the C-channels facing each other to produce a closed shape (rectangular), and the other orientation with the members facing away (referred to as an I-shaped hereafter). Fig. 1 shows the rectangular and I-shaped orientations and Fig. 2 shows dimension for each section. Both orientations were tested to determine if orientation affects the failure pattern and if one orientation leads to a higher failure load than the other. The closed R-section provides exceptional torsional resistance, which could lead to an increased buckling capacity.

One test for each member type was used to determine each of the buckling strengths. A total of 71 experimental tests were conducted. Sixty specimens were unique and explored a different

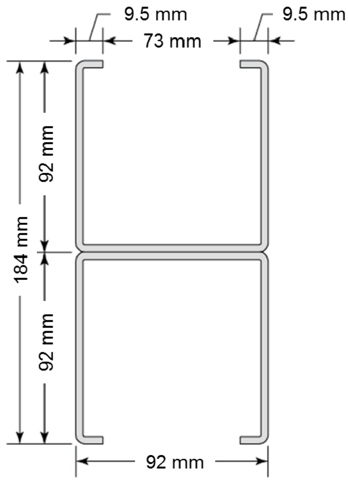


(a) (b)

Fig. 1 Rectangular and I-shaped orientations

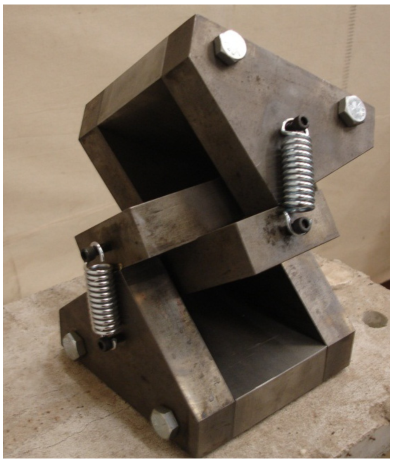


(a)

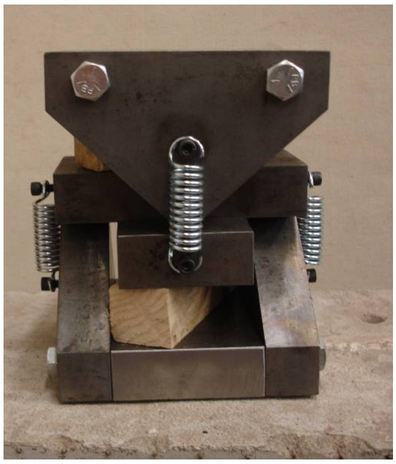


(b)

Fig. 2 Dimension for rectangular and I-shaped sections



(a)



(b)

Fig. 3 (a) Pivot free to rotate; and (b) Pivot restrained to show initial position

specimen type. At the conclusion of the 60 specimens tested, there was a repeat of 11 tests to confirm a truly pinned condition was used on all the testing. To confirm this, the 11 tests used a gimbel pivot shown in Fig. 3. The pivot represents a true pinned connection with an almost frictionless surface. This is required to have the effective length factor *k* equal to 1.0, which is used in the AISI-2007 Specification of the maximum buckling capacity. Fig. 3 shows the mobility of the pivot, which allows the test specimen to fail in either the strong or weak axis without an influence on the failure pattern.

Not all of the built-up members that were tested were in compliance with the fastener spacing requirements of the AISI-2007 Specification (Section D1.2). The reason for testing some members that did not meet the Specification requirements was to evaluate Section D1.2 of AISI-2007.

3.2 Specimen properties

All members that were tested were created from two, lipped C-channels which were connected by 102 mm (4 in.) long welds at the top and bottom, in accordance with AISI-2007 Section D1.2. There were also intermediate weld locations throughout the member which had a weld length of 25 mm (1 in.). The different intermediate weld patterns are shown in Fig. 4. All welds were approximately 4.8 mm (3/16 in.) thick. All intermediate welds were equally spaced throughout each member.

The thickness of the C-channels was a variable during the experimental testing. The thicknesses chosen were based off common built-up members used in cold-formed trusses. There were a total of three nominal thicknesses used in the testing which were 1.6, 2 and 2.5 mm (0.064, 0.08 and 0.1 in.). All of the members tested had a web length of 92 mm (3.625 in.) and were square in shape (i.e., flange width = 3.625 in. or 92 mm). This was the only web length investigated during the testing, because previous testing (Whittle and Ramseyer, 2009) focused on smaller web lengths of 41 and 67 mm (1.625 and 2.625 in.).

Besides the variable thickness, the change in the number of intermediate welds and member length made up the other varying factors in the built-up specimen. In addition to the locations of the intermediate welds described in Fig. 4, the welds were also tested on just a single side of the

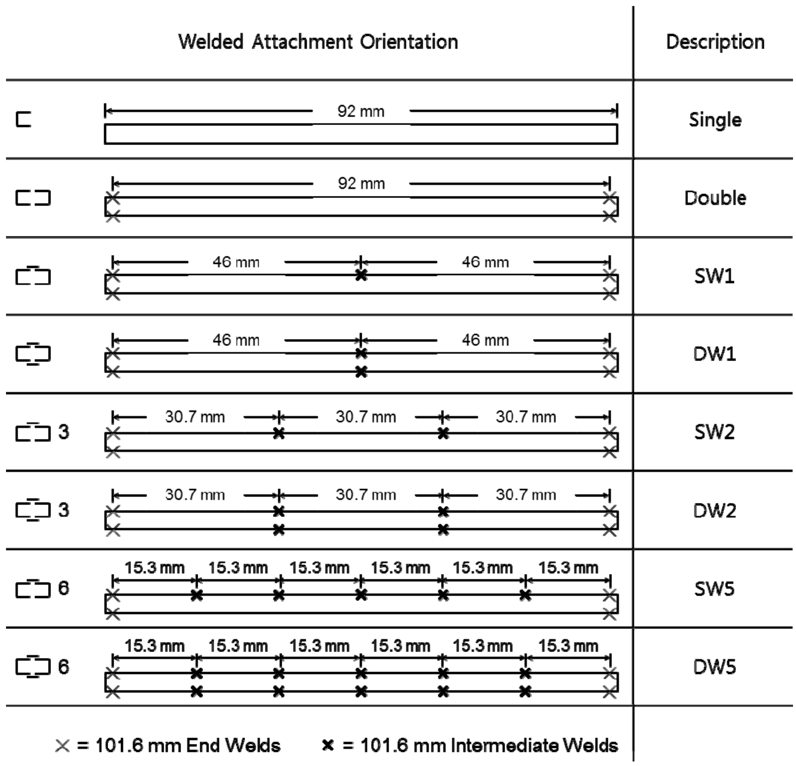


Fig. 4 Intermediate attachment orientations and descriptions

member and both sides of the member. There were two lengths of 1.8 and 1 m (71 and 42 in.) investigated during this research. The selection of the 1 m (71 in.) length was based on the previous research done by Whittle and Ramseyer (2009) to be able to compare results and see if the same trends were present. The 1 m (42 in.) length was chosen based on the elastic buckling model from the Cold-Formed Steel (CFS) program. The CFS program evaluates the members to determine at what lengths different buckling modes occur. It was determined that a 1 m (42 in.) member would provide the greatest chance of distortional buckling for all member thicknesses rather than the global buckling mode that occurred with the longer 1.8 m (71 in.) members.

3.3 Test setup

The tests were performed using 2 different setups. The first setup discussed is for the 1.8 m (71 in.) specimen. The loads were applied using a hand pump that is attached to a hydraulic pump, allowing the operator to easily control the rate of loading. On each end of the test is a greased swivel pivot which allows for a pinned connection and an effective length coefficient (k) value of 1. The member set between the two pivots in an upright position. The vertical displacement of the specimen is measured through an LVDT (Linear Variable Displacement Transducer) that is located at the bottom of the specimen below the pivoting head. The horizontal displacement is measured at third points on the specimen using strain gauges. The final instrument used was a load cell to measure the load applied to the built-up member. A 445 kN (100 kips) load cell was used for early testing; however, at higher loads a 1335 kN (300 kips) load cell was used. The chains were used for safety to prevent the specimen from propelling out of the test setup after failure had occurred.

The load on the 1 m (42 in.) sections was applied using a machine that evenly applies the load to the member instead of using a hand pump and hydraulic pump. The same pivots were used on each side of the built-up member and all of the same instruments were used to record the data to ensure consistency within the data.

3.4 Test procedure

Before fabricating some pieces, the geometric properties of the C-channels were taken to ensure that the channels meet certain tolerances. Material properties of the steel were obtained by carrying out coupon tests on each of the three thicknesses used (Table 1). The fabrication process involved multiple steps. The C-channels came in 3.7 m (144 in.) lengths, allowing multiple specimens to be made at one time. The first step was welding the two C-channels together. Clamps were placed throughout the specimen to ensure that the heat of the welds would not cause the member to spread apart before the C-channels could be fully welded together. The welding included the 102 mm (4 in.) long welds on each end of the specimen and 25 mm (1 in.) long welds at the intermediate attachments. The end welds were started 25 mm (1 in.) from the edge of the C-channels: this allowed the members to be cut on a band saw as one piece after the welding process to ensure the edges were flat and proper bearing on the pivots occurred. After welding, the members were cut to the proper lengths of 1 to 1.8 m (42 or 71 in.).

Before each member was placed in the test rig a plum bob was used to ensure that all pieces of the test setup were in line so the force on the member would be purely axial. The specimen was placed in the test rig with just enough pressure to hold the specimen still while at the same time allowing any final adjustments to be made to the specimen to line it up with the rest of the setup. A safety chain was connected from the specimen to a frame column behind the test setup. Finally, the

Table 1 Steel coupon test results

Specimen	Thickness (mm)	Original length (mm)	New length (mm)	Elongation (mm)	Area (mm^2)	P_y (kN)	P_u (kN)	F_y (MPa)	F_u (MPa)
1.6A	1.56	50.65	64.03	0.2643	20.1	9.72	11.35	490	571.9
1.6B	1.54	50.09	64.26	0.283	19.9	9.83	11.13	501.2	567
1.6C	1.53	51.44	64.69	0.2578	19.9	9.83	11.13	501.2	567.7
1.6_avg	-	-	-	-	-	-	-	497.5	568.9
2A	1.93	50.37	62.66	0.2441	25.5	10.8	14.24	429.8	567
2B	1.91	50.75	64.36	0.2683	25.3	10.8	14.14	432.6	567.7
2C	1.91	50.32	64.69	0.0286	24.8	10.5	13.8	431.9	566.3
2_avg	-	-	-	-	-	-	-	431.4	567
2.5A	2.5	51.38	65.51	0.2748	32.5	16.3	18.16	508.2	567
2.5B	2.57	50.5	64.21	0.2716	33.7	16.6	18.87	500.5	568.4
2.5B	2.56	51.38	64.59	0.257	33.7	16.5	18.81	499.1	567
2.5_avg	-	-	-	-	-	-	-	502.6	567.5

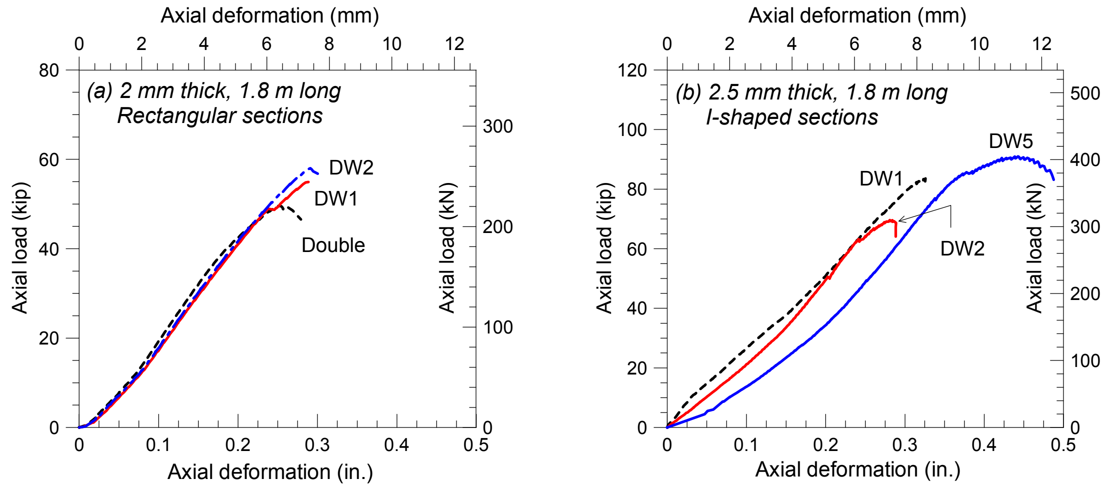
P_y = Yield axial load, P_u = Ultimate axial load; F_y = Yield stress; F_u = Ultimate stress

wire potentiometers for lateral displacement were magnetically connected to the specimen, and the LVDT for vertical displacement was connected to the bottom of the load cell. From a safe distance and location, the operator began to add the load using either the hand pump for the 1.8 m (71 in.) test or the machine for the 1 m (42 in.) test. The final buckling of the specimen was usually apparent by either the load vs. axial shorting graph or a sudden failure where the specimen would attempt to come out of the test rig after buckling.

4. Test results and analysis

4.1 Results and analysis of rectangular members

The axial load-displacement relations for the selected specimens are plotted in Fig. 4. The axial load was measured using a load cell, whereas the corresponding axial displacement was measured using an LVDT. An essentially linear relationship was revealed until buckling with small variation for most of the specimens. The maximum buckling capacity of the member, labeled P_{test}, was the largest axial load applied to the member when failure occurred. The nominal loads of the members, P_n, were calculated in accordance with AISI-2001 or AISI-2007 Specification Section C4 column design method (in combination with Section D1.2 built-up member slenderness modifications). The global buckling was considered in accordance to Section C4 of the AISI-2001 Specification, while all the buckling modes were considered in AISI-2007. The effective area (A_e) of each member was calculated with the applied load as the maximum test load, P_{test}. In all cases the effective area was lower than the gross area of the section. This reduction in area is to take into account the wide flange's susceptibility to multiple failure modes. The use of the effective area instead of the gross area gives a lower nominal axial strength and a more conservative value as seen in Eq. (3).



(a) (b)

Fig. 5 Measured axial load-displacement relations

Table 2 Comparison of maximum buckling load to nominal load (Rectangular members)

Length (m)	Section shape	Wth. (mm)	Thk. (mm)	Weld type	P_{test} (kN)	A_e (mm^2)	L/r_x	P_n (kN)		Buckling mode			P_{test} / P_n	
								P_{n_2001}	P_{n_2007}	Tested	AISI-2001	AISI-2007	P_{n_2001}	P_{n_2007}
1.8	Rec.	92	1.6	double	153.0	419	52.2	90.7	77.3	*F*	*I*	*F-T*	1.69	1.98
1.8	Rec.	92	1.6	SW1	161.9	429	52.2	134.4	103.5	*F*	*I*	*F-T*	1.20	1.56
1.8	Rec.	92	1.6	DW1	168.1	445	52.2	131.6	103.5	*F*	*I*	*F-T*	1.28	1.62
1.8	Rec.	92	1.6	SW2	159.8	411	52.2	146.5	103.5	*F*	*I*	*F-T*	1.09	1.54
1.8	Rec.	92	1.6	DW2	177.8	458	52.2	137.9	102.6	*F*	*I*	*F-T*	1.29	1.73
1.8	Rec.	92	1.6	SW5	173.3	439	52.2	146.7	103.5	*F*	*I*	*F-T*	1.18	1.68
1.8	Rec.	92	1.6	DW5	178.6	452	52.2	144.3	103.5	*F*	*I*	*F-T*	1.24	1.73
1.8	Rec.	92	2.0	double	220.6	748	51.9	159.3	105.5	*F*	*I*	*F-T*	1.38	2.09
1.8	Rec.	92	2.0	SW1	213.9	633	51.9	193.5	144.8	*F*	*I*	*F-T*	1.11	1.48
1.8	Rec.	92	2.0	DW1	244.3	723	51.9	184.0	144.8	*F*	*I*	*F-T*	1.33	1.69
1.8	Rec.	92	2.0	SW2	224.3	647	51.9	195.1	144.8	*F*	*I*	*F-T*	1.15	1.55
1.8	Rec.	92	2.0	DW2	258.0	745	51.9	184.7	144.8	*F*	*I*	*F-T*	1.40	1.78
1.8	Rec.	92	2.0	SW5	234.8	667	51.9	198.0	144.8	*F*	*I*	*F-T*	1.19	1.62
1.8	Rec.	92	2.0	DW5	273.0	776	51.9	182.9	144.8	*F*	*I*	*F-T*	1.49	1.89
1.8	Rec.	92	2.5	double	360.7	1122	45.7	170.9	156.1	*F*	*I*	*F-T*	2.11	2.31
1.8	Rec.	92	2.5	SW1	376.4	996	45.7	213.3	220.0	*F*	*I*	*F-T*	1.76	1.71
1.8	Rec.	92	2.5	DW1	388.4	1028	45.7	202.8	220.0	*D*	*I*	*F-T*	1.92	1.77
1.8	Rec.	92	2.5	SW2	449.3	1154	45.7	216.2	220.0	*F-T*	*I*	*F-T*	2.08	2.04

Table 2 Continued

Length (m)	Section shape	Wth. (mm)	Thk. (mm)	Weld type	P_{test} (kN)	A_e (mm^2)	L/r_x	P_n (kN)		Buckling mode			P_{test} / P_n	
								P_{n_2001}	P_{n_2007}	Tested	AISI-2001	AISI-2007	P_{n_2001}	P_{n_2007}
1.8	Rec.	92	2.5	DW2	445.2	1143	45.7	204.6	220.0	*F*	*I*	*F-T*	2.18	2.02
1.8	Rec.	92	2.5	SW5	418.4	1055	45.7	220.1	220.0	*D*	*I*	*F-T*	1.90	1.90
1.8	Rec.	92	2.5	DW5	419.9	1059	45.7	203.2	220.0	*D*	*I*	*F-T*	2.07	1.91
1	Rec.	92	1.6	double	160.9	380	30.9	173.9	136.4	*D*	*I*	*D*	0.93	1.18
1	Rec.	92	1.6	SW1	168.7	377	30.9	178.9	155.3	*D*	*I*	*D*	0.94	1.09
1	Rec.	92	1.6	DW1	172.2	385	30.9	176.8	155.3	*D*	*I*	*D*	0.97	1.11
1	Rec.	92	2.0	double	196.9	527	30.7	234.9	185.2	*D*	*I*	*D*	0.84	1.06
1	Rec.	92	2.0	SW1	241.8	617	30.7	225.6	208.2	*D*	*I*	*D*	1.07	1.16
1	Rec.	92	2.0	DW1	252.3	644	30.7	220.5	208.2	*D*	*I*	*D*	1.14	1.21
1	Rec.	92	2.5	double	452.3	1063	27.1	309.6	297.4	*D*	*I*	*D*	1.46	1.52
1	Rec.	92	2.5	SW1	528.2	1173	27.1	307.9	345.4	*D*	*I*	*D*	1.72	1.53
1	Rec.	92	2.5	DW1	474.1	1053	27.1	324.3	345.4	*D*	*I*	*D*	1.46	1.37

F = Flexural buckling mode; *I* = Inelastic buckling mode; *F-T* = Flexural-torsional buckling mode; *D* = Distortional buckling mode

Table 3 Comparison of maximum buckling load to nominal load (I-shaped members)

Length (m)	Section shape	Wth. (mm)	Thk. (mm)	Weld type	P_{test} (kN)	A_e (mm^2)	L / r_x	P_n (kN)		Buckling mode			P_{test} / P_n	
								2001	2007	Tested	AISI-2001	AISI-2007	P_{n_2001}	P_{n_2007}
1.8	I-shaped	92	1.6	double	158.0	490	45.3	131.8	77.3	*D*	*I*	*F-T*	1.20	2.04
1.8	I-shaped	92	1.6	SW1	141.1	374	45.3	170.0	130.2	*F&D*	*I*	*F-T*	0.83	1.08
1.8	I-shaped	92	1.6	DW1	135.0	358	45.3	174.2	130.2	*F&D*	*I*	*F-T*	0.78	1.04
1.8	I-shaped	92	1.6	SW2	154.8	399	45.3	166.9	130.2	*D*	*I*	*F-T*	0.93	1.19
1.8	I-shaped	92	1.6	DW2	152.3	392	45.3	168.5	130.2	*D*	*I*	*F-T*	0.90	1.17
1.8	I-shaped	92	1.6	SW5	145.6	368	45.3	176.5	130.2	*D*	*I*	*F-T*	0.83	1.12
1.8	I-shaped	92	1.6	DW5	156.7	396	45.3	169.3	130.2	*D*	*I*	*F-T*	0.93	1.20
1.8	I-shaped	92	2	double	214.1	727	45.5	185.5	105.5	*D*	*I*	*F-T*	1.15	2.03
1.8	I-shaped	92	2	SW1	203.5	602	45.5	216.8	178.6	*F*	*I*	*F-T*	0.94	1.14
1.8	I-shaped	92	2	DW1	208.4	617	45.5	213.9	178.6	*D*	*I*	*F-T*	0.97	1.17
1.8	I-shaped	92	2	SW2	180.2	520	45.5	231.5	178.6	*D*	*I*	*F-T*	0.78	1.01
1.8	I-shaped	92	2	DW2	211.2	610	45.5	212.2	178.6	*D*	*I*	*F-T*	1.00	1.18
1.8	I-shaped	92	2	SW5	228.7	650	45.5	203.1	178.6	*D*	*I*	*F-T*	1.13	1.28

Table 3 Continued

Length (m)	Section shape	Wth. (mm)	Thk. (mm)	Weld type	P_{test} (kN)	A_e (mm^2)	L / r_x	P_n (kN) 2001	P_n (kN) 2007	Buckling mode Tested	Buckling mode AISI-2001	Buckling mode AISI-2007	P_{test} / P_n P_{n_2001}	P_{test} / P_n P_{n_2007}
1.8	I-shaped	92	2	DW5	179.0	509	45.5	232.2	178.6	*D*	*I*	*F-T*	0.77	1.00
1.8	I-shaped	92	2.5	double	368.4	1146	45.7	249.9	156.1	*D*	*I*	*F-T*	1.47	2.36
1.8	I-shaped	92	2.5	SW1	385.0	1019	45.7	297.7	287.8	*D*	*I*	*F-T*	1.29	1.34
1.8	I-shaped	92	2.5	DW1	367.6	973	45.7	304.7	287.8	*D*	*I*	*F-T*	1.21	1.28
1.8	I-shaped	92	2.5	SW2	346.8	891	45.7	314.5	287.8	*D*	*I*	*F-T*	1.10	1.20
1.8	I-shaped	92	2.5	DW2	309.7	795	45.7	326.9	287.8	*D*	*I*	*F-T*	0.95	1.08
1.8	I-shaped	92	2.5	SW5	316.2	797	45.7	324.4	287.8	*D*	*I*	*F-T*	0.97	1.10
1.8	I-shaped	92	2.5	DW5	404.7	1021	45.7	293.9	287.8	*D*	*I*	*F-T*	1.38	1.41
1	I-shaped	92	1.6	double	179.1	423	26.8	168.3	136.4	*D*	*I*	*D*	1.06	1.31
1	I-shaped	92	1.6	SW1	177.9	398	26.8	177.6	168.1	*D*	*I*	*D*	1.00	1.06
1	I-shaped	92	1.6	DW1	180.6	404	26.8	176.1	168.1	*D*	*I*	*D*	1.03	1.07
1	I-shaped	92	2	double	264.0	707	26.9	218.7	185.2	*D*	*I*	*D*	1.21	1.43
1	I-shaped	92	2	SW1	268.0	684	26.9	217.0	223.1	*D*	*I*	*D*	1.24	1.20
1	I-shaped	92	2	DW1	253.4	646	26.9	223.6	223.1	*D*	*I*	*D*	1.13	1.14
1	I-shaped	92	2.5	double	483.2	1135	27.1	320.2	297.4	*D*	*I*	*D*	1.51	1.62
1	I-shaped	92	2.5	SW1	509.6	1131	27.1	312.1	378.7	*D*	*I*	*D*	1.63	1.35
1	I-shaped	92	2.5	DW1	502.2	1115	27.1	314.4	378.7	*D*	*I*	*D*	1.60	1.33

F = Flexural buckling mode; *I* = Inelastic buckling mode; *F-T* = Flexural-torsional buckling mode; *F&T* = Flexural and torsional buckling mode; *D* = Distortional buckling mode

Table 2 gives a summary of the members that had a closed orientation which is labeled as "rectangular" in the table. Within the weld type column, the term "double" refers to members that had no intermediate weld attachments. The terms SW and DW represent a single-sided weld and a double-sided weld, respectively. The numerical value after the SW or DW symbol tells the number of intermediate weld attachments through the member, where a 1 is a mid-point weld, a 2 is a third-point weld, and a 5 is a sixth-point weld. For example, SW2 indicates a member that only has intermediate welds on one side and those welds are located at the third-points of the member. A visual description of 3rd point welds is shown in Fig. 4. Note that only the intermediate weld attachments of SW2, DW2, SW5 and DW5 meet Section C4.5 of AISI-2001 or D1.2 of AISI-2007. Table 2 also includes both the maximum axial load (P_{test}) applied to the member in testing, along with the nominal capacities (P_{n_2001} and P_{n_2007}) calculated using both 2001 and 2007 AISI Specifications and the measured and predicted buckling failure modes.

The test results of the 92 mm (3.625 in.) wide built-up rectangular members were compared to the previous experimental results of the same members but with smaller widths of 41 and 67 mm (1.625 and 2.625 in.) (Whittle and Ramseyer, 2009). The results were compared to see if the same patterns appeared for the larger members as did with the smaller ones. The main pattern of interest was an increase in the (P_{test}/P_n) ratio for thicker material, which means the AISI-2001 Specification becomes more conservative in terms of axial strength for thicker members (Whittle and Ramseyer 2009). Fig. 6 shows the pattern that formed during the current research of 92 mm (3.625 in.) wide members with a 1.8 m (71 in.) length, and Fig. 7 shows the (P_{test}/P_n) ratio for all 1 m (42 in.) long rectangular members.

From visual comparison of these graphs, it can be seen that for rectangular 1 and 1.8 m (42 and 71 in.) built-up members the same pattern occurs, where the ratio becomes more conservative with a greater thickness. This applies to both AISI-2001 and AISI-2007 Specifications. However, another pattern is generated from the comparison of all three graphs. It can be seen by comparing Fig. 6 and the previous results (Whittle and Ramseyer 2009) that the (P_{test}/P_{n_2001}) ratio is getting closer to 1.0 and less conservative the larger the member width becomes. Looking at Fig. 7 the (P_{test}/P_{n_2001}) ratio drops below 1.0 for the 1.6 mm (0.064 in.) section which results in an un-conservative nominal capacity based on AISI-2001. This problem, however, is not seen for the AISI-2007 Specification.

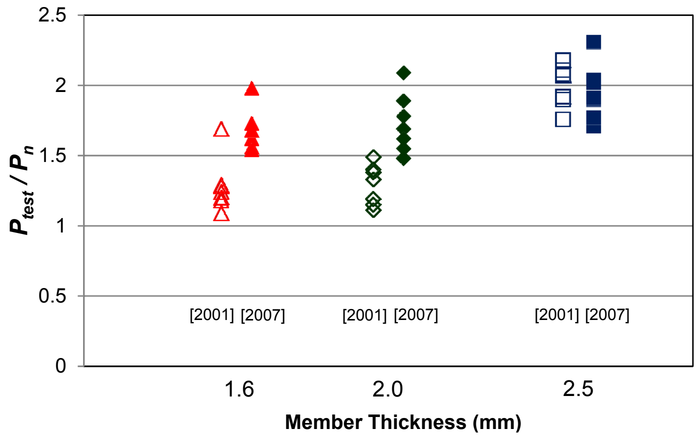


Fig. 6 (P_{test}/P_n) ratio for 92 mm (3.625 in.) wide, 1.8 m (71 in.) long members

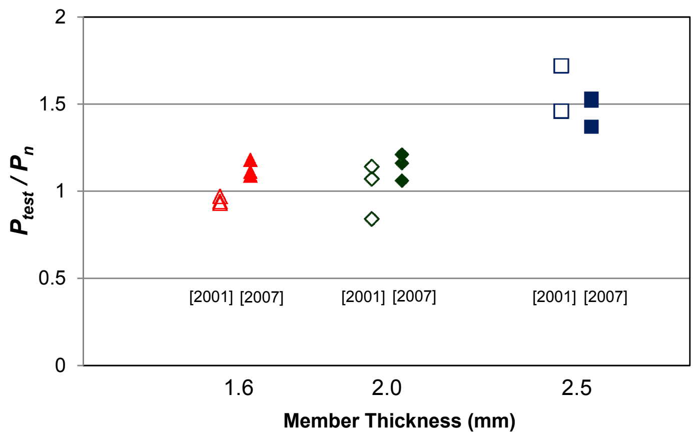


Fig. 7 (P_{test}/P_n) ratio for 92 mm (3.625 in.) wide, 1 m (42 in.) long members

In analyzing the results of the tests for the 1.8 m long members in comparison with AISI-2001, the axial capacity based on the modified slenderness ratio was conservative for all 1.8 m (71 in.) members. The 1.6 mm (0.064 in.) thick member with third-point single sided welds was the least conservative out of all 1.8 m (71 in.) long specimens, at a value of 9% conservative. The most conservative member had a value of 118% conservative and came from the 2.5 mm (0.1 in.) thick member with double-sided third-point intermediate welds. For the 1 m (42 in.) long members, all of the 1.6 mm (0.064 in.) thick members had an un-conservative value which ranged from 7% to 3% un-conservative. For the 2.5 mm (0.1 in.) thick members, all tests gave conservative results, with the largest coming from the 2.5 mm (0.1 in.) thick member with a single-sided mid-point weld, at a value of 72% conservative.

On the other hand, the AISI-2007 Specification overestimates the capacities of all of the 1.8 m (71 in.) and 1 m (42 in.) long members. The axial capacities for most of the specimens (except for 7 specimens) predicted by AISI-2007 are larger than AISI-2001 by 25% on average. Particularly, the AISI-2007 capacities are overly conservative in terms of axial strength for all the 1.8 m (71 in.) long members by a margin of safety of at least 48% and up to 131% conservative (Fig. 6; Table 2). The 1 m (42 in.) long members with 2.5 mm (0.1 in.) thickness are also highly conservative by 47% on average (Fig. 6; Table 2).

4.2 Results and analysis of I-shaped members

Table 3 gives a summary of all the tests that were performed on members with an I-shaped orientation. The tests of the I-shaped orientation were done to see if there is a significant change in the maximum axial buckling capacity of the member with a change in orientation. The same tests that were performed on the rectangular sections were chosen for the I-shaped member tests. The final data are compared to the results of the rectangular members along with seeing if all the same trends are present in the I-shaped members that were discussed in the preceding section. Fig. 78 shows the (P_{test}/P_n) ratio for the 1.8 m (71 in.) long I-shaped members, while Fig. 89 shows the same ratio for all 1 m (42 in.) long I-shaped members.

For the I-shaped orientation the overall trend of an increase in the (P_{test}/P_n) ratio with an increase in member thickness remains true. Out of the members that meet the AISI-2001 Specification Section C4.5, only 3 of the 14 tested 1.8 m (71 in.) long members with a thickness less than 2.5 mm (0.1 in.) had a conservative value, with the highest at 20% conservative. The other 9 tests gave un-conservative results with a value as high as 23% un-conservative. Within the 1 m (42 in.) long members, all tests gave a conservative value with a maximum of 63% conservative occurring with the 2.5 mm (0.1 in.) thick member having a single-sided mid-point weld.

When the AISI-2007 prediction is made, a similar trend is found; however, there are no un-conservative predictions. For both the AISI-2001 and AISI-2007, the (P_{test}/P_n) ratio increases as the thickness of the member increases. The scatter is larger than the AISI-2001 predictions. Particularly, the capacities of the I-shaped members are highly under-predicted by AISI-2007 compared with AISI-2001. Two primary reasons are that: 1) the 2007 AISI torsional buckling specification (Section C4.1.2) gives relatively low values for P_n; however, there were no observed torsional buckling modes of failures from the tested "doubly-symmetric built-up" sections; and 2) that the 2007 AISI distortional buckling capacity appears to significantly underestimate the actual

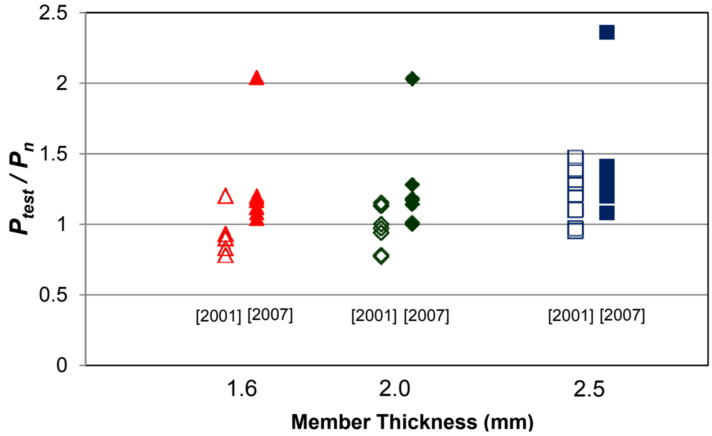


Fig. 8 (P_{test}/P_n) ratio for 1.8 m (71 in.) long I-shaped orientation

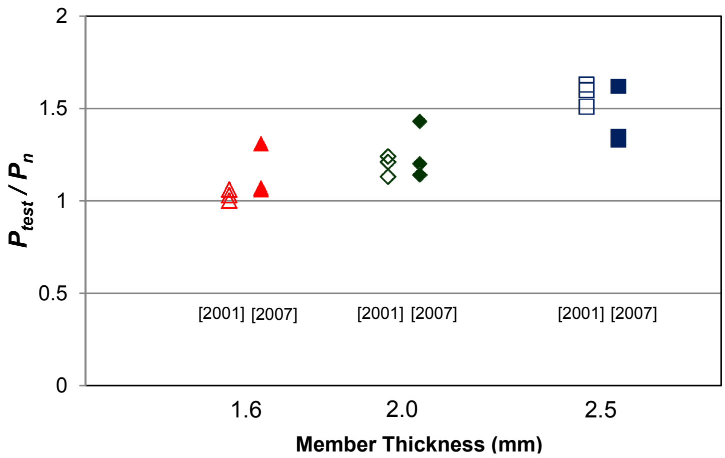


Fig. 9 (P_{test}/P_n) ratio for 1 m (42 in.) long I-shaped orientation

capacity. Note that Section 4.2 of AISI-2007 was not available in the 2001 AISI Specification.

4.3 Comparison of effects of member orientation

When the buckling load of the 1.8 m (71 in.) long rectangular members is compared to that of the I-shaped members, it can be seen that the I-shaped members have a lower buckling capacity than that of the rectangular members (Tables 2 and 3). The 1.6 mm (0.064 in.) thick I-shaped members are an average of 11% lower than the 1.6 mm (0.064 in.) thick rectangular members. The 2 mm (0.08 in.) thick I-shaped members are an average of almost 20% lower, and the 2.5 mm (0.1 in.) thick I-shaped members are also an average of 20% lower.

There are significant differences between rectangular and I-shaped members for the 1.8 m (71 in.) members. These lower capacities for I-shaped members are also resulting in a less conservative nominal capacity calculation. It can be seen that many of the I-shaped members are un-conservative according to the AISI-2001 Specification while all of the rectangular members have a conservative value.

The rectangular 1.8 m (71 in.) specimens normally failed in a form of global buckling. However, this was not always the case and the intermediate weld attachments did affect the final failure pattern of the member. For the single-sided welds of the 1.6 and 2 mm (0.064 and 0.08 in.) thick members the failure pattern was flexure buckling with a separation of the flanges on the opposite side as the intermediate welds. The global-flexural buckling can be seen in Fig. 10 along with a close view on the buckling of the flanges. A single-sided member of a 2.5 mm (0.1 in.) thick member has experienced flexural-torsional buckling. The torsion on the member caused bending in the strong-axis of the member, along with the weak-axis flexural buckling. This failure was unique during the testing, because no other member showed an obvious bending in the strong-axis.

For 2.5 mm (0.1 in.) thick members, the five intermediate single-sided welds along with all double-sided weld patterns failed by either a crushing of the end or an individual buckling of the flanges. Fig. 11 shows both of these failures on the SW5 member, where the top of the member was crushed along with the flanges on the right side of the member failing. It can be seen within the Fig. 11 that no flexural buckling occurred on the member; instead it was these distortional buckling modes that failed the member. Fig. 12 shows a distortional failure of the DW1 member, with the metal bulging out at the web along with bending of the flanges.

The I-shaped 1.8 m (71 in.) long members were much more susceptible to distortional buckling of the flange and web than the rectangular members. The majority of the I-shaped members failed in a form of distortional buckling (Fig. 13); however, there were a few showing a slight flexural buckling pattern so the failure mode could be flexural or distortional. Two members that showed both failure modes were the 1.6 mm (0.064 in.) thick SW1 and DW1 members, which are shown in Fig. 14. Here there is a slight global buckling of the overall member, but there is also distortional buckling of the flanges. The third member in Fig. 14 shows a 2 mm (0.08 in.) thick SW1 member, which was the only I-shaped member to show only a flexural buckling pattern.

For all 1 m (42 in.) long members the buckling mode was a form of distortional buckling, which consisted of a crushing at the end of the member, crippling of the flange and web of the member, or a combination of the two. Fig. 13(c) shows the buckling pattern of I-shaped members, which represents the failure pattern of all I-shaped 1 m (42 in.) long members. The failure in the flanges of I-shaped members can be seen; however, there was also buckling in the web of some members.

In terms of the fastener spacing, similar results are shown for both rectangular and I-shaped orientations. Although only the double side stitch pattern of two or five intermediate welds (*DW2* or *DW5*) complies with the AISI 2007 upper limit of the fastener spacing, the result showed that the specimens with the larger spacing also generally achieved a buckling strength larger than AISI 2007 nominal strength. However, there was no definite relationship between the strength and weld spacing in this experimental study.

4.4 Confirmation of pinned end condition

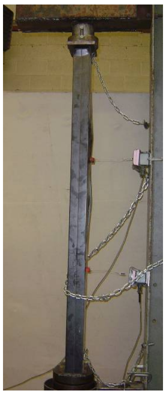
At the conclusion of the testing of 60 members, selected 11 members were retested to confirm that the initial end pivots had a truly pinned end connection and show that the effective length factor k is 1. The results of a set of 11 tests with a new pivot (see Fig. 3) are shown in Table 4.

Two important observations can be seen by the results of the new gimbel pivot tests. First, the

(a)

(b)

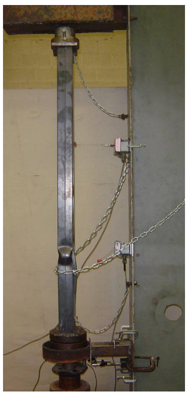
Fig. 10 Flexural buckling of 1.8 m (71 in.) long, 1.6 mm (0.064 in.) thick SW5 rectangular member



(a)

(b)

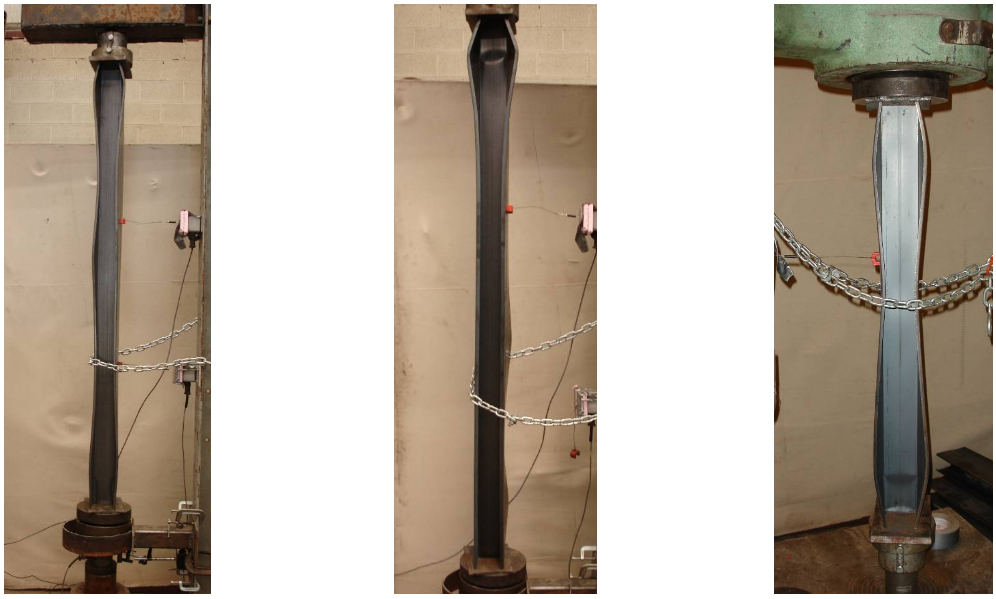
Fig. 11 Crushing at end and individual flange buckling of 1.8 m long (71 in.), 2.5 mm (0.1 in.) thick SW5 rectangular member



(a)

(b)

Fig. 12 Flange distortional buckling of 1.8 m (71 in.) long, 2.5 mm (0.1 in.) thick DW1 rectangular member



(a) (b) (c)

Fig. 13 Distortional buckling of I-shaped members [In order left to right: 2 mm (0.08 in.) thick, 1.8 m (71 in.) long SW3 member; 2.5 mm (0.1 in.) thick, 1.8 m (71 in.) long SW5 member; and 2.5 mm (0.1 in.) thick, 1 m (42 in.) long SW1 member]

(a) (b) (c)

Fig. 14 Mixed flexural and distortional buckling modes of 1.8 m (71 in.) long I-shaped members [In order left to right: 1.6 mm (0.064 in.) thick SW1, 1.6 mm thick (0.064 in.) DW1, and 2 mm (0.08 in.) thick SW1 members]

Table 4 Comparison of new pivot to original pivot

Length (m)	Section shape	Wth. (mm)	Thk. (mm)	Weld type	P_{test} (kN)	P_{retest} (kN)	P_{retest} / P_{test}	A_e (mm^2)	L/r_x	Buckling mode			P_{retest} / P_n	
										Tested	AISI-2001	AISI-2007	P_{n_2001}	P_{n_2007}
1.8	I-shaped	92	1.6	SW2	154.8	155.8	1.01	0.93	0.93	*F*	*I*	*F-T*	0.93	1.2
1.8	I-shaped	92	1.6	DW2	152.3	152.1	1	0.9	0.9	*F*	*I*	*F-T*	0.9	1.17
1.8	I-shaped	92	1.6	SW5	145.6	154.8	1.06	0.82	0.82	*F*	*I*	*F-T*	0.82	1.19
1.8	I-shaped	92	1.6	DW5	156.7	160.8	1.03	0.93	0.93	*F*	*I*	*F-T*	0.93	1.24
1.8	I-shaped	92	2	SW2	180.2	176	0.98	0.78	0.78	*F*	*I*	*F-T*	0.78	0.99
1.8	I-shaped	92	2	DW2	211.2	220.4	1.04	1	1	*F*	*I*	*F-T*	1	1.23
1.8	I-shaped	92	2	SW5	228.7	178	0.78	1.13	1.13	*F*	*I*	*F-T*	1.13	1
1.8	I-shaped	92	2	DW5	179.0	210.3	1.17	0.77	0.77	*F*	*I*	*F-T*	0.77	1.18
1	I-shaped	92	1.6	double	179.1	168.5	0.94	1.06	1.06	*D*	*I*	*D*	1.06	1.24
1	I-shaped	92	1.6	SW1	177.9	167.9	0.94	1	1	*D*	*I*	*D*	1	1
1	I-shaped	92	1.6	DW1	180.6	158	0.87	1.03	1.03	*D*	*I*	*D*	1.03	0.94

F = Flexural buckling mode; *I* = Inelastic buckling mode;
F-T = Flexural-torsional buckling mode; *D* = Distortional buckling mode

assumption that the original end condition of pinned-pinned, which has been used throughout all of the testing, is confirmed to be true with the data of the specimens. Five of the eight 1.8 m (71 in.) tests had a slight increase in failure capacity. If the initial end pivots had provided even a partial restraint the gimbel pivot results when compared would have been consistently lower. Out of the five that produced an ultimate failure load below the original tests, three of these were within 6% of the original data.

5. Conclusions

Based on the examination of the previous and current AISI Specifications for cold-formed “built-up” members and from results of an extensive experimental study, the following important conclusions were drawn:

(1) The results of the testing showed that both AISI-2001 and AISI-2007 Specifications become more conservative in terms of axial strength for thicker members and less conservative for wider members, exhibiting inconsistencies in the calculated values by AISI-2001 or AISI-2007 as compared to the maximum capacity loads determined in the experimental testing. This may be considered in future updates.

(2) According to AISI-2001, the tested built-up members range from a conservative ratio of (P_{test}/P_n) of 2.18 to a non-conservative value of 0.77. This is in part due to little consideration of distortional and local buckling modes and their lower capacities. The 2001 AISI Specification is more likely to give a non-conservative nominal capacity value

for members that are susceptible to distortional failure rather than a form of global buckling.

(3) According to AISI-2007 that incorporated the new or modified Specification of distortional, torsional and flexural-torsional buckling capacity, the tested built-up members had conservative maximum buckling loads. Particularly, the AISI-2007 capacities are overly conservative for all the 1.8 m (71 in.) long members by a margin of safety of at least 48% and up to 131% conservative. This is partly because AISI-2007 considers the instability of the torsional buckling mode, which however was not observed for the tested doubly-symmetric built-up members.

(4) The orientation of the member significantly impacts the maximum load of the member, as much as 20% for the 1.8 m (71 in.) tests. For members that use the I-shaped orientation, a reduction factor in the range of 0.75 to 0.8 may be added to the Specification. The orientation effect is more significant for wider members.

(5) The fastener strength and spacing requirements of the AISI-2007 Specification D1.2, including the modified slenderness ratio (Eq. D1.2-1), need to be considered. Further, given that this provision in AISI-2007 is conservative in terms of axial strength for both the closed- and open-section built-up members, the intermediate fastener or spot weld spacing requirement could be relieved.

(6) The current 2007 AISI Specification is quite complicated for practicing engineers. Hence, there is a need for further simplification, while simultaneously considering the aforementioned conclusions. For this, additional testing should be performed particularly on the shorter sections that are more vulnerable to distortional buckling.

Acknowledgments

The work presented in this paper was sponsored by the University of Oklahoma and by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No. 2012-005905). The views expressed are those of authors, and do not necessarily represent those of the sponsor.

References

Anbarasu, M., Kumar, S. and Sukumar, S. (2013), "Study on the effect of ties in the intermediate length Cold Formed Steel (CFS) columns", *Struct. Eng. Mech., Int. J.*, **46**(3), 323-335.

American Iron and Steel Institute (AISI) (2001a), North American Specification for the Design of Cold-Formed Steel Structural Members; (2001 Edition), Washington, D.C., USA.

American Iron and Steel Institute (AISI) (2001b), Commentary on North American Specification for the Design of Cold-Formed Steel Structural Members: (2001 Edition), Washington, D.C., USA.

American Iron and Steel Institute (AISI) (2007), North American Specification for the Design of Cold-Formed Steel Structural Members: (2007 Edition), Washington, D.C., USA.

Brueggen, B. and Ramseyer, C. (2005), "Capacity of built-up cold-formed steel axial compression members", *Proceedings of the Structural Stability Research Council Conference*, Rolla, MI, USA.

Heva, Y.B. and Mahendran, M. (2013), "Flexural-torsional buckling tests of gold-formed steel compression members at elevated temperatures", *Steel Compos. Struct., Int. J.*, **14**(3), 205-227.

Kang, T.H.-K., Piyawat, K. and Ramseyer, C. (2011), "Design buckling strength curve for built-up cold-formed sections", *Proceedings of the 6th International Symposium on Steel Structures*, Seoul, Korea,

November.
Phan, D.T., Lim, J.B.P., Tanyimboh, T.T. and Sha, W. (2013), "An efficient genetic algorithm for the design optimization of cold-formed steel portal frame buildings", *Steel Compos. Struct., Int. J.*, **15**(5), 519-538.
Piyawat, K., Ramseyer, C. and Kang, T.H.-K. (2011), "Nonlinear buckling of built-up cold-formed sections", *Int. J. Theor. Appl. Multiscale Mech.*, **2**(2), 146-164.
Piyawat, K., Ramseyer, C. and Kang, T.H.-K. (2013), "Development of an axial load capacity equation for doubly-symmetric built-up cold-formed sections", *ASCE J. Struct. Eng.*, **139**(12), 04013008.
Valsa Ipe, T., Sharada Bai, H., Manjula Vani, K. and Iqbal, M.M.Z. (2013), "Flexural behavior of cold-formed steel concrete composite beams", *Steel Compos. Struct., Int. J.*, **14**(2), 105-120.
Wehbe, N., Bahmani, P. and Wehbe, A. (2013), "Behavior of concrete/cold formed steel composite beams: Experimental development of a novel structural system", *Int. J. Concrete Struct. Mater.*, **7**(1), 51-59.
Whittle, J. and Ramseyer, C. (2009), "Buckling capacities of axially loaded, cold-formed, built-up C-channels", *Thin-Wall. Struct.*, **47**(2), 190-201.

CC