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EXPERIMENTAL STUDY OF UNLIPPED CHANNEL BEAMS SUBJECT TO WEB CRIPPLING UNDER ONE FLANGE LOAD CASES

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A B S T R A C T

Cold-formed steel members are becoming increasingly popular in the building industry due to their superior strength to weight ratio and ease of fabrication as opposed to hot-rolled steel members. However, they are susceptible to various buckling modes at stresses below the yield stress of the member because of their relatively high width-to-thickness ratio. Web crippling is one of the failure modes that occurs in steel channel sections under transverse concentrated loads or reactions. Recently a test method has been proposed by AISI to obtain the web crippling capacities under both one-flange and two-flange load cases. Using this test method 21 tests were conducted in this research to investigate the web crippling behaviour and strengths of an unlipped channel section with stocky webs known as DuraGal Channels under end-one-flange (EOF) and interior one-flange (IOF) load cases. DuraGal channels with different web slenderness and bearing lengths were tested with their flanges unfastened to supports. In this research the suitability of the currently available design rules for unlipped channels subject to web crippling under one flange load cases was investigated, and suitable modifications were proposed where necessary. This paper presents the details of this experimental study and the results.

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Stocky web

1. Introduction

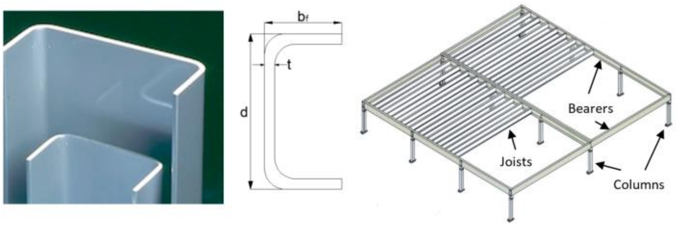
Cold-formed steel members have many advantages over hot-rolled steel members. Among them DuraGal channel sections are commonly used as bearers of floor systems in residential, industrial and commercial buildings [1]. They are thicker channel sections with varying geometry to suit various requirements including higher moment capacities and longer spans. Figure 1(a) shows the DuraGal channel section profile while Figure 1(b) shows its applications in buildings as joists and bearers. Table 1 shows the nominal dimensions of DuraGal channel sections available in the market.

Web crippling is a form of localized failure mode that can occur when the members are subjected to transverse concentrated loadings and/or reactions. (see Figure 2). Cold-formed steel joists and bearers that are unstiffened against this type of loading are vulnerable to these failures. In a typical floor system, web crippling failures can occur at bearer to column and joist to bearer connections depending on various structural details given in Table 2. Failure modes of bearers can be different according to the loading locations such as interior columns, end columns and joists supported by bearers. One-flange loading or reaction occurs when the clear distance between the bearing edges of adjacent opposite concentrated actions or reactions is greater than $1.5d_1$, where d_1 is the depth of the flat portion of the web. Two-flange loading or reaction occurs when the clear distance between the bearing edges of adjacent opposite concentrated actions or reactions is less than or equal to $1.5d_1$. End loading or reaction occurs when the distance from the edge of the bearing to the end of the member is less than or equal to $1.5d_1$ while interior loading or reaction occurs when the distance from the edge of the bearing to the end of the member is greater than $1.5d_1$. To simulate these practical loading conditions, there are four loading cases for web crippling as recommended in the cold-formed steel specifications including American and Australian standards [2,3]. These loading cases are used to investigate the web crippling capacities of cold-formed steel beams. They are End-One-Flange (EOF), End-Two-Flange (ETF), Interior-One-Flange (IOF) and Interior-Two-Flange (ITF) loading as shown in Figure 3.

Current cold-formed steel design rules to predict the web crippling capacities are empirical as they were developed based on extensive testing of many cold-formed steel sections such as C-, Z- and hat sections and built-up sections undertaken since 1940s [4-28]. Since 2005, a unified bearing capacity equation has been developed that defines specific coefficients for the key parameters influencing the bearing capacities of C-, Z-, Hat and built-up sections [13]. They are clear web height to thickness ratio (d_1/t_w), inside bent radius to thickness ratio (r_i/t_w), bearing length to thickness ratio (l_b/t_w), in addition to web thickness (t_w) and yield stress (f_y) [2,3]. However, it should be noted that these capacity equations are not applicable to some of the DuraGal channels due to their large inside bent radius to thickness ratios (r_i/t_w).

The details of suitable test procedures that should be adopted in web crippling studies are presented in the AISI standard test method published in 2008. These test procedures are different to those used by Young and Hancock [19,20] who investigated the web crippling behaviour of DuraGal channels using experimental studies. The AISI standard test method [29] recommends that the test specimen shall be both laterally and torsionally stable. Thus, for a channel section where the geometry does not permit the application of the load through the shear centre, the test specimen shall consist of two opposed sections. The cold-formed steel shapes shall be interconnected using rigid connecting elements such as angles to form the box shape. When using rigid connecting elements, they shall be located at approximately the ¼ and ¾ points along the longitudinal axis of the box shape. However, the test set-ups used in the past research [19,20], are different to those recommended by the AISI standard test method [29] for EOF and IOF load cases. Hence there is a need to investigate the effects of test set-up given in the AISI standard test method on web crippling capacities.

This research is aimed at investigating the web crippling behaviour and strength of unlipped channels with stocky webs under EOF and IOF load cases and determining the accuracy of currently used design rules. Test specimen length and test setup were selected based on the AISI standard test method [29]. Experimental web crippling capacities were compared with the predicted web crippling capacities using the current design rules and suitable modifications were proposed where necessary.



(a) Duragal channel section (b) Floor system

Fig. 1 Cold-formed steel floor systems

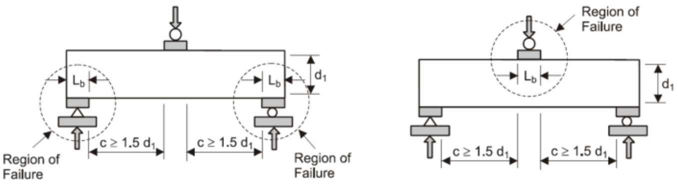
Fig. 2 Web crippling failure at a reaction point

Table 1
Duragal channel sections

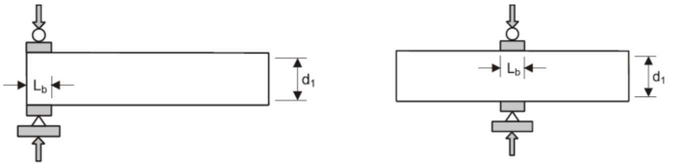
Section	Depth (mm)	Flange (mm)	Thickness (mm)	Radius (mm)
300x90x8	300	90	8.0	8
300x90x6	300	90	6.0	8
250x90x6	250	90	6.0	8
230x75x6	230	75	6.0	8
200x75x6	200	75	6.0	8
200x75x5	200	75	4.7	4
180x75x5	180	75	4.7	4
150x75x5	150	75	4.7	4
125x65x4	125	65	3.8	4
100x50x4	100	50	3.8	4
75x40x4	75	40	3.8	4

Table 2
Different conditions for single web channel sections

Conditions	Options
Support condition	Fastened versus Unfastened
Flange condition	Stiffened (lipped) versus Unstiffened (unlipped)
Loading condition	EOF, IOF, ETF and ITF load cases



(a) End one flange loading (EOF) (b) Interior one flange loading (IOF)



(c) End two flange loading (ETF) (d) Interior two flange loading (ITF)

Fig. 3 Loading conditions for web crippling tests [2,3]

2. Previous studies on web crippling

Theoretical elastic methods [30-32] can be used to analyse the web crippling behaviour of cold-formed steel members subjected to different load conditions. However, it should be noted that the web element of a cold-formed steel member is not identical to a four sided simply supported rectangular plate. The web of a cold-formed steel member cannot be considered as a rectangular plate with idealized boundary conditions (simply supported or clamped at its four sides). Also, the determination of critical elastic buckling load does not necessarily imply the failure of the web. Hence the additional load carrying capacity developed in the web beyond the elastic buckling load should be estimated. Due to these difficulties associated with the theoretical analysis, the development of web crippling design equations in most of the previous studies were based on experimental data.

Winter and Pian [4] investigated the web crippling capacities of cold-formed steel I-sections under four different load cases while Baehre [7] investigated the web crippling capacities of hat sections subjected to IOF loading. Hetrakul and Yu [8] researched the web crippling behaviour of cold-formed steel sections having single unreinforced webs. Wing [9] and Wing and Schuster [10] investigated the web crippling capacities of multi-web cold-formed steel sections under all load cases, except for EOF loading case. In this study the test specimens were fastened to the reaction supports. Santaputra et al. [11] conducted web crippling tests of hat sections and I-beams fabricated from very high-strength steels under various loading conditions. Bhakta et al. [12] experimentally investigated the influence of flange restraint on the web crippling capacity of beam web elements.

Prabakaran [13] completed an extensive statistical analysis of the web crippling capacities of cold-formed steel sections by using the available experimental data found in the literature with an aim to develop one simplified design equation. He recommended a unified equation with different coefficients for the design of I-sections, single web sections and multi-web sections. Cain et al. [14] experimentally investigated the web crippling of Z-sections subjected to EOF loading and I-sections subjected to IOF loading. Gerges [15] and Gerges and Schuster [16] investigated the web crippling resistance of single web cold-formed steel members with large inside bent radius to thickness (r_i/t_w) ratios, subjected to EOF loading. Also they developed new parameter coefficients for Prabakaran's [13] web crippling equation based on tests performed on C-sections fastened to the support. An experimental study of stiffened C-and Z-sections subjected to web crippling was carried out by Beshara and Schuster [17]. ETF and ITF loading conditions were considered with particular emphasis on large r_i/t_w ratios, and the specimens being fastened to the support.

An experimental investigation was carried out by Young and Hancock [20] to investigate the behaviour of cold-formed unlipped DuraGal channels subjected to web crippling under all four loading conditions (EOF, IOF, ETF and ITF). Figure 4 shows the test set-up used by Young and Hancock [20] for IOF load case. Based on the results of their research, the design web crippling strength predictions given by the old American and Australian standards [33,34] were found to be unconservative for the unlipped channel sections. In their paper, a simple plastic mechanism expression for web crippling strength of unlipped channels is also proposed. Macdonald et al. [21] conducted experimental and numerical studies to investigate the web crippling behaviour of lipped channel beams under ETF, ITF, EOF and IOF load cases. Figure 5 shows the experimental setup used in Macdonald et al.'s [21] tests. They found that the bearing length, corner radii and clear height of web had an effect on the web crippling strength of lipped channel beams (LCB), particularly for EOF and IOF load cases. Uzzaman et al. [23-26] and Yousefi el al. [27,28] conducted experimental and numerical studies to investigate the effect of offset web holes on the web crippling strength of cold-formed steel lipped channel beams. They also did web crippling tests of LCBs without web openings.

Recent web crippling studies also included an experimental investigation of a new hollow flange channel beam [35,36] and LCBs [37] under EOF and IOF load cases. Their study led to suitable web crippling design rules based on AS/NZS 4600 and AISI S100 design standards. As part of their studies on DuraGal channel beams, Gunalan and Mahendran [38] conducted an experimental investigation into the web crippling capacities of cold-formed steel unlipped channels with stocky webs under ETF and ITF load cases. The flanges of these channel sections were not fastened to the supports in this study. It was found that the specimen lengths proposed by the AISI testing method should be used for the web crippling tests under ETF and ITF load cases. A detailed comparison of ultimate web crippling capacity results with those predicted by the current design equations in AS/NZS 4600, AISI S100 and Young and Hancock [20] showed that these equations are unconservative for these stocky channel sections under ETF and ITF load cases. Hence new design equations were proposed within these guidelines to accurately predict the web crippling capacities of unlipped channel sections based on test results.

(a) End view (b) Front view

Fig. 4 Young and Hancock's [20] web crippling test set-up for IOF load case

(a) EOF load case (b) IOF load case

Fig. 5 Macdonald et al.'s [21] web crippling test set-up

3. Current design rules

3.1. AS/NZS 4600 and AISI S100

Many different design equations have been proposed and used to predict the web crippling capacity in the past. Web crippling research commenced in 1939 at Cornell University with the first design specification published in 1940 by the American Iron and Steel Institute. Subsequent research at various institutions throughout the world led to the present day design standards in both AS/NZS 4600 [3] and AISI S100 [2]. In the older version of American Specification [33], different design equations were used to predict the web crippling capacity of cold-formed steel beams. Each of these design equations is only applicable to a certain type of cross section geometry and a particular load case. However, the new unified web crippling capacity equation (Equation 1) adopted in AS/NZS 4600 [3] and AISI S100 [2] is applicable to different types of section geometry and load cases (ETF, ITF, EOF and IOF). These standards provide design guidelines for the bearing capacity (R_b) of open cold-formed steel sections, which is based on Prabakaran [13] who performed an extensive statistical analysis of more than 1200 experimental web crippling capacities of a range of cold-formed steel sections and proposed a suitable unified design equation based on four web crippling coefficients (Equation 1). This design rule takes into consideration the clear height of web to thickness ratio (d_1/t_w), inside bent radius to thickness ratio (r_i/t_w), bearing length to thickness ratio (l_b/t_w), yield stress (f_y) and web thickness (t_w). Suitable values of the four coefficients in Equation 1 are given in Table 3 for unlipped channels under EOF and IOF load cases, where the flanges are not connected to the supports (unfastened). It should be noted that these coefficients are applicable for section where the inside bent radius to thickness ratio (r_i/t_w) is less than or equal to one.

$$R_b = Ct_w^2 f_y \sin\theta\left(1 - C_r\sqrt{\frac{r_i}{t_w}}\right)\left(1 + C_l\sqrt{\frac{l_b}{t_w}}\right)\left(1 - C_w\sqrt{\frac{d_1}{t_w}}\right) \tag{1}$$

where C = coefficient; t_w = thickness of web; f_y = yield stress; r_i = inside bent radius; l_b = bearing length; d_1 = depth of the flat portion of the web measured along the plane of the web; θ = angle between the plane of the web and the plane of the bearing surface; C_r, C_l and C_w = coefficients of inside bent radius, bearing length and web slenderness, respectively.

3.2. Young and Hancock [20]

Young and Hancock [20] conducted an experimental study on cold-formed unlipped DuraGal channels with comparatively stocky webs subjected to web crippling. Figure 4 shows their test set-up used for IOF load case where support reaction were transferred through the section web which is different to the test method given in AISI standard test method [29]. The specimen lengths were taken as 3(l_b +d) for both EOF and IOF load cases where l_b is the bearing length and d is the overall depth of the section. Test results were compared with the design equations in the older version of AS/NZS 4600 [34] and AISI [33]. It was found that these design equations are accurate under EOF load case, but are unconservative under IOF load case for unlipped channels.

The web crippling capacities of DuraGal channels from their tests are compared with the predictions from the current design equations based on AS/NZS 4600 [3] and AISI S100 [2] (Tables 4 and 5). The design rules in AS/NZS 4600 are identical to those in AISI S100, and hence only AS/NZS 4600 values are reported in this paper. Overall twisting failure was observed for Section 75x45x4 and hence it was ignored in these tables. The mean values of test to predicted web crippling capacities of unlipped channels by AS/NZ 4600 [3] are 0.83 and 0.86 for EOF and IOF load cases, respectively. The corresponding coefficients of variation (COV) are 0.09 and 0.04, respectively. Tables 4 and 5 results show that AS/NZS 4600 [3] and AISI S100 [2] design equations are up to 32% unconservative for some of the channel sections when higher bearing lengths are used. Hence there is a need to investigate the applicability of the current AS/NZS 4600 and AISI S100 design equations for increased bearing lengths. Also, it should be noted that these design equations restricts the r_i/t_w ratio to one (Table 3) for IOF load case and hence are not applicable to many DuraGal sections in Table 5.

Young and Hancock [20] also developed design equations to predict the web crippling capacities of channels with stocky webs based on their test results. These equations were derived using a combination of theoretical and empirical analyses. It was assumed that the bearing load is applied eccentrically to the web due to the presence of the corner radii, which produces bending of the web out of its plane. This will lead to a plastic mechanism as shown in Figures 6 and 7.

$$P_{pm} = \frac{M_p N_m}{r}\left[C_a - C_b\left(\frac{h}{t}\right)\right] \tag{2}$$

$$M_p = \frac{f_y t_w{}^2}{4} \tag{3}$$

$$r = r_i + \frac{t_w}{2} \tag{4}$$

$$N_m = N + id \quad \text{for interior loading} \tag{5a}$$

$$N_m = N + \frac{ed}{2} \quad \text{for end loading} \tag{5b}$$

where P_{pm} = web crippling strength; M_p = plastic moment per unit length; r and r_i = centreline and inside corner radii, respectively; h = depth of the flat portion of the web; d = overall depth of the web; t_w = thickness of the web f_y = yield stress; N = bearing length; N_m = the assumed mechanism length; C_a = 1.44; C_b = 0.0133. The correction factors for interior loading are i = 1.3 and 1.4 for IOF and ITF load cases, respectively, while for end loading they are e = 1.0 and 0.6 for EOF and ETF load cases, respectively.

Table 3
AS/NZS 4600 web crippling coefficients for unfastened unlipped channels

Load case	C	C_r	C_l	C_w	ϕ_w	r_i/t_w	d_1/t_w	l_b/t_w	l_b/d_1
EOF	4	0.40	0.6	0.03	0.85	≤ 2	≤ 200	≤ 210	≤ 2
IOF	13	0.32	0.1	0.01	0.85	≤ 1	≤ 200	≤ 210	≤ 2

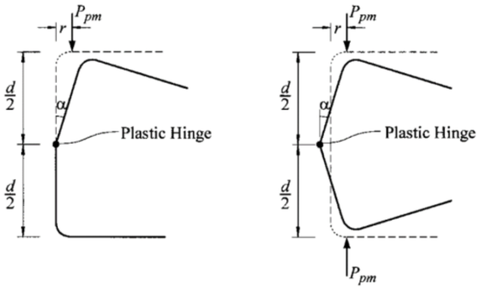
ϕ_w = Capacity reduction factor

Table 4
Young and Hancock's [20] test results for EOF load case

Section	d (mm)	b_f (mm)	t_w (mm)	r_i (mm)	L (mm)	l_b (mm)	f_y (MPa)	E (MPa)	P_{Test} (kN)	$P_{Test}/P_{AS/NZS4600}$	$P_{Test}/P_{Eq.(2)}$
300x90x6	298.6	91.0	6.00	8.4	1079.0	45.0	435	203000	62.5	0.90	1.11
300x90x6	298.6	90.9	6.00	8.4	1167.5	90.0	435	203000	64.8	0.74	0.94
250x90x6	249.7	89.9	5.99	7.9	925.9	45.0	445	203000	61.3	0.82	1.04
250x90x6	249.3	90.1	5.99	7.9	1018.1	90.0	445	203000	64.3	0.68	0.86
200x75x5	198.8	76.0	4.72	4.2	764.6	37.5	415	203000	43.7	0.87	0.97
200x75x5	198.7	75.8	4.71	4.2	839.8	75.0	415	203000	49.3	0.78	0.87
125x65x4	125.6	65.7	3.84	3.9	528.8	32.5	405	203000	29.7	0.90	1.15
125x65x4	125.0	65.5	3.85	3.9	594.0	65.0	405	203000	35.3	0.85	1.01
100x50x4	99.3	50.5	3.85	4.1	440.0	25.0	440	203000	31.4	0.94	1.35
100x50x4	99.3	50.4	3.85	4.1	490.0	50.0	440	203000	34.4	0.83	1.11
Mean										0.83	1.04
COV										0.09	0.14

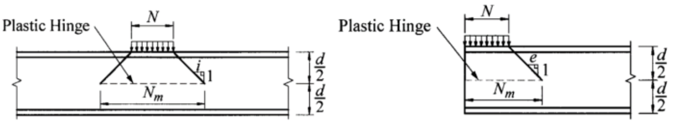
Table 5
Young and Hancock's [20] test results for IOF load case

Section	d (mm)	b_f (mm)	t_w (mm)	r_i (mm)	L (mm)	l_b (mm)	f_y (MPa)	E (MPa)	P_{Test} (kN)	$P_{Test}/P_{AS/NZS4600}$	$P_{Test}/P_{Eq.(2)}$
300x90x6	298.6	91.3	6.00	8.4	1125.0	45.0	435	203000	134.6	0.90	1.07
300x90x6	298.7	91.3	6.00	8.4	1169.0	90.0	435	203000	143.4	0.88	1.04
250x90x6	249.2	90.0	5.99	7.9	974.3	45.0	445	203000	132.3	0.84	1.03
250x90x6	249.8	89.9	5.99	7.9	1023.0	90.0	445	203000	142.8	0.83	0.99
200x75x5	198.7	75.9	4.72	4.2	816.8	37.5	415	203000	91.2	0.90	0.94
200x75x5	198.9	75.9	4.74	4.2	855.2	75.0	415	203000	94.5	0.85	0.86
125x65x4	125.0	65.5	3.86	3.9	587.0	32.5	405	203000	57.4	0.88	1.07
125x65x4	125.0	65.7	3.86	3.9	618.5	65.0	405	203000	63.6	0.90	1.02
100x50x4	99.2	50.4	3.84	4.1	505.0	25.0	440	203000	56.3	0.83	1.18
100x50x4	99.2	50.4	3.83	4.1	529.2	50.0	440	203000	57.9	0.79	1.05
Mean										0.86	1.02
COV										0.04	0.08



(a) One flange loading (b) Two flange loading

Fig. 6 Mechanism model proposed by Young and Hancock [20]



(a) Interior loading (b) End loading

Fig. 7 Plastic hinge position and mechanism length, (N_m) assumed by [20]

4. Experimental study

4.1. Test specimens

After a detailed study of the previous studies on the web crippling behaviour of unlipped channel beams, two series of experimental studies were conducted to investigate the behaviour of cold-formed steel unlipped channels with stocky webs subject to web crippling under EOF and IOF load cases. Twenty one tests were conducted with flanges of test sections not fastened to the bearing plates. Suitable test sections and thicknesses were selected based on the available literature and the standard DuraGal sections and thicknesses commonly used in structural applications. The section depth of DuraGal steel channels varies from 75 mm to 300 mm and the thickness varies from of 4 mm to 8 mm. Hence four commonly used sections with three nominal thicknesses of 4, 5 and 6 mm were selected in the current study. Test specimen length and test setup were selected based on the AISI standard test method [29]. Tables 6 and 7 include their measured external dimensions (*d* and b_f), thicknesses (t_w), internal radius (r_i) and length (*L*). Three different bearing lengths l_b (50 mm, 100 mm and 150 mm) were used for both EOF and IOF load cases.

The nominal yield stress of DuraGal steel channel sections considered in this study is 450 MPa. However, an experimental study was undertaken to determine the accurate mechanical properties. Tensile coupon tests were conducted on four different sections to obtain their stress-strain curves and mechanical properties (elastic modulus, yield stress and ultimate strength). Test specimens were cut in the longitudinal direction of DuraGal channel sections. The base metal thickness and width of each specimen were measured at three points within the gauge length using a micrometer and a vernier calliper, respectively. The averages of these measured dimensions were used in the calculations of mechanical properties. The tensile specimens were tested in an Instron testing machine by loading at a constant strain rate (3.3×10^{-4} s^{-1}) until failure. A calibrated extensometer with a 50 mm gauge length was used to measure the longitudinal strain. Table 8 summarizes the mechanical properties (yield stress, ultimate stress and elastic modulus) determined from the tensile coupon tests.

Table 6
Test specimen details and results for EOF load case

Test	Section	d (mm)	b_f (mm)	t_w (mm)	r_i (mm)	L (mm)	l_b (mm)	P_{Test} (kN)
E-1	230x75x6	230.0	74.6	5.95	8.0	990	100	77.3
E-2	230x75x6	230.0	74.5	6.00	8.0	1140	150	89.7
E-3	180x75x5	179.0	74.9	4.60	4.0	840	100	56.7
E-4	180x75x5	179.5	74.9	4.70	4.0	991	150	65.9
E-5	150x75x5	149.5	75.1	4.75	4.0	750	100	61.6
E-6	150x75x5	151.0	75.0	4.70	4.0	900	150	63.4
E-7	100x50x4	100.5	50.0	3.85	4.0	450	50	38.6*
E-8	100x50x4	100.5	49.9	3.90	4.0	600	100	41.3^{T}
E-9	100x50x4	101.0	49.9	3.85	4.0	750	150	39.3^{T}

* - Corresponding Young and Hancock's [20] value is 34.4 kN;
T - Combined twisting and web crippling failure.

Table 7
Test specimen details and results for IOF load case

Test	Section	d (mm)	b_f (mm)	t_w (mm)	r_i (mm)	L (mm)	l_b (mm)	P_{Test} (kN)
I-1	230x75x6	229.0	74.9	6.0	8.0	840	50	136.0
I-2	230x75x6	229.5	74.9	6.0	8.0	990	100	150.5
I-3	230x75x6	229.5	74.7	6.0	8.0	1140	150	157.0
I-4	180x75x5	180.0	75.7	4.7	4.0	690	50	88.8
I-5	180x75x5	180.0	74.6	4.7	4.0	840	100	100.0
I-6	180x75x5	179.0	75.4	4.7	4.0	990	150	110.7
I-7	150x75x5	149.5	74.9	4.7	4.0	595	50	91.0
I-8	150x75x5	150.0	74.9	4.7	4.0	750	100	103.1
I-9	150x75x5	150.5	75.0	4.7	4.0	900	150	111.8
I-10	100x50x4	101.0	49.8	3.8	4.0	450	50	61.9*
I-11	100x50x4	101.0	50.0	3.8	4.0	600	100	70.5
I-12	100x50x4	101.0	49.9	3.8	4.0	750	150	71.0^{T}

* - Corresponding Young and Hancock's [20] value is 57.9 kN;
T - Combined twisting and web crippling failure.

Table 8
Mechanical properties of test specimens

Section	230x75x6	180x75x5	150x75x5	100x50x4
Yield strength (MPa)	483	457	468	449
Ultimate strength (MPa)	540	532	547	539

Elastic modulus = 200,000 MPa

4.2. Test set-up and procedure

Tests were conducted using a 300 kN Instron testing machine in the Structural Laboratory. Figures 8 and 9 show the test set-up used in the web crippling tests of this research for EOF and IOF load cases, respectively (see Figures 3(a) and (b)). Two channel sections were considered for EOF and IOF load cases as recommended in [29]. A 25 x 25 x 5.0 EA is fastened to the top and bottom flanges to interconnect the two sections at ¼ and ¾ points along the span. The support system was designed to ensure that the test beam had pinned supports at the top and bottom using half rounds except at one bottom support, where a roller support was simulated by ensuring a smooth surface between half round and test surfaces. Preliminary tests with and without simulating a roller support at one bottom end showed that its effect on the web crippling failure load is negligible (<2.5%).

Test specimens were located between the bearing plates and a small load was applied first to allow the loading and support systems to settle evenly on the bearings. The measuring system was then initialised with zero values and the loading was commenced. The cross-head of the testing machine was moved at a constant rate of 0.7 mm/minute until failure. During the tests, the displacements of specimens were recorded in addition to the applied load. Displacement transducers were located on the test beam near the supports (for EOF load case) and near the loading point (for IOF load case) to measure the lateral (web) deflections as shown in Figures 8 and 9, respectively.

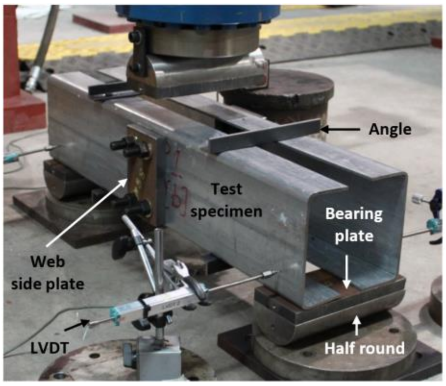


Fig. 8 Web crippling test set-up for EOF load case

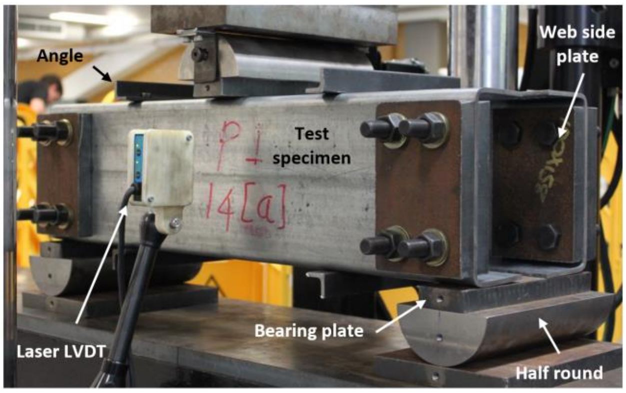
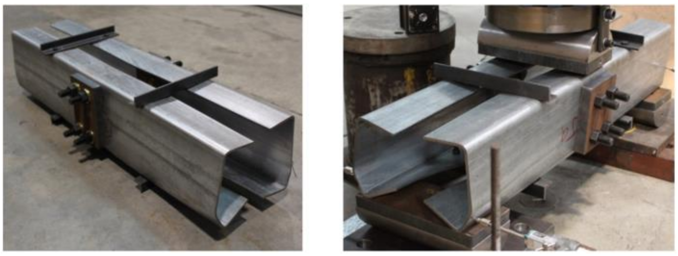


Fig. 9 Web crippling test set-up for IOF load case

4.3. Test results and discussion

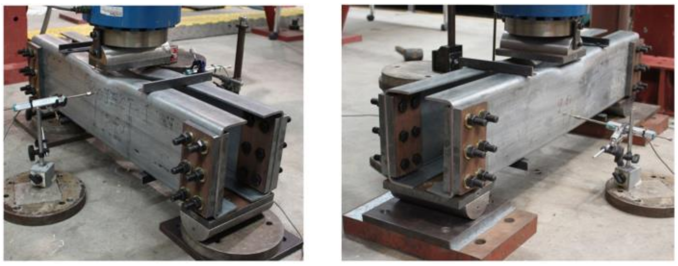
Tables 6 and 7 show the web crippling capacities (ultimate loads) of DuraGal channel sections as obtained from this experimental study for EOF and IOF load cases, respectively while Figures 10 and 11 show the typical failure modes of channels under these load cases, respectively. Young and Hancock's [20] tests were based on a different test set-up (Figure 4) and these tests (Tables 4 and 5) were repeated in our study according to the new AISI standard test method [29] and their results reasonably agree with our corresponding results as shown in Tables 6 and 7. Their test results were found to be slightly lower compared to our results. This may be due to the varying imperfection levels and possible variations in the yield strength of the test specimens. Hence it was concluded that both these test set-ups can be used to conduct the web crippling experimental study under EOF and IOF load cases. Therefore the test results from Young and Hancock [20] are also used for further investigation together with the current test results.

(a) Test E-1 (b) Test E-2



(c) Test E-3 (d) Test E-5

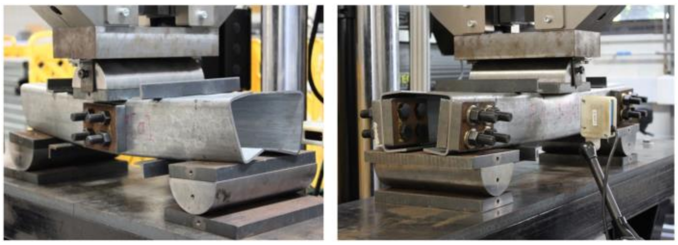
Fig. 10 Web crippling failure modes under EOF load case



(a) Test I-2 (b) Test I-3

(c) Test I-2 (d) Test I-7

Fig. 11 Web crippling failure modes under IOF load case



(a) Test E-8 (EOF load case) (b) Test I-12 (IOF load case)

Fig. 12 Combined twisting and web crippling failure

Figure 12 shows the combined twisting and web crippling failure mode of channel sections when longer specimen lengths were used (Tests E8, E9 and I12). Such twisting failures were not considered here for further investigations in Tables 9 and 10. Figures 13 (a) and (b) show the typical load versus deflection curves from the web crippling tests under EOF and IOF load cases, respectively.

Tables 9 and 10 compare the experimental ultimate web crippling capacities with the predictions from the design equation (Equation 1) based on AS/NZS 4600 [3] and AISI S100 [2]. The test results from Young and Hancock [20] are also included in these tables. For the prediction of web crippling capacities, support and flange conditions were taken as unfastened, unstiffened flanges and one-flange loading or reaction based on Table 2 and the corresponding web crippling coefficients are given in Table 11. When applying the design rules of AS/NZS 4600, the coefficients prescribed by the standards are used. For EOF load case, the mean value of test to predicted web crippling capacity of DuraGal channels by AS/NZS 4600 is 0.80 while the corresponding coefficient of variation (COV) is 0.11. For IOF load case, the mean value of test to predicted web crippling capacity of DuraGal channels by AS/NZS 4600 is 0.83 while the corresponding COV is 0.05. Tables 9 and 10 show that AS/NZS 4600 and AISI S100 design equations are about 34% unconservative for some cases under EOF load case, and they are about 24% unconservative under IOF load case.

Tables 9 and 10 also compare the test results with the predictions from the design equation (Eq. 2) given in Young and Hancock [20]. The coefficients proposed by Young and Hancock for use with Equation 2 are given in Table 12. For EOF load case, the mean value of test to predicted web crippling capacity of unlipped channels with stocky webs by Young and Hancock [20] is 0.96 while the corresponding coefficient of variation (COV) is 0.19. For IOF load case, the mean value of test to predicted web crippling capacity of DuraGal channels is 0.95 with a COV of 0.13. Tables 9 and 10 show that Young and Hancock's [20] design equations are up to 35% unconservative under EOF load case and are up to 26% unconservative under IOF load case, when higher bearing lengths are used.

Based on the comparison of test results with the currently available design rules, it was found that they are not accurately predicting the web crippling capacities of stocky web channels. Hence there is a need to modify the existing design rules and/or propose new design rules to predict the web crippling capacities of unlipped channels with stocky webs.

Table 9

Comparison of test results with predictions for EOF load case

Test	Section	l_b (mm)	P_{Test} (kN)	Test/Predicted ultimate load ratios AS/NZS	Prop. 1(a)	Eq. (2)	Prop. 2
E-1	230x75x6	100	77.3	0.74	1.02	0.93	1.00
E-2	230x75x6	150	89.7	0.73	1.08	0.86	1.02
E-3	180x75x5	100	56.7	0.75	1.00	0.80	0.93
E-4	180x75x5	150	65.9	0.72	1.03	0.70	0.90
E-5	150x75x5	100	61.6	0.73	0.96	0.80	0.89
E-6	150x75x5	150	63.4	0.66	0.95	0.65	0.82
E-7	100x50x4	50	38.6	0.90	1.11	1.20	1.19
E-8^{Y}	300x90x6	45	62.5	0.90	1.06	1.11	1.13
E-9^{Y}	300x90x6	90	64.8	0.74	1.00	0.94	1.08
E-10^{Y}	250x90x6	45	61.3	0.82	0.95	1.04	0.97
E-11^{Y}	250x90x6	90	64.3	0.68	0.92	0.86	0.92
E-12^{Y}	200x75x5	37.5	43.7	0.87	0.94	0.97	0.93
E-13^{Y}	200x75x5	75	49.3	0.78	0.98	0.87	0.95
E-14^{Y}	125x65x4	32.5	29.7	0.90	1.02	1.15	1.04
E-15^{Y}	125x65x4	65	35.3	0.85	1.10	1.01	1.07
E-16^{Y}	100x50x4	25	31.4	0.94	1.01	1.35	1.15
E-17^{Y}	100x50x4	50	34.4	0.83	1.02	1.11	1.10
Mean				0.80	1.01	0.96	1.00
COV				0.11	0.06	0.19	0.10

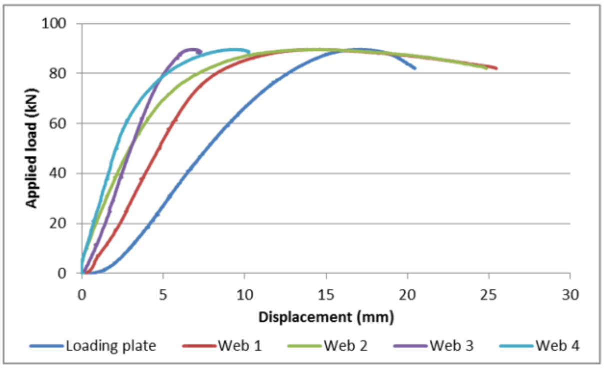
Y - Tests conducted by Young and Hancock [20]

Table 10

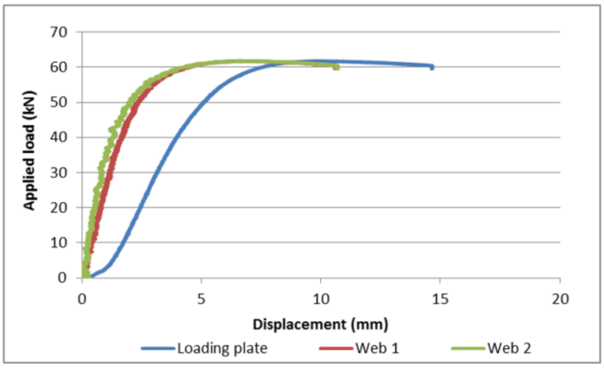
Comparison of test results with predictions for IOF load case

Test	Section	l_b (mm)	P_{Test} (kN)	Test/Predicted load ratios AS/NZS	Prop. 1(a)	Eq. (2)	Prop. 2
I-1	230x75x6	50	136.0	0.79	0.93	1.00	1.00
I-2	230x75x6	100	150.5	0.80	0.94	0.96	1.03
I-3	230x75x6	150	157.0	0.78	0.92	0.89	1.00
I-4	180x75x5	50	88.8	0.77	0.96	0.80	0.83
I-5	180x75x5	100	100.0	0.79	0.98	0.77	0.85
I-6	180x75x5	150	110.7	0.81	1.01	0.74	0.87
I-7	150x75x5	50	91.0	0.76	0.95	0.86	0.87
I-8	150x75x5	100	103.1	0.79	0.98	0.81	0.88
I-9	150x75x5	150	111.8	0.80	0.99	0.75	0.87
I-10	100x50x4	50	61.9	0.84	1.03	1.09	1.12
I-11	100x50x4	100	70.5	0.86	1.05	0.97	1.10
I-12^{Y}	300x90x6	45	134.6	0.90	1.05	1.07	1.15
I-13^{Y}	300x90x6	90	143.4	0.88	1.03	1.04	1.15
I-14^{Y}	250x90x6	45	132.3	0.84	1.00	1.03	1.05
I-15^{Y}	250x90x6	90	142.8	0.83	0.99	0.99	1.06
I-16^{Y}	200x75x5	37.5	91.2	0.90	1.12	0.94	0.97
I-17^{Y}	200x75x5	75	94.5	0.85	1.06	0.86	0.93
I-18^{Y}	125x65x4	32.5	57.4	0.88	1.08	1.07	1.06
I-19^{Y}	125x65x4	65	63.6	0.90	1.10	1.02	1.08
I-20^{Y}	100x50x4	25	56.3	0.83	1.02	1.18	1.13
I-21^{Y}	100x50x4	50	57.9	0.79	0.97	1.05	1.08
Mean				0.83	1.01	0.95	1.00
COV				0.05	0.05	0.13	0.11

Y - Tests conducted by Young and Hancock [20]



(a) EOF load case (Test E-2)



(b) IOF load case (Test I-10)

Fig. 13 Typical load versus deflection curves

5. Proposed design rules

5.1. AS/NZS 4600 and AISI S100

Since the currently available web crippling capacity equations were found to be unconservative for unlipped channels with stocky webs, new design equations are proposed to predict the web crippling capacities of these channels based on experimental results. This approach is similar to that used in the current cold-formed steel design codes [2,3] in which Equation 1 is proposed with modified web crippling coefficients C, C_r, C_l and C_w given in Table 11. Experimental ultimate web crippling capacities are compared with the predictions from Equation 1 with the proposed coefficients (Proposal 1(a)). For EOF load case, the mean value of test to predicted web crippling capacity of DuraGal channel is 1.01 while the corresponding COV is 0.06. For IOF load case, the mean value of test to predicted web crippling capacity of DuraGal channel is 1.01 while the corresponding COV is 0.05. It shows that the web crippling capacities predicted by Equation 1 with proposed coefficients agree well with the experimental web crippling capacities of unlipped channels with stocky webs under IOF and EOF load cases.

The North American Cold-formed Steel Specification [2] recommends a statistical model to determine a suitable capacity reduction factor. This model accounts for the variations in material, fabrication and loading effects. The capacity reduction factor is given by Equation 6 (a).

$$\varphi_w = 1.52 M_m F_m P_m e^{-\beta_0 \sqrt{\left\{V_m^2 + V_f^2 + C_p V_p^2 + V_q^2\right\}}} \tag{6a}$$

with $C_p = \left[1 + \frac{1}{n}\right]\left[\frac{m}{m-2}\right]$ (6b)

where ϕ_w = capacity reduction factor; M_m, V_m = mean and coefficient of variation of the material factor = 1.1, 0.1; F_m and V_f = mean and coefficient of variation of the fabrication factor = 1.0, 0.05; V_q = coefficient of variation of load effect = 0.21; β_o = target reliability index for cold-formed steel members = 2.5; C_p = correction factor depending on the number of tests; P_m = mean value of the tested to predicted load ratio; V_p = coefficient of variation of the tested to predicted load ratio, but not less than 6.5%; n = number of tests; m = degree of freedom = n - 1.

Using Equation 6 with the mean and COV values in Table 11 gave a capacity reduction factor (ϕ_w) of 0.91 for both EOF and IOF load cases for Proposal 1(a). Hence the coefficient C was modified in Proposal 1(b) (Table 11) in order to propose a universal capacity reduction factor of 0.85 for web crippling subjected to EOF and IOF load cases.

5.2. Young and Hancock [20]

It was found that the web crippling design equations proposed by Young and Hancock [20] are unsafe for some DuraGal channels. Hence new coefficients are proposed in Table 12 to predict the web crippling capacities of DuraGal channels using Equation 2 (Proposal 2). Experimental ultimate web crippling capacities are compared with the predictions in Tables 9 and 10 using the proposed coefficients given in Table 12. For EOF load case, the mean value of test to predicted web crippling capacity of DuraGal channel is 1.00 while the corresponding COV is 0.10. For IOF load case, the mean value of test to predicted web crippling capacity of DuraGal channel is 1.00 while the corresponding COV is 0.11. It shows that the web crippling capacities predicted by Equation 2 with the proposed coefficients in Table 12 agree well with the experimental web crippling capacities of unlipped channels with stocky webs under IOF and EOF load cases. The corresponding capacity reduction factor (ϕ_w) is 0.87 for both EOF and IOF load cases, respectively.

Table 11
Proposed coefficients based on AS/NZS 4600 design rules

Load case	Coefficients	C	C_r	C_l	C_w	Mean	COV	ϕ_w
EOF	AS/NZS 4600	4.0	0.4	0.6	0.03	0.80	0.11	0.68
EOF	Proposal 1(a)	9.1	0.5	0.1	0.03	1.01	0.06	0.91
EOF	Proposal 1(b)	9.6	0.5	0.1	0.03	0.96	0.06	0.87
IOF	AS/NZS 4600	13.0	0.32	0.1	0.01	0.83	0.05	0.75
IOF	Proposal 1(a)	9.0	0.2	0.1	0.01	1.01	0.05	0.91
IOF	Proposal 1(b)	9.5	0.2	0.1	0.01	0.96	0.05	0.87

Table 12
Proposed coefficients based on Young and Hancock's [20] design rules

Load case	Coefficients	C_a	C_b	e	i	Mean	COV	ϕ_w
EOF	[20]	1.44	0.0133	1	N/A	0.96	0.19	0.73
EOF	Proposal 2	0.82	0.0110	3	N/A	1.00	0.10	0.87
IOF	[20]	1.44	0.0133	N/	1.3	0.95	0.13	0.79
IOF	Proposal 2	0.87	0.0101	N/	2.6	1.00	0.11	0.87

6. Conclusions

This paper has described an experimental study into the web crippling capacities of cold-formed steel unlipped channels with stocky webs under EOF and IOF load cases. Twenty one tests were conducted on DuraGal channel sections with stocky webs for different bearing lengths. The flanges of these channel sections were not fastened to the supports in this study. A full description of the web crippling and ultimate strength behaviour of cold-formed steel sections is presented in this paper including ultimate loads, failure modes and load-deformation curves. It was found that the test method proposed by AISI S909 [29] and the test method used by Young and Hancock [20] gave similar ultimate loads for web crippling tests under EOF and IOF load cases. A detailed comparison of current and previous test results with those predicted by the current design equations in AS/NZS 4600, AISI S100 and Young and Hancock [20] showed that these equations are unconservative for these stocky channel sections under EOF and IOF load cases. Hence new design equations were proposed within these guidelines to accurately predict the web crippling capacities of unlipped channel sections. Future research in this field should include experimental and numerical studies of all the commonly used cold-formed steel beam sections with a goal to develop an improved, unified web crippling design method based on the direct strength method for inclusion in the cold-formed steel standards.

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