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Experimental investigation into the behaviour of back-to-back gapped built-up cold-formed steel channel sections under compression

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Abstract

Back-to-back gapped built-up cold-formed steel channel-sections are used as compression members in cold-formed steel structures, such as trusses, space frames and portal frames etc. Because of the complex and non-uniform cross section of the back-to-back gapped built- up cold-formed steel channel columns, it is difficult to calculate the strength of these sections accurately. Current guidance by the direct strength method in the AISI Specification and the Australian/New Zealand Standard doesn't include the gap between the back-to-back channels, thus not being able to predict the axial capacities of these sections accurately. In the literature, very few results have been reported for such columns and specially investigated the effect of link-channel's spacing on axial strength of such columns. This issue is addressed herein. Forty new experimental results are reported, conducted on back-to-back gapped built-up cold-formed steel channel-sections, covering stub to slender columns. Axial capacity of the columns, load-axial shortening, load-axial strain, failure modes and deformed shapes were observed and reported in this paper. Also, the effect of link-channel's spacing on axial strength, is investigated. Test strengths are compared against the design strengths calculated in accordance with AISI and Australian/New Zealand standard for cold-formed steel structures. It is shown that the design standards can be conservative by as much as 53%, while predicting axial strength of such columns. Therefore, a modification to the non-dimensional slenderness, that considers the gap, is proposed which leads the design standards being within 5% conservative to the test results.

Keywords: Gap, Cold-formed steel, Back-to-back gapped sections, Buckling, Direct strength method, Link-channel, Axial strength.

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Nomenclature

A'	Overall web length of section;
A_1	Cross sectional area of single channel-section;
A_e	Effective area of the section;
B'	Overall flange width of section;
C'	Overall lip width of section;
CFS	Cold-formed steel;
COV	Coefficient of variation;
E	Young's modulus of elasticity;
F_e	Least of the elastic flexural, torsional, and flexural torsional buckling stress;
F_n	Nominal buckling stress as per AISI & AS/NZS;
F_y	Yield stress which is equal to the 0.2% proof stress ($\sigma_{0.2}$);
I_1	Moment of inertia of single channel-section;
k	Effective length factor;
l	Effective length of the built-up gapped section;
L	Total length of the built-up gapped section;
P	Applied axial load;
$P_{AISI\& AS/NZS}$	Axial strength from AISI & AS/NZS;
P_{DSM}	Axial strength from Direct Strength Method;
P_{EXP}	Axial strength from experiments;
$P_{M\text{-}DSM}$	Axial strength from Modified Direct Strength Method;
S	Longitudinal spacing of link-channels ;
w'	Gap between back-to-back channel-sections;
λ_c	Non-dimensional slenderness ratio as per AISI & AS/NZS;
$\lambda_{c,GAP}$	λ_c as for sections with gap;
$\sigma_{0.2}$	Static 0.2% proof stress;

1 Introduction

In this paper, the results of forty new experimental tests on back-to-back gapped built-up cold-formed steel channel sections, with the sections acting as columns, are presented. Fig.1 shows the details of gapped section investigated herein. As can be seen from Fig 1, the gap is formed through a link-channel screwed between the webs of the back-to-back channel-sections. Such gaps are commonly introduced in struts in steel trusses and columns in portal frames, increasing the lateral stability of such columns.

In the literature, only three such experimental results are available, as reported by Rondal and Niazi [1] in 1990; the values of non-dimensional slenderness in these tests ranged from 1.08 to 1.16. The forty new experimental tests reported herein have a value of non-dimensional slenderness ranging from 0.23 to 1.42, thus covering stub to slender columns.

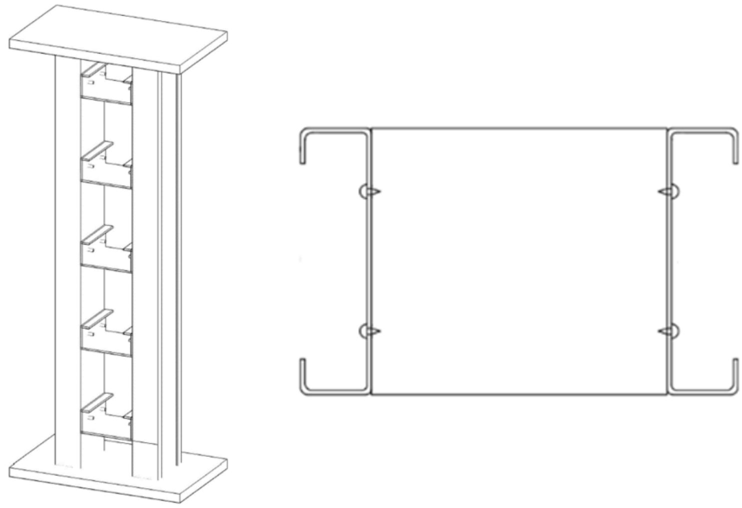
In current design standards, such as American Iron and Steel Institute [2] and Australian and New Zealand Standards AS/NZS 4600:2005 [3], the beneficial effect of the gap is ignored i.e. the design axial compressive strength is simply twice that of a single channel-section. This is the case regardless of whether the Effective Width Method (EWM) (reproduced in Section 2) or the Direct Strength Method (DSM) is used. It should be noted that the DSM does not include post-local-buckling capacity, however, Kumar and Kalyanaraman [4], modified the DSM equations, referred here as M-DSM, to include post-local-buckling capacity. The axial strength calculated in accordance with EWM, DSM and M-DSM are all presented in this paper.

Ting et al. [5] recently presented an experimental and numerical investigation on the behaviour of back-to-back built-up CFS channel sections under axial compression. The experimental tests reported herein, extends the work of Ting et al. [5]. As a result of the gap, for some combinations of column length and gap size, the lowest flexural buckling mode may be as shown in Fig. 2a, as opposed to overall buckling of the whole column, taking into consideration of the gap, as shown in Fig. 2b. As mentioned previously, the design approach of the design standards ignores the beneficial presence of the gap.

A non-linear finite element model was developed by Roy et al. [6], which showed good agreement against the experimental results for back-to-back gapped built-up cold-formed steel channel sections under compression. Other work includes that of Zhang and Young [7] who considered back-to-back built-up channel-sections, but these were with an opening, not with a gap. Dabaon et al. [8] investigated CFS built-up battened columns, while Stone and LaBoube [9] considered back-to-back channel-sections, which were flange stiffened and track sections. Whittle et al. [10] and Piyawat et al. [11] considered built-up channel-sections, but these were welded connection. The non-linear behaviour of axially loaded back-to-back cold-formed steel un-lipped channel sections and cold-formed stainless steel built-up channel sections were investigated by Roy et al. [12,13]. A numerical investigation on built-up columns with battens and stiches are presented by Crisan et al. [14], where they have checked the accuracy of European and American standards, while calculating compressive strength of such built-up batten columns. Other works includes that of Fratamico et al. [15] and Anbarasu et al. [16] who considered back-to-back built-up CFS channels, without any gap under compression. Fratamico et al. [15] investigated built-up columns and investigated the effect of screw spacing for back-to-back channels, again without any gap. On the other hand, Anbarasu et al. [16] investigated the behaviour and strength of cold-formed steel web stiffened built-up batten columns, without any gap.

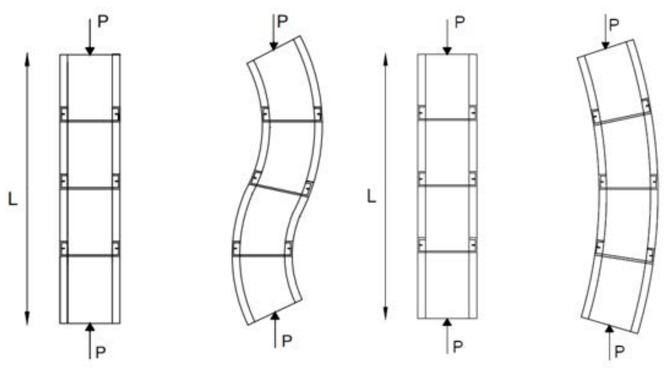
Fig. 3 shows the nominal geometry of the two sections considered in this paper: GBU75 and GBU90. Forty experimental test results are reported. All test specimens were brake-pressed from G550 structural steel sheets. The experimental tests were conducted for different lengths in combination with different link-channel spacing. The effect of gap, link-channel spacing, load-axial shortening, load-axial strain behaviour and buckling failure modes for different cross sections and lengths of back-to-back gapped built-up columns has been investigated in this paper, none of which is available in the literature. The experimental test results are compared against the tests results of back-to-back built-up CFS column with no gap by Ting et al. [5].

Using the experimental results, it is shown that design in accordance with the American Iron and Steel Institute (AISI) and Australian and New Zealand Standards (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 finite element results. Full details of this work can be found in Roy et al. [6].



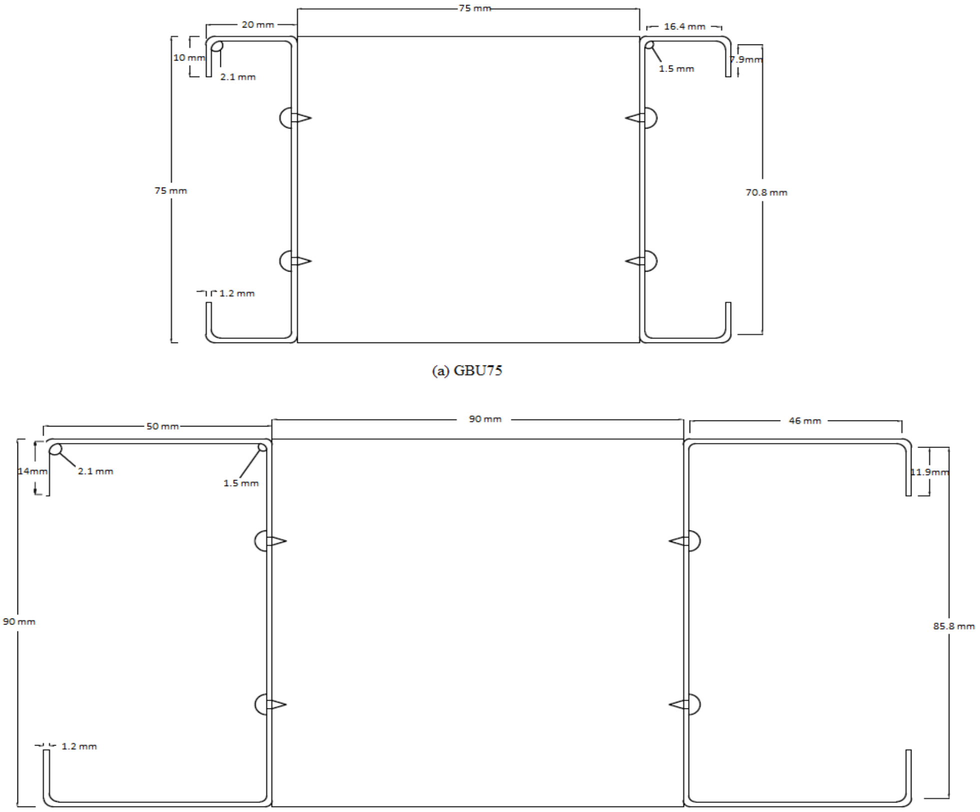
(a) General arrangement (b) Cross-section

Figure 1: Back-to-back gapped built-up cold-formed steel channel-sections



(a) Mode-A (b) Mode-B

Figure 2: Overall flexural buckling modes of back-to-back gapped built-up cold-formed steel channel-sections



(a) GBU75

(b) GBU90

Figure 3: Nominal cross-sections of back-to-back gapped built-up CFS channel sections considered herein

2. AISI & AS/NZ Standard design guidelines

In accordance with AISI & AS/NZ standards, for built-up sections, the design axial compressive strength is simply twice that of a single channel-section, the un-factored design strength of a single channel-section is as follows:

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

The nominal buckling stress (F_n) can be calculated from:

$$\lambda_c \leq 1.5:\ F_n = (0.658^{\lambda_c^2})\, F_y \tag{2}$$

$$\lambda_c > 1.5,\ F_n = \left(\frac{0.877}{\lambda_c^2}\right) F_y \tag{3}$$

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

3 Experimental investigation

3.1 Test specimens

Fig. 3 shows details of the cross-sections of the two back-to-back gapped built-up cold-formed steel channel columns considered in this paper: GBU75 and GBU90. As indicated by the name, GBU75 and GBU90 are built-up from C75 and C90 channel-sections, respectively. In this paper, the Link-channel through which the gap is formed use the same channel-section as that of the built-up section i.e. C75 and C90 channel-sections are used for the link-channel in GBU75 and GBU90, respectively.

The experimental test programme comprised 40 specimens, subdivided into four different column heights: 300 mm, 500 mm, 1000 mm, and 2000 mm. The columns were tested with pin-ended conditions, apart from the 300 mm columns which were tested as stub columns. In Table 1, the specimens have been sub-divided into stub, short, intermediate and slender columns. In the experimental test programme, the following longitudinal spacing of link-channels (S) were considered:

- Columns of 300 mm height; spacing of 50 mm and 200 mm
- Columns of 500 mm height; spacing of 100 mm and 400 mm
- Columns of 1000 mm height; spacing of 225 mm and 900 mm
- Columns of 2000 mm height; spacing of 475 mm and 1900 mm

3.2 Material Properties

In order to determine the material properties of test sections, tensile coupon tests were conducted. The tensile coupons were prepared from the centre of the web plate, in accordance with British Standard for Testing and Materials [17]. Five of each coupons were obtained from longitudinal and transverse direction of the untested specimens. MTS test machine was used to test the coupons. To determine the tensile strain, two strain gauges and a calibrated extensometer of 50 mm gauge length were used. The average modulus of elasticity was 205GPa and yield strength was 565 MPa.

3.3 Labelling

The back-to-back gapped built-up cold-formed steel channel-sections were labelled such that the type of section, longitudinal link-channel spacing, nominal length of specimen and specimen number were expressed by the label. Fig. 4 shows an example of the labelling used. The channel-sections are denoted by their web depth i.e. 75 in the label. The intermediate fastener spacing is denoted as S for the spacing. The column length is stated last in the label as L.

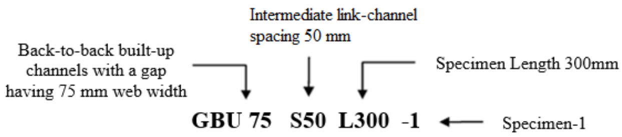


Figure 4: Specimen labelling

3.4 Test-rig and testing procedure

A photo of the test setup is shown in Fig. 5. The external load cell was placed at the top of the column. Six LVDTs were used, the position of LVDTs are shown in Fig. 5. To measure the strain, two longitudinal strain gauges along with three other strain gauges were used on the web of the columns. Strain gauge arrangements are shown in Fig. 6. A Universal Testing Machine (UTM) GT-7001-LC60, of 600 kN capacity, was used to apply axial load to the columns. The displacement control was used to apply the axial force to the columns, which can include the post buckling behaviour of the columns. Displacement rate was kept as 0.03 mm/s for all test specimens. Strain values were recorded from longitudinal strain gauges near the top end plate and middle of the columns to verify that the load was applied through the centroid of the sections. In order to ensure, there is no gap between the two pin-ends and end plates of the specimen, all columns were loaded initially up to 25% of their expected failure load and then released. LVDT and strain gauge readings were recorded with each increment of loading.

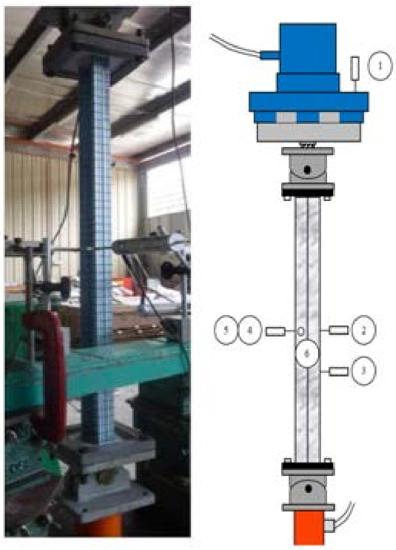


Figure 5: Photograph of the test set-up for intermediate columns.

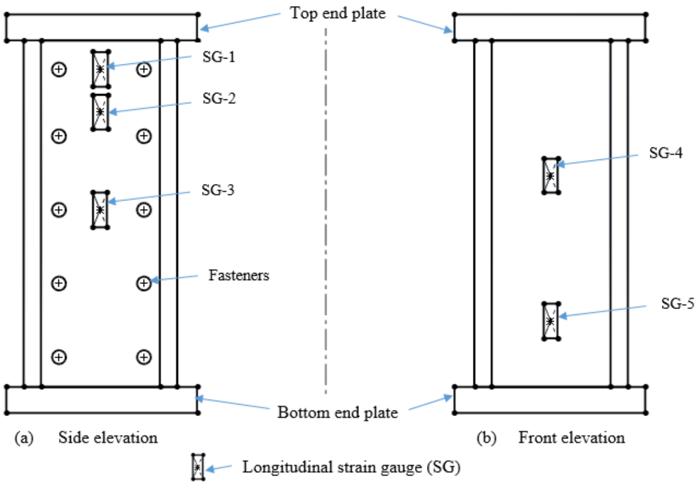
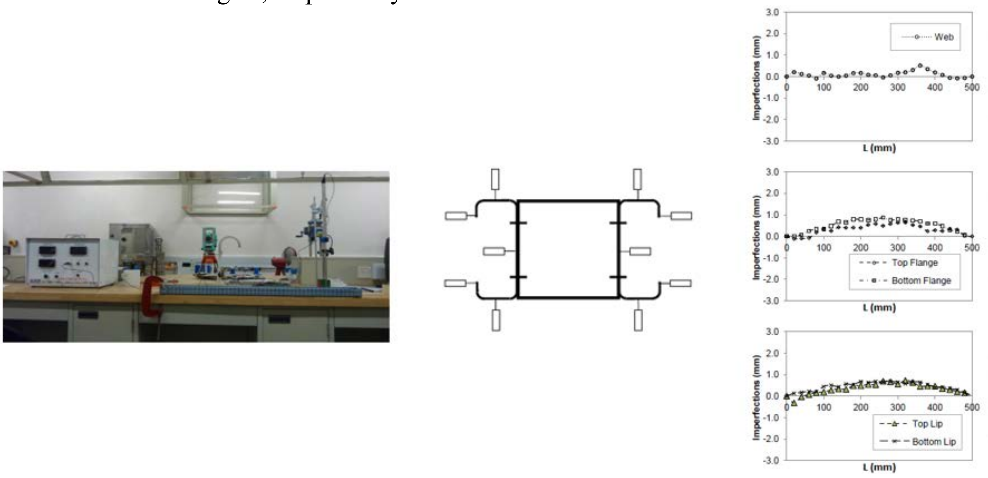


Figure 6: Position of the strain gauges

3.5 Measurement of initial geometric imperfections

Initial geometric imperfections were measured as shown in Fig. 7(a). A LVDT with an accuracy of 0.01 mm, was used to record the readings at every 20 mm along the length of the sections. The imperfections were measured at the centre of the web, flanges, and edge of the lips for all sections. LVDT positions are shown in Fig. 7(b). In Fig. 7(c), a typical length-imperfection plot is shown for GBU75-S100-L500-1. The maximum imperfections of the test specimens were 1.8 mm, 1.7 mm, 1.6 mm and 1.9 mm for the 300 mm, 500 mm, 1000 mm and 2000 mm column lengths, respectively.



(a) Imperfection measurement setup (b) LVDT positions (c) Typical imperfection profile (GBU75-S100-L500)

Figure 7: Details of imperfection measurements

3.6 Experimental results

Column dimensions and the experimental failure loads (P_{EXP}) are shown in Table 1. Also shown in Table 1, are the buckling modes. As can be seen, strength of the built-up sections were reduced significantly for all columns beyond 1000 mm length for both GBU75 and GBU90 with two intermediate link-channels. On the other hand, for GBU75 with no intermediate link-channel, significant reduction in axial strength was observed for column length higher than 500 mm. This is because the intermediate link-channels holds the individual back-to-back channels together.

Failure modes were different for stub, short, intermediate and slender columns. In total, 16 stub columns were tested (see Table 1). GBU75-S50-L300 and GBU90-S50-L300 test specimens with three link-channels spaced at 50 mm, failed through local buckling. Back-to-back channels remain integral at failure, showing some plastic deformation near the bottom of the stub columns as shown in Fig. 8. The failure modes of GBU75-L300 series, were different from the BU75-L300 series (Ting et al. [5]) because the link-channels in GBU75-L300 provided sufficient restraint to prevent buckling at mid-height of the column. Unlike BU75-L300, for GBU90-L300 series columns, localized deformation was observed near the top or bottom end of the columns.

Load-axial shortening behaviour for GBU75-S225-L1000-1 is plotted in Fig. 14. It is observed that the relationship was almost linear up to a load of 53 kN, which is approximately 69% of the ultimate failure load for GBU75-S225-L1000-1. After that, nonlinear behaviour is continued until the failure load is reached, which is 77.09 kN.

GBU75-S100-L500 with three intermediate link-channels at 100 mm spacing buckled as Mode A, leading to a hinge-like angular buckling shape at about one-third height, near to the top of the column. The buckling shape is shown in Fig. 10. Both short (500 mm length) and intermediate (1000 mm length) columns showed similar buckling shapes, although 1000 mm long columns showed clearer deformed shapes (see Fig. 10(b)).

Local and distortional buckling were not noticeable for slender columns. Overall buckling was observed for slender columns of both GBU75 and GBU90 series. Localized deformation was noticeable on the compression side of specimens near the mid-height of the column as shown in Fig. 10 (c). For Mode B, GBU75-S475-L2000 uses four link-channels while GBU75-S1900-L2000 uses two link-channels.

Five strain gauges were used to determine axial strain at mid-length and end of all columns. Load -axial strain relationships for GBU75-S50-L300-1 and GBU90-S50-L300-1 are plotted in Fig. 11(a) and 11(b) respectively. S-E denotes the axial strain at the end of column, where S-M is the strain at the middle of the column (see Fig.6). Maximum compressive micro-strain observed at failure load, as shown in Fig. 11 (a), is 812 and 987 in S-E and S-M points respectively for GBU75-S50-L300-1 column. Similarly, as shown in Fig.11(b), for GBU90-S50-L300-1, axial strain values obtained at failure load is 1050 and 1207 respectively for S-E and S-M points i.e. at the end and at middle height of columns.

The effect of increase in the vertical spacing of link-channels, are investigated and shown in Table 1. As can be seen from Table 1(a), the average strength of stub column of GBU75 series is decreased by 5%, when the vertical spacing between the link-channels is increased from 50 mm to 200 mm. For short columns, when the link channel spacing is increased from 100 mm to 400 mm, the axial strength of the gapped built-up columns is decreased by 5.8% on average. For intermediate columns, the average decrease in strength is by around 17% when increasing the spacing from 225 mm to 900 mm for GBU75 columns. Reduction in strength for slender columns is approximately by 16% for GBU75, when the screw spacing is increased from 475 mm to 1900 mm. On the other hand, for GBU90 short columns, increasing the vertical spacing of link-channels from 100 mm to 400 mm, reduces the axial strength by 2.3%. For short GBU90 columns, the axial strength is reduced by 4.8%, when the spacing is increased from 100 mm to 400 mm.

(a) GBU75-S50-L300 (b) GBU75-S200-L300 (c) GBU90-S50-L300 (b) GBU75-S200-L300

Figure 8: Photograph of stub columns at failure

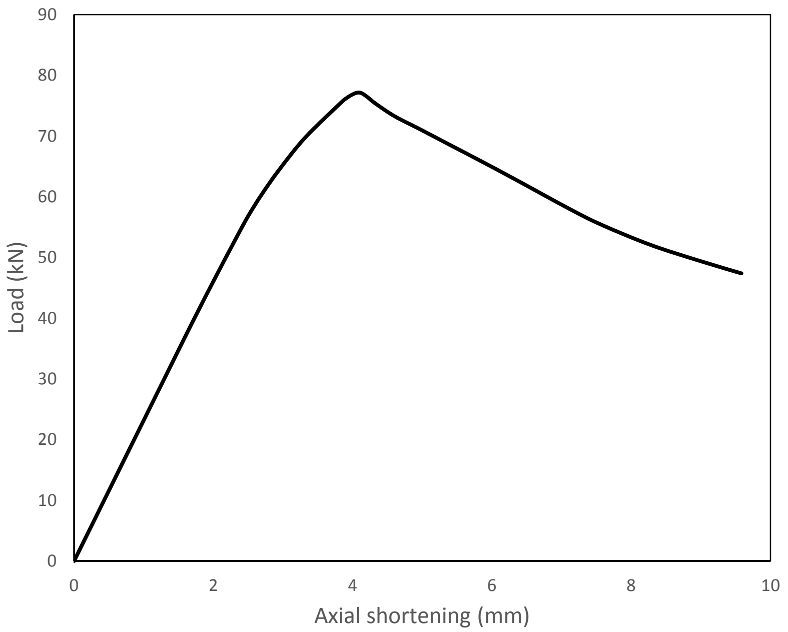
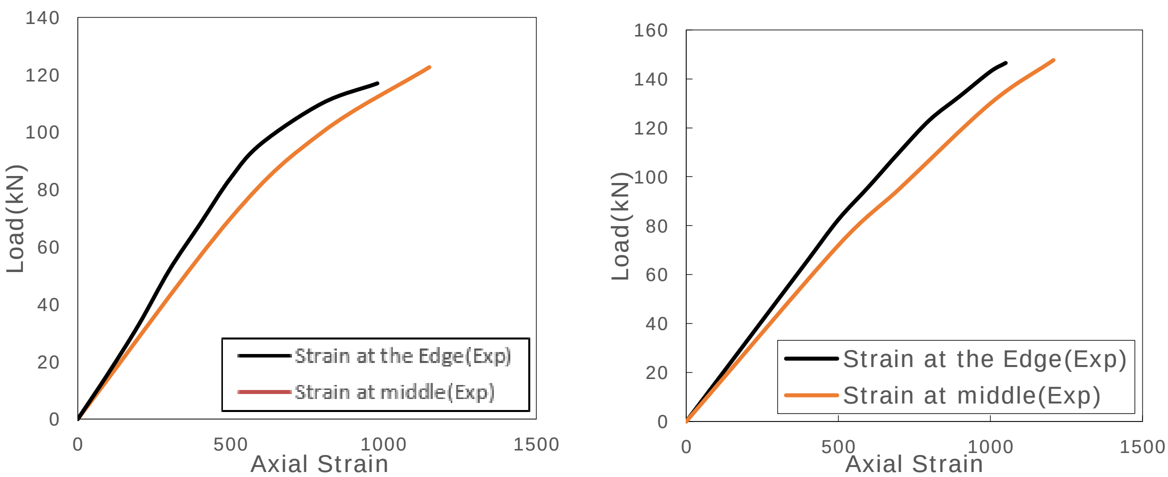


Figure 9: Load-axial shortening relationship for GBU75-S225-L1000-1

(a) GBU75-S100-L500 (Mode-A) (b) GBU75-S225-L1000 (Mode-A) (c) GBU75-S475-L2000 (Mode-B)

Figure 10: Photograph of short, intermediate and slender columns at failure



(a) GBU75S50L300-1 (b) GBU90S50L300-1

Figure 11: Load versus axial-strain for GBU75 and GBU90 columns

Table 1: Axial strength and failure modes of built-up back-to-back gapped channel-sections

a) GBU75

Specimen	Web A' (mm)	Flange B' (mm)	Lip C' (mm)	Length L (mm)	Spacing S (mm)	Gap between columns w' (mm)	Slenderness λ_c -	$\lambda_{C,GAP}$ -	Experimental Results P_{EXP} (kN)	Failure mode - -
Stub										
GBU75-S50-L300-1	73.2	19.8	11.2	271	50.0	73.2	0.38	0.26	122.6	Local
GBU75-S50-L-300-2	73.6	19.9	11.1	270	50.1	73.6	0.39	0.27	120.5	Local
GBU75-S50-L300-3	73.6	19.8	11.1	268	50.2	73.6	0.38	0.26	121.9	Local
GBU75-S200-L300-1	73.6	19.7	11.1	268	201.0	73.6	0.42	0.29	114.7	Local
GBU75-S200-L300-2	73.6	19.7	11.2	271	200.0	73.6	0.42	0.29	114.3	Local
GBU75-S200-L300-3	72.3	18.5	10.5	263	199.0	72.3	0.41	0.28	117.9	Local
Short										
GBU75-S100-L500-1	73.6	19.8	11.3	678	100.2	73.6	0.57	0.37	113.9	Mode A
GBU75-S100-L500-2	73.6	19.9	11.2	679	100.0	73.6	0.57	0.36	109.8	Mode A
GBU75-S100-L500-3	73.5	19.8	11.3	681	100.0	73.5	0.59	0.38	115.1	Mode A
GBU75-S400-L500-1	73.6	19.9	11.2	679	399.0	73.6	0.60	0.40	108.2	Local +Distortional
GBU75-S400-L500-2	73.5	19.8	11.1	680	400.0	73.5	0.61	0.41	101.8	Local +Distortional
GBU75-S400-L500-3	73.5	19.8	11.1	680	400.0	73.5	0.61	0.41	101.1	Local +Distortional
Intermediate										
GBU75-S225-L1000-1	76.1	19.8	10.4	1131	225.0	76.1	0.89	0.75	77.1	Mode A
GBU75-S225-L1000-2	76.2	20.3	10.4	1132	225.0	76.2	0.88	0.74	76.2	Mode A
GBU75-S225-L1000-3	75.8	19.8	10.4	1183	224.8	75.8	0.92	0.77	73.2	Mode A
GBU75-S900-L1000-1	75.9	19.8	10.4	1133	900.0	75.9	0.98	0.83	65.3	Mode A
GBU75-S900-L1000-2	76.0	19.9	10.3	1132	897.5	76.0	0.99	0.85	61.5	Mode A
GBU75-S900-L1000-3	76.0	19.8	10.3	1182	900.0	76.0	1.00	0.86	61.2	Mode A
Slender										
GBU75-S475-L2000-1	73.6	20.3	10.6	2183	474.3	73.6	1.36	1.23	25.6	Mode B
GBU75-S475-L2000-2	73.9	20.3	10.6	2183	474.5	73.9	1.36	1.23	25.2	Mode B
GBU75-S475-L2000-3	73.9	20.4	10.8	2184	474.8	73.9	1.36	1.23	25.7	Mode B
GBU75-S1900-L2000-1	73.8	20.3	10.8	2183	1901	73.8	1.41	1.26	21.3	Mode B
GBU75-S1900-L2000-2	73.9	20.4	10.7	2183	1907	73.9	1.42	1.27	20.9	Mode B
GBU75-S1900-L2000-3	73.9	20.4	10.8	2184	1902	73.9	1.42	1.26	21.6	Mode B

(b) GBU90

Specimen	Web A' (mm)	Flange B' (mm)	Lip C' (mm)	Length L (mm)	Spacing S (mm)	Gap Between Columns w' (mm)	Slenderness λ_c -	$\lambda_{C,GAP}$ -	Experimental Results P_{EXP} (kN)	Failure mode - -
Stub										
GBU90-S50-L300-1	92.2	49.5	14.5	265	50.0	92.2	0.23	0.13	147.7	Local
GBU90-S50-L300-2	90.7	49.6	14.6	270	50.3	90.7	0.23	0.13	146.8	Local
GBU90-S200-L300-1	90.7	49.6	14.6	258	200.0	90.7	0.23	0.13	140.6	Local
GBU90-S200-L300-2	90.7	49.5	14.6	270	200.0	90.7	0.24	0.14	138.5	Local
GBU90-S200-L300-3	90.7	49.5	14.6	262	199.0	90.7	0.23	0.13	139.4	Local
Short										
GBU90-S100-L500-1	90.5	49.4	14.6	680	100.5	90.5	0.41	0.23	132.5	Mode A
GBU90-S100-L500-2	90.6	49.4	14.6	680	100.5	90.6	0.41	0.23	133.7	Mode A
GBU90-S100-L500-3	88.9	49.4	15.5	680	100.3	88.9	0.41	0.24	133.2	Mode A
GBU90-S400-L500-1	90.5	49.5	13.4	680	400.0	90.5	0.42	0.26	129.7	Local +Distortional
GBU90-S400-L500-2	90.5	49.5	14.6	680	400.0	90.5	0.45	0.27	130.4	Local +Distortional
GBU90-S400-L500-3	90.3	49.5	14.7	680	400.0	90.3	0.45	0.28	129.5	Local +Distortional
GBU90-S400L-500-4	90.6	49.4	14.6	680	401.0	90.6	0.45	0.27	130.6	Local +Distortional
Intermediate										
GBU90-S225-L1000-1	90.5	49.7	14.4	1133	225.3	90.5	0.85	0.64	86.5	Mode A
GBU90-S225-L1000-2	89.8	48.5	13.7	1183	224.8	89.8	0.86	0.65	87.5	Mode A
GBU90-S900-L1000-1	90.6	49.6	14.4	1132	892.0	90.6	0.86	0.66	82.9	Mode A
GBU90-S900-L1000-2	90.6	49.7	14.4	1183	900.0	90.6	0.87	0.67	83.3	Mode A

4. Comparison with design standards

Table 2 compares the experimental strengths with the design strengths calculated in accordance with AISI and AS/NZS, DSM and M-DSM. Fig. 12(a) shows the experimental and finite element strengths of the GBU75 columns plotted against length. For ease of reference, the experimental strengths of the back-to-back built-up channel-sections after Ting et al. [5] are also shown. As can be seen, the presence of the gap has increased the strength of the column by around 29%, when the column length is approximately 700 mm. As can be expected, for the stockier and slenderer sections, the increase in strength is less.

Also shown in Fig. 12(a) are the design strengths calculated in accordance with AISI and AS/NZS. Two curves are shown. The lower curve is the strength of the built-up back to back channel-section calculated using λ_c. As can be seen, this curve is very conservative to both the experimental and finite element strengths by as much as 53%. This can be expected since the beneficial effect of the gap is ignored i.e. the design axial compressive strength is simply twice that of a single channel-section.

A theoretical equation for the elastic critical bucking load (P), that takes into account the gap, is as follows [18]:

$$\mathrm{kl}\sin\mathrm{kl} + \left(\frac{\mathrm{I}}{\mathrm{I_0}} - 2\right)(1 - \cos\mathrm{kl}) = 0 \qquad (7)$$

Where,

$$\mathrm{k}^2 = \frac{\mathrm{P}}{2\mathrm{EI_1}} \qquad (8)$$

Solving the above equations numerically for P, leads to a value for the non-dimensional slenderness, $\lambda_{c,GAP}$. In Fig. 12(a), the upper curve is calculated using the value of $\lambda_{c,GAP}$. As can be seen, use of $\lambda_{c,GAP}$, results in the AISI and AS/NZS being close to the experimental test results, being within 5% conservative to the design standards. For ease of reference, the DSM and M-DSM curves are also shown, again with use of the value of $\lambda_{c,GAP}$. As can be seen, both DSM and M-DSM are close to the AISI and AS/NZS curves, albeit slightly lower. The same trends can be seen in Fig. 12(b) for the GBU90 columns.

Fig. 13(a) and (b) shows the same strength of the GBU75 and GBU90 columns, respectively, but for varying values of non-dimensional slenderness, λ_c. As mentioned previously, Rondal and Niazi [1], tested three gapped built-up columns having values of λ_c ranging from 1.08 to 1.16. The range λ_c covered in this paper is from 0.2 to 1.42, thus providing additional points to Rondal and Niazi [1].

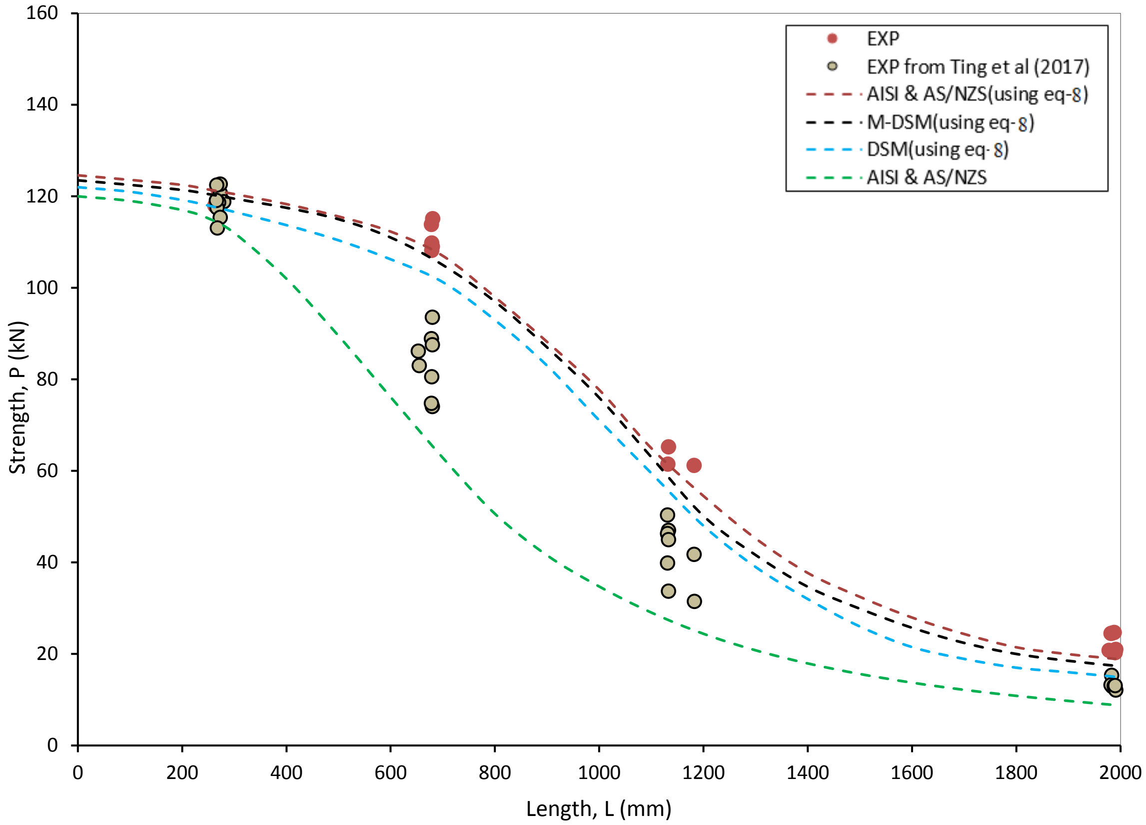
Table 2: Comparison of expeirmental and design strengths

(a) GBU75

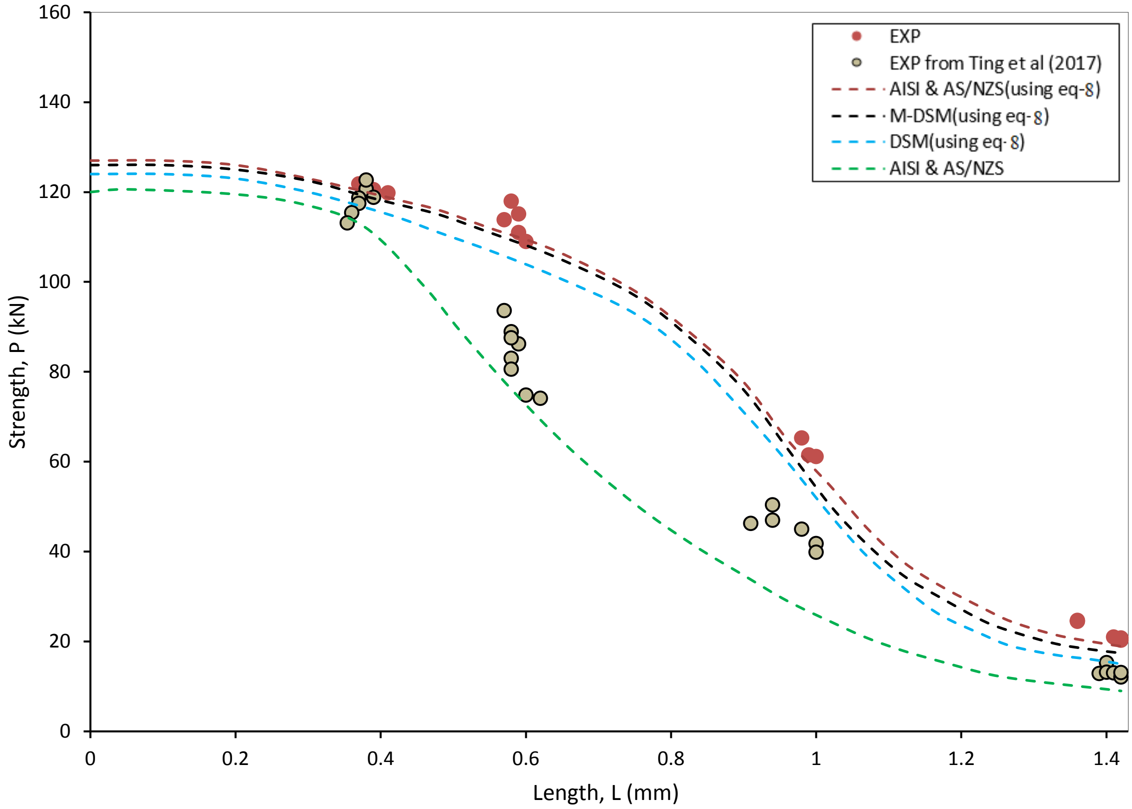
Specimen	AISI	AISI &AS/NZS using eq-8	DSM using eq-8	MDSM using eq-8	Comparison			
	P_{AISI} (kN)	$P_{AISI\text{-}eq\text{-}8}$ (kN)	P_{DSM} (kN)	$P_{M\text{-}DSM}$ (kN)	P_{EXP}/P_{AISI} -	$P_{EXP}/P_{AISI\text{-}eq\text{-}8}$ -	P_{EXP}/P_{DSM} -	$P_{EXP}/P_{M\text{-}DSM}$ -
Stub								
GBU75-S50-L300-1	112.89	120.50	116.51	117.94	1.09	1.02	1.05	1.04
GBU75-S50-L300-2	112.34	119.85	115.37	117.34	1.07	1.01	1.05	1.03
GBU75-S50-L300-3	111.70	119.31	115.70	118.69	1.09	1.02	1.05	1.03
GBU75-S200-L300-1	105.43	114.74	112.10	111.31	1.09	1.00	1.02	1.03
GBU75-S200-L300-2	104.88	114.45	110.30	111.98	1.09	1.00	1.04	1.02
GBU75-S200-L300-3	105.72	116.14	110.93	112.64	1.12	1.02	1.06	1.05
Mean					1.09	1.01	1.05	1.03
COV					0.012	0.011	0.014	0.013
Short								
GBU75-S100-L500-1	67.30	113.30	101.26	112.00	1.69	1.01	1.12	1.02
GBU75-S100-L500-2	65.18	109.18	100.49	109.12	1.68	1.01	1.09	1.01
GBU75-S100-L500-3	69.72	114.31	101.61	112.23	1.65	1.01	1.13	1.03
GBU75-S400-L500-1	63.90	108.25	94.87	108.10	1.69	1.00	1.14	1.00
GBU75-S400-L500-2	61.43	105.56	94.15	108.02	1.66	0.96	1.08	0.94
GBU75-S400-L500-3	62.80	108.15	94.34	108.35	1.74	1.01	1.16	1.01
Mean					1.69	1.00	1.12	1.01
COV					0.031	0.017	0.029	0.030
Intermediate								
GBU75-S225-L1000-1	42.62	76.62	60.58	66.74	1.81	1.01	1.27	1.16
GBU75-S225-L1000-2	42.38	76.31	60.03	66.51	1.80	1.00	1.27	1.15
GBU75-S225-L1000-3	45.79	76.12	59.75	66.10	1.60	0.96	1.22	1.11
GBU75-S900-L1000-1	31.98	64.72	50.13	58.33	2.04	1.01	1.30	1.12
GBU75-S900-L1000-2	31.39	60.87	49.73	57.34	1.96	1.01	1.24	1.07
GBU75-S900-L1000-3	30.80	60.38	49.42	57.17	1.99	1.01	1.24	1.07
Mean					1.87	1.01	1.26	1.11
COV					0.164	0.020	0.029	0.036
Slender								
GBU75-S475-L2000-1	11.77	23.17	18.75	21.07	2.09	1.06	1.31	1.17
GBU75-S475-L2000-2	11.23	22.88	18.44	21.57	2.18	1.07	1.33	1.13
GBU75-S475-L2000-3	11.45	22.97	18.62	21.70	2.15	1.07	1.33	1.14
GBU75-S1900-L2000-1	10.42	19.68	16.38	18.28	2.01	1.07	1.28	1.15
GBU75-S1900-L2000-2	10.27	20.21	16.43	17.51	1.97	1.00	1.23	1.16
GBU75-S1900-L2000-3	10.87	19.81	16.32	18.47	1.91	1.05	1.27	1.12
Mean					2.05	1.05	1.29	1.14
COV					0.106	0.026	0.036	0.016

(b) GBU90

Specimen	AISI	AISI& AS/NZS using eq-8	DSM using eq-8	M-DSM using eq-8	Comparison			
	P_{AISI} (kN)	$P_{AISI-eq-8}$ (kN)	P_{M-DSM} (kN)	P_{M-DSM} (kN)	P_{EXP}/P_{AISI} -	$P_{EXP}/P_{AISI-eq-8}$ -	P_{EXP}/P_{DSM} -	P_{EXP}/P_{M-DSM} -
Stub								
GBU90S50L300-1	138.31	145.20	140.34	142.12	1.07	1.02	1.05	1.04
GBU90S50L300-2	137.88	144.33	139.79	141.18	1.06	1.02	1.05	1.04
GBU90S200L300-1	129.01	137.24	132.68	135.50	1.09	1.02	1.06	1.04
GBU90S200L300-2	129.89	137.93	131.98	134.94	1.07	1.00	1.05	1.03
GBU90S200L300-3	130.71	138.02	132.21	135.06	1.07	1.01	1.05	1.03
Mean					1.07	1.01	1.05	1.03
COV					0.011	0.008	0.004	0.006
Short								
GBU90S100L500-1	107.34	130.62	123.07	125.97	1.23	1.01	1.08	1.05
GBU90S100L500-2	107.90	130.84	122.22	126.16	1.24	1.02	1.09	1.06
GBU90S100L500-3	107.87	130.10	122.51	128.54	1.24	1.02	1.09	1.04
GBU90S400L500-1	105.44	127.96	118.82	126.00	1.23	1.01	1.09	1.03
GBU90S400L500-2	105.96	128.08	120.63	126.50	1.23	1.02	1.08	1.03
GBU90S400L500-3	104.77	127.20	120.18	125.70	1.24	1.02	1.08	1.03
GBU90S400L500-4	105.12	127.77	120.43	127.20	1.24	1.02	1.08	1.03
Mean					1.24	1.02	1.08	1.04
COV					0.004	0.004	0.007	0.013
Intermediate								
GBU90S225L1000-1	59.21	81.40	67.85	74.62	1.46	1.06	1.28	1.16
GBU90S225L1000-2	60.33	82.97	68.01	75.98	1.45	1.05	1.29	1.15
GBU90S900L1000-1	57.10	78.92	63.87	70.45	1.45	1.05	1.30	1.18
GBU90S900L1000-2	58.54	79.80	64.89	71.88	1.42	1.04	1.28	1.16
Mean					1.45	1.05	1.29	1.16
COV					0.016	0.008	0.005	0.011

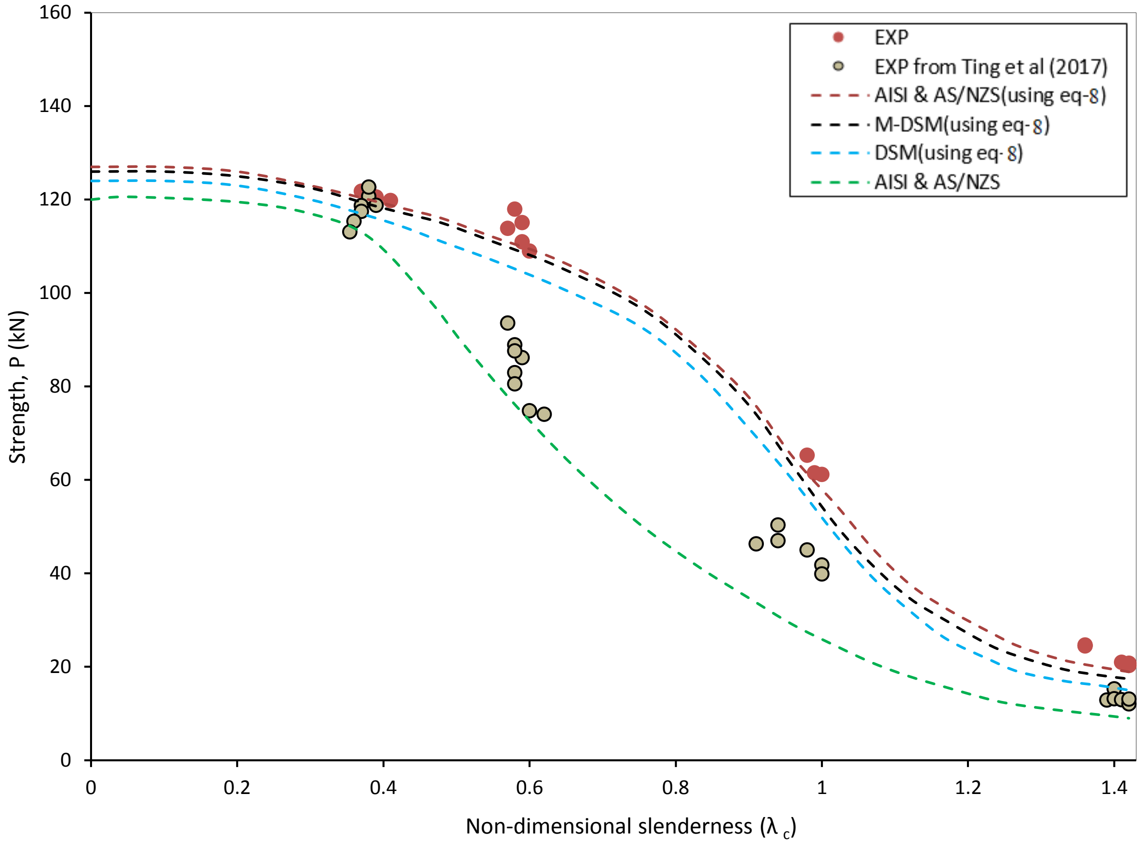


(a) GBU75

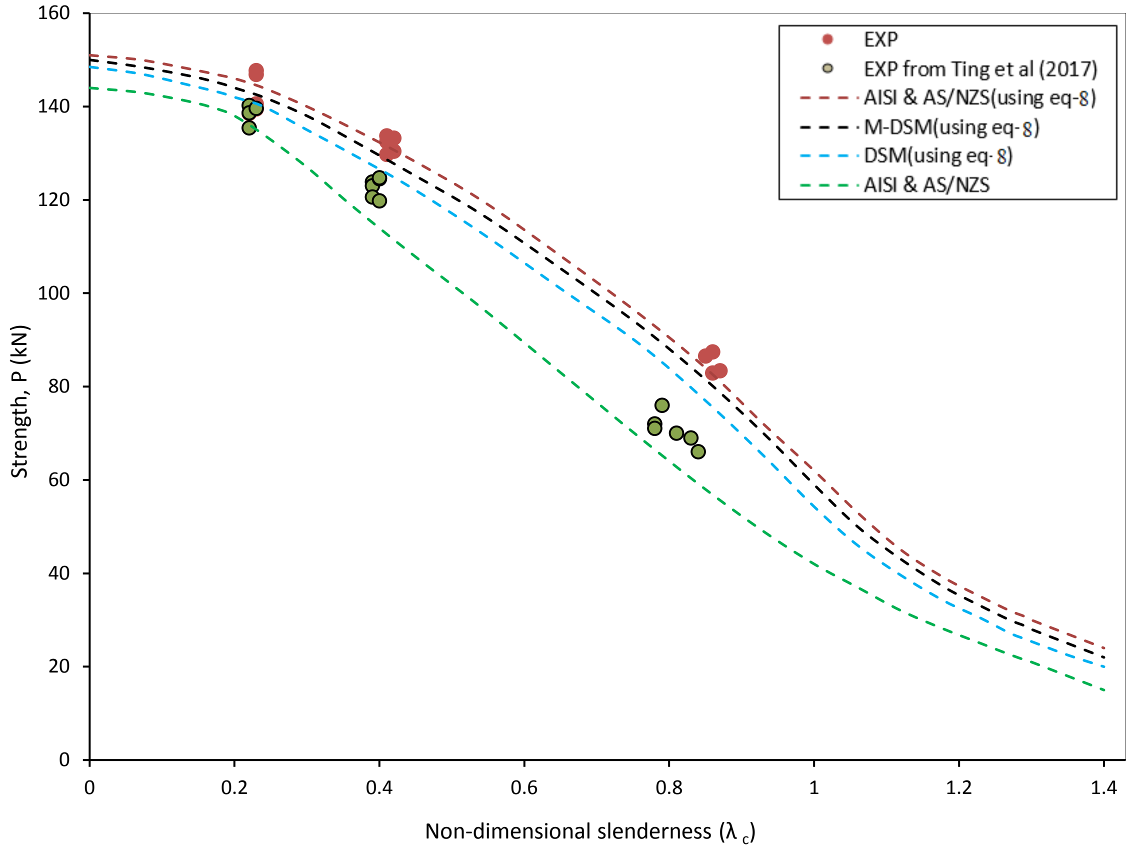


(b) GBU90

Figure 12: Varition of axial strength against length



(a) GBU75



(b) GBU90

Figure 13: Varition of axial strength against λ_c

5 Conclusions

A detailed experimental investigation on the axial strength of back-to-back gapped built-up CFS channel-sections is presented in this paper. A total of 40 tests are reported. The failure modes, load-axial shortening, load-axial strain and deformed shapes at failure is discussed. Effect of the gap on axial strength of columns are investigated. Also investigated the effect of link-channel spacing on the axial strength of back-to-back gapped built-up columns. Different buckling modes at failure are discussed as well. The results are compared against the current AISI and AS/NZS standard.

The column strengths are compared against the design strengths calculated using the AISI & AS/NZS, Direct Strength Method and Modified Direct Strength Method. Test results were as much as 53% higher than the design strengths when non-dimensional slenderness (λ_c) was used to calculate design capacity of such columns. From the experimental results, it can be concluded that the axial strength calculated in accordance with the current design guidelines for back-to-back gapped built-up CFS columns, can be conservative by as much as 53% when λ_c was used to calculate the design capacity. However, the design standards were conservative by only 5% on average to the experimental results, when $\lambda_{c,GAP}$ was used. Hence it is recommended to use $\lambda_{c,GAP}$ while calculating the axial strength of back-to-back gapped built-up CFS columns. Further details can be found in Roy et al. [6], where a non-linear finite element model is developed and verified against the experimental results for back-to-back built-up gapped CFS channel sections.

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