Web Crippling Tests of Cold-formed Steel Channels under Two Flange Load Cases

S. Gunalan

Science and Engineering Faculty, Queensland University of Technology
Brisbane, QLD, 4000, Australia.

M. Mahendran

Science and Engineering Faculty, Queensland University of Technology
Brisbane, QLD, 4000, Australia.

Abstract:

Cold-formed steel members have many advantages over 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 a form of localized failure mode that can occur when the members are subjected to transverse high concentrated loadings and/or reactions. The four common loading conditions are the end-one-flange (EOF), interior-one-flange (IOF), end-two-flange (ETF) and interior-two-flange (ITF) loadings. Recently a test method has been proposed by AISI to obtain the web crippling capacities under these four loading conditions. Using this test method 42 tests were conducted in this research to investigate the web crippling behaviour and strengths of unlipped channels with stocky webs under ETF and ITF cases. DuraGal sections having a nominal yield stress of 450 MPa were tested with different web slenderness and bearing lengths. The flanges of these channel sections were not fastened to the supports. In this research the suitability of the currently available design rules for unlipped channels subject to web crippling was investigated, and suitable modifications were proposed where necessary. In addition to this, a new design rule was proposed based on the direct strength method to predict the web crippling capacities of tested beams. This paper presents the details of this experimental study and the results.

Keywords: Cold-formed Steel structures, Unlipped channels, Web crippling, ETF and ITF Load cases, Experiments.

Corresponding author's email address: m.mahendran@qut.edu.au

1. Introduction

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. 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 dimensions 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 one of the failure modes that occurs in steel channel sections at points of transverse concentrated loading or supports applied on a short length of the beam (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 as 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. 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 have to be 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. One-flange loading or reaction occurs when the clear distance between the bearing edges of adjacent opposite concentrated actions or reactions is greater than $1.5d_l$. 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 $1.5d_l$. 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 $1.5d_l$. Interior loading or reaction occurs when the distance from the edge of the bearing to the end of the member is greater than $1.5d_l$.

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 [4-24]. 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_l/t_w), inside bent radius to thickness ratio (r_i/t_w) and 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 the increased inside bent radius to thickness ratios (r_i/t_w).

The AISI standard test method published in 2008 [25] presents the details of suitable test procedures that should be adopted in web crippling studies. These test procedures are different to those used by Young and Hancock [19,20] who investigated the web crippling behaviour of unlipped channels with stocky webs using experimental studies. The AISI standard test method [25] recommends that the specimen length should be at least equal to three times the flat portion of clear web height (d_l) for ETF load case while it should be at least equal to five times d_l for ITF load case. Web crippling capacities vary with specimen length as this will influence the failure zone. However, test specimen lengths used in the past research [19,20], are different to those recommended by the AISI standard test method [25] for ETF and ITF load cases. Hence there is a need to investigate the effects of using the specimen lengths 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 ETF and ITF 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 [25]. Experimental web crippling capacities were compared with the predicted web crippling capacities using the current design rules and suitable modifications were proposed where necessary. New design rules were also developed under the direct strength method format.

2. Previous Studies on Web Crippling

The web crippling of cold-formed steel members subjected to different load conditions can be analysed using different theoretical elastic methods [26-28]. 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, most of the previous studies have relied on experimental data in developing web crippling design equations.

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 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 the 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 more than 1200 experimental data found in the literature. The aim of his study was to develop one simplified design equation to calculate the web crippling capacity of cold-formed steel sections. Based on the results of his research, Prabakaran [13] 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 ratios, subjected to EOF loading. Also he developed new parameter coefficients for Prabakaran's [13] web crippling equation based on tests performed on C-sections fastened to the support. An experimental investigation of cold-formed steel 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 inside bent radius to thickness ratio r_i/t_w , and the specimens being fastened to the support during testing.

An experimental investigation was carried out by Young and Hancock [20] to investigate the behaviour of cold-formed unlippped channels with stocky webs 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 ETF load case. Based on the results of their research, the design web crippling strength predictions given by the old American and Australian standards [29,30] were found to be unconservative for the unlipped channel sections tested. In their paper, a simple plastic mechanism expression for web crippling strength of unlipped channels is also proposed.

Recently, 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 radius and clear height of web had an effect on the web crippling strength of lipped channel beams (LCB), particularly for the IOF and EOF load cases. Uzzaman et al. [23,24] 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 under ETF and ITF load cases. Figure 6 shows the experimental setup used in Uzzaman et al.'s [23,24] tests. Uzzaman et al. [23,24] also did web crippling tests of LCBs without web openings under the same load cases.

3. Current Design Rules

3.1. AS/NZS 4600 and AISI S100

In the past, many different design equations have been proposed and used to predict the web crippling capacity of cold-formed steel beams. 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 [29], 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_l/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 ETF and ITF 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.

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

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

3.2. Young and Hancock [20]

An experimental study was conducted by Young and Hancock [20] on cold-formed unlipped DuraGal channels with comparatively stocky webs subjected to web crippling. The specimen lengths were taken as bearing length l_b plus $1.5d$ and $3d$ for ETF and ITF load cases, respectively, where d is the overall depth of the section. Test results were compared with the design equations in the older version of AS/NZS 4600 [30] and AISI [29]. It was found that these design equations are unconservative for unlipped channels. Tables 4 and 5 show the web crippling capacities of DuraGal channels from their tests, which are compared with the predictions from the current design equations based on AS/NZS 4600 [3] and AISI S100 [2]. 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. The mean values of test to predicted web crippling capacities of unlipped channels by AS/NZ 4600 [3] are 0.95 and 1.05 for ETF and ITF load cases, respectively. The corresponding coefficients of variation (COV) are 0.12 and 0.16, respectively. Tables 4 and 5 results show that AS/NZS 4600 [3] and AISI S100 [2] design equations are up to 25% unconservative for some of the channel sections when higher bearing lengths are used. Also, these design equations are not applicable to sections with larger r_i/t_w ratios. Hence there is a need to investigate the applicability of the current AS/NZS 4600 and AISI S100 design equations for larger bearing lengths.

Based on their test results, Young and Hancock [20] developed design equations to predict the web crippling capacities of channels with stocky webs. 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 corner radii, which produces bending of the web out of its plane. This will cause a plastic mechanism as shown in Figures 7 and 8 where N_m is the assumed mechanism length.

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

$$\text{with } M_p = \frac{f_y t_w^2}{4} \quad (3)$$

$$r = r_i + \frac{t_w}{2} \quad (4)$$

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

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

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

The bearing failure for a smaller bearing length is likely to be flange crushing (failure at the corner region instead of web crippling (failure at the web mid-height). These two different failure modes were not considered separately in Young and Hancock [20] who compared all their test results with their proposed equation as shown in Tables 4 and 5. It was observed that some of the test/predicted ratios were much higher than one, indicating possible flange crushing. However, it should be noted that Young and Hancock's [20] design equation is only suitable for channels subjected to web crippling (plastic mechanism at the middle of the web)

and hence their empirical co-efficients should be modified by considering only the test results for pure web crippling failures.

4. Experimental Study

Following a review of the previous studies on web crippling 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 ETF and ITF load cases. Forty two tests were conducted with flanges of test sections not fastened to the bearing plates.

4.1. Test Specimens

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 while their thickness varies from 4 mm to 8 mm. Hence seven commonly used sections with three nominal thicknesses of 4, 5 and 6 mm were selected in the current study. Tables 6 and 7 include their measured external dimensions (d and b_f), thicknesses (t_w), internal corner radius (r_i) and length (L). Four bearing lengths l_b (25, 50 mm, 100 mm and 150 mm) were used for both ETF and ITF load cases. Test specimen length and test setup were selected based on the AISI standard test method [25]. Accordingly the specimen length should be at least equal to three times the flat portion of clear web height (d_l) for the ETF load case while it should be at least equal to five times the flat portion of clear web height for the ITF load case.

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 seven 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 steel sections. Their shapes and sizes were in accordance with AS 1391 [31]. 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 a 50 kN Instron testing machine by loading at a constant strain rate ($3.3 \times 10^{-4} \text{ s}^{-1}$) until failure.

Table 8 summarizes the mechanical properties (yield stress, ultimate stress and elastic modulus) determined from the tensile coupon tests.

4.2. Test Set-up and Procedure

Figures 9 and 10 show the test set-up used in the web crippling tests of this research for ETF and ITF load cases, respectively (see Figures 3(c) and (d)). Tests were conducted using a 300 kN Instron testing machine in the Structural Laboratory at the Queensland University of Technology. The support system was designed to ensure that the test beam had pinned supports at the top and bottom using half rounds. Single channel section was considered for ETF and ITF load cases as was done in [20-24]. It should be noted that no sign of twisting was observed during experiments.

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 were recorded in addition to the applied load. Two laser displacement transducers were located on the test beam near the loading point to measure the vertical (flange) and lateral (web) deflections, respectively, as shown in Figures 9 and 10.

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 ETF and ITF load cases, respectively while Figures 11 and 12 show the typical failure modes of channels under these load cases, respectively. It was observed that the influence zone length extended to more than the specimen length used by Young and Hancock [20] for some of the test specimens. This behaviour varied between the tests depending on the web crippling parameters (r_i/t_w , l_b/t_w and d_l/t_w ratios). Tests I1-I5 and E1-E5 were undertaken to study the effect of specimen length and their results show that the ultimate load increased by 5-10% when the specimen length was increased to the values recommended by the AISI test method [25]. This variation is expected to increase further with increased r_i/t_w , l_b/t_w and d_l/t_w ratios. Hence it is concluded that the lengths proposed by the AISI testing method in [25] should be used for web crippling tests under ETF and ITF load cases. Further finite element analysis based research is

continuing to investigate the web crippling behaviour of channel sections with varying lengths under ETF and ITF load cases.

Two of the tests were repeated and the consistency of test results was validated (see Table 6). Young and Hancock's [20] tests were based on shorter lengths and these tests (Tables 4 and 5) were repeated in our study (with shorter lengths) and their results reasonably agree with our corresponding results in Tables 6 and 7. Their test results were found to be only slightly higher for the same length. This may be due to the varying imperfection levels and possible variations in the yield strength of the test specimens. It was also observed that web crippling capacities did not vary much for Section 100x50x4 with different lengths, considering the experimental variations such as cross-sectional dimensions and imperfections.

Tables 9 and 10 compare the test results with the predictions from the current and proposed design rules. Only the test samples which comply with the AISI standard test method [25] are considered in these tables. Figure 13 shows the failure mode of combined flange crushing and web crippling of channel sections when smaller bearing lengths were used. Such combined flange crushing and web crippling failures were not considered here for further investigations in Tables 9 and 10. Figures 14(a) and (b) show the typical load versus deflection curves from the web crippling tests under ETF and ITF load cases, respectively. Figure 15 shows the typical load versus deflection curves for a DuraGal section (Test E-2) with flange bent outwards (Stage 1 in Figure 15). In this case the load versus deflection curves were nearly flat in the initial stage of the test. The section withstood about 1-2 kN until the flanges were bent to the horizontal position by the loading plate (Stage 2). Thereafter the section deformed (similar to other tests) as shown in Figure 15 (Stage 3) and failed by forming a hinge at web mid height (Stage 4).

Experimental ultimate web crippling capacities are compared with the predictions from the design equation (Equation 1) based on AS/NZS 4600 [3] and AISI S100 [2] in Tables 9 and 10. For the prediction of web crippling capacities, support and flange conditions were taken as unfastened, unstiffened flanges and two-flange loading or reaction based on Table 2 and the corresponding web crippling coefficients are given in Table 11. It should be noted that, when applying the design rules of AS/NZS 4600, the coefficients prescribed by the standards are used. For ETF load case, the mean value of test to predicted web crippling capacity of unlippped channels with stocky webs by AS/NZS 4600 is 0.85 while the corresponding

coefficient of variation (COV) is 0.07. For ITF load case, the mean value of test to predicted web crippling capacity by AS/NZS 4600 is 0.86 while the corresponding COV is 0.08. Tables 9 and 10 show that AS/NZS 4600 and AISI S100 design equations are about 26% unconservative for some cases under ETF load case while they are 22% unconservative under ITF load case.

Experimental ultimate web crippling capacities are also compared with the predictions from the design equation given in Young and Hancock [20] (Tables 9 and 10). The web crippling coefficients proposed by Young and Hancock are given in Table 12. For ETF load case, the mean value of test to predicted web crippling capacity of unlipped channels with stocky webs by Young and Hancock [20] is 0.82 while the corresponding coefficient of variation (COV) is 0.22. For ITF load case, the mean value of test to predicted web crippling capacity is 0.88 while the corresponding COV is 0.15. Tables 9 and 10 show that Young and Hancock's [20] design equations are up to 47% unconservative under ETF load case and they are up to 31% unconservative under ITF 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.

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 ETF load case, the mean value of test to predicted web crippling capacity of unlipped channels with stocky webs is 1.00 while the corresponding COV is 0.05. For ITF load case, the mean value of test to predicted web crippling capacity is 1.01 while the corresponding COV is 0.04. 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 ETF and ITF load cases.

Capacity Reduction Factor (ϕ_w)

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

$$\phi_w = 1.52 M_m F_m P_m e^{-\beta_0 \sqrt{\{V_m^2 + V_f^2 + C_p V_p^2 + V_q^2\}}} \quad (6)$$

where ϕ_w is capacity reduction factor; M_m , V_m are mean and coefficient of variation of the material factor = 1.1, 0.1; F_m and V_f are mean and coefficient of variation of the fabrication factor = 1.0, 0.05; V_q is coefficient of variation of load effect = 0.21; β_0 is target reliability index for cold-formed steel members = 2.5; C_p is correction factor depending on the number of tests = $\left[1 + \frac{1}{n} \left\lfloor \frac{m}{m-2} \right\rfloor\right]$; P_m is mean value of the tested to predicted load ratio; V_p is coefficient of variation of the tested to predicted load ratio, but not less than 6.5%; n is number of tests, m is degree of freedom = $n - 1$.

Using Equation 6 with the mean and COV values in Table 11 gave capacity reduction factors (ϕ_w) of 0.91 and 0.92 for ETF and ITF load cases, respectively for Proposal 1(a). 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 ETF and ITF 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 their web crippling capacities 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 ETF load case, the mean value of test to predicted web crippling capacity of DuraGal channel is 1.01 while the corresponding COV is 0.09. For ITF load case, the mean value of test to predicted web crippling capacity is 1.00 while the corresponding COV is 0.10. 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 ETF and ITF load cases.

The corresponding capacity reduction factors (ϕ_w) are 0.88 and 0.86 for ETF and ITF load cases, respectively.

5.3. Direct Strength Method (DSM)

The DSM proposed by Schafer [32] is one of the alternative methods to determine the strength of cold-formed steel members. Recently Keerthan and Mahendran [33] have developed suitable DSM based equations for web crippling of a hollow flange channel beam. A similar approach was used to develop suitable design rules for the web crippling capacity of unlipped channel sections under the DSM format (Proposal 3). Equations 7(a) and (b) show the proposed DSM design equations for the web crippling capacity of unlipped channel sections under ETF and ITF load cases, respectively. In these equations the DSM based nominal web crippling capacity (P_u) is proposed using P_{cr} (elastic buckling capacity in web crippling) and P_y (web yield capacity).

Equations 8(a) and (b) present the equivalent yield capacities in web crippling based on a 45° load distribution to the middle from the bearing plate edges for ETF and ITF load cases, respectively. The effect of corners on the yield capacity was not considered in Equations 8(a) and (b). Detailed finite element analyses will be carried out to investigate the effect of corners on the yield capacity in web crippling (P_y).

The buckling loads (P_{cr}) can be calculated using Equation 9, provided a realistic buckling coefficient (k) is known. Lagerqvist and Johansson [34] proposed a suitable equation for the buckling coefficient of plate girders under ITF load case. Based on preliminary numerical studies the buckling coefficients for the ETF and ITF load cases were found to be approximately 1 and 2, respectively. Detailed finite element analyses will be carried out to recalibrate Lagerqvist and Johansson's [34] equation to suit unlipped channels with stocky webs under ETF and ITF load cases.

$$\frac{P_u}{P_y} = 0.187 \left[1 - 0.04 \left(\frac{P_{cr}}{P_y} \right)^{0.5} \right] \left(\frac{P_{cr}}{P_y} \right)^{0.5} \quad \text{for ETF load case} \quad (7a)$$

$$\frac{P_u}{P_y} = 0.283 \left[1 - 0.04 \left(\frac{P_{cr}}{P_y} \right)^{0.5} \right] \left(\frac{P_{cr}}{P_y} \right)^{0.5} \quad \text{for ITF load case} \quad (7b)$$

$$P_y = f_{yw} t_w \left(l_b + \frac{d_l}{2} \right) \quad \text{for ETF load case} \quad (8a)$$

$$P_y = f_{yw} t_w (l_b + d_l) \quad \text{for ITF load case} \quad (8b)$$

$$P_{cr} = \frac{\pi^2 E k t_w^3}{12[1-\nu^2]d} \quad (9)$$

$$\lambda = \sqrt{\frac{P_y}{P_{cr}}} \quad (10)$$

Experimental ultimate web crippling capacity results were processed within the DSM format and are shown in Figures 16(a) and (b) for ETF and ITF load cases, respectively, where the slenderness (λ) was calculated using Equation 10. These figures show the non-dimensional web crippling capacity curves for unlipped channel sections and compare them with experimental results. It can be seen that the proposed DSM equations predict the web crippling capacities of unlipped channel sections reasonably well (Tables 9 and 10). Further FEA based research is continuing to improve the buckling coefficients (k) and DSM equations using more web crippling capacity data.

5.4. Simplified Method for DuraGal Channels

The Duragal channels are comparatively stocky among the commonly used cold-formed steel members since their thicknesses vary from 4 to 8 mm. It was found that these sections failed inelastically in our experimental study. Figures 17(a) and (b) show that the variation of $P_{Test}/(P_{cr} P_y)^{0.5}$ ratios with respect to slenderness ($\lambda = (P_y/P_{cr})^{0.5}$) is a constant for ETF and ITF load cases, respectively. Using this outcome it was decided to propose a simplified method (Equation 11) as was done in [35, 36] for the shear capacity of steel beams. Tables 9 and 10 show that the web crippling capacities predicted by Equation 11 (Proposal 4) agree well with the experimental results of DuraGal channels under ETF and ITF load cases, respectively. Hence Equation 11 can be used to predict the web crippling capacities of (DuraGal) channels with stocky webs under these load conditions.

$$P_u = n(P_{cr} P_y)^{0.5} \quad \text{for ETF and ITF load cases} \quad (11)$$

where P_{cr} and P_y are obtained from Equations 8 and 9; $n = 0.18$ and 0.28 for ETF and ITF load cases, respectively.

6. Conclusions

This paper has described an experimental investigation into the web crippling capacities of cold-formed steel unlipped channels with stocky webs under ETF and ITF load cases. Forty two tests were conducted on DuraGal channel sections with stocky webs under 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 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 specimen lengths proposed by the AISI testing method should be used for 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. Suitable design rules for the web crippling capacities of unlipped channel sections were also developed under the direct strength method format. Further finite element analyses are continuing to improve the DSM equations using more web crippling capacity data.

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Table Captions

Table 1: Duragal channel sections

Table 2: Different conditions for single web channel sections

Table 3: AS/NZS 4600 web crippling coefficients for unfastened unlipped channels under ETF and ITF load cases

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

Table 1: Duragal channel sections

Section	Depth d (mm)	Flange b _f (mm)	Thickness t _w (mm)	Radius r _i (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 versus Unstiffened (Lipped versus Un-lipped)	
Loading condition	One flange versus Two flanges	EOF, IOF, ETF and ITF load cases
Loading location	End versus Interior	

Table 3: AS/NZS 4600 web crippling coefficients for unfastened unlipped channels under ETF and ITF load cases

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
ETF	2	0.11	0.37	0.01	0.75	≤ 1	≤ 200	≤ 210	≤ 2
ITF	13	0.47	0.25	0.04	0.80	≤ 1			

ϕ_w = Capacity reduction factor

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

Section	d (mm)	b _f (mm)	t _w (mm)	r _i (mm)	L (mm)	l _b (mm)	f _y (MPa)	Test Ultimate load (kN)	Ultimate load ratios	
									Test/ AS/NZS 4600	Test/ Eq. (2)
300x90x6	298.3	91.2	6.01	8.4	495.2	45	435	45.4	0.88	1.16
	298.5	90.9	5.98	8.4	539.6	90	435	49.4	0.80	0.96
250x90x6	249.4	89.9	5.98	7.9	421	45	445	46.9	0.89	1.13
	249.2	89.8	5.98	7.9	465.1	90	445	50.6	0.80	0.89
200x75x5	198.7	75.9	4.72	4.2	336.9	37.5	415	31.2	0.98	0.98
	198.9	75.9	4.72	4.2	375.3	75	415	40.2	1.04	0.91
125x65x4	125.3	65.3	3.84	3.9	219.8	32.5	405	23.4	1.12	1.23
	125.6	65.4	3.83	3.9	252.5	65	405	28.2	1.12	1.02
100x50x4	99.4	50.3	3.83	4.1	175	25	440	22.6	1.07	1.34
	99.1	50.4	3.83	4.1	200.2	50	440	24.8	0.97	1.01
75x40x4	74.4	40.4	3.84	3.9	113.6	20	450	18.3	0.88	1.23
	74.3	40.5	3.85	3.9	152	40	450	22.1	0.88	1.00
Mean									0.95	1.07
COV									0.12	0.13

Elastic modulus = 203,000 MPa

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

Section	d (mm)	b _f (mm)	t _w (mm)	r _i (mm)	L (mm)	l _b (mm)	f _y (MPa)	Test ultimate load (kN)	Ultimate load ratios	
									Test/ AS/NZS 4600	Test/ Eq. (2)
300x90x6	298.6	91	5.97	8.4	944.1	45	435	144.6	1.32	1.09
	298.8	90.9	6	8.4	990	90	435	149.1	1.15	1.01
250x90x6	249.5	89.9	5.99	7.9	796.5	45	445	148.4	1.22	1.08
	249.6	90	6.01	7.9	838.4	90	445	148.5	1.03	0.97
200x75x5	198.8	76	4.73	4.2	638	37.5	415	99.8	1.16	0.96
	198.7	75.9	4.72	4.2	675.2	75	415	100.1	1.00	0.86
125x65x4	125	65.45	3.84	3.9	407.6	32.5	405	64.1	1.15	1.14
	125	65.55	3.83	3.9	440.1	65	405	60.0	0.93	0.92
100x50x4	99.2	50.4	3.83	4.1	325	25	440	66.3	1.15	1.31
	99.3	50.4	3.83	4.1	350	50	440	58.3	0.87	1.00
75x40x4	74.6	40.5	3.84	3.9	243	20	450	54.9	0.91	1.25
	74.5	40.5	3.84	3.9	263.8	40	450	51.3	0.74	1.01
Mean									1.05	1.05
COV									0.16	0.13

Elastic modulus = 203,000 MPa

Table 6: Test specimen details and results for ETF load case

Test	Section	d (mm)	b _f (mm)	t _w (mm)	r _i (mm)	L (mm)	l _b (mm)	Ultimate load (kN)
E-1	250x90x6	249.0	90.1	6.04	8.0	375	50	49.2
E-2		252.2	89.8	6.01	8.0	501	50	52.1
E-3		251.9	89.3	6.02	8.0	626	50	52.7
E-4		249.4	90.0	6.04	8.0	750	50	50.8
E-5		251.1	90.1	6.03	8.0	1000	50	52.0
E-6	200x75x6	198.4	75.1	5.86	8.0	600	25	48.1 ^{C+}
E-7		197.9	74.2	5.87	8.0	600	50	48.1
E-8		197.7	75.2	5.88	8.0	600	100	53.9
E-9	200x75x5	198.5	76.1	4.71	4.5	600	150	39.6
E-10		198.4	76.1	4.70	4.5	600	50	31.6
E-11		197.2	75.9	4.69	4.5	600	100	35.4
E-12	150x75x5	152.2	75.1	4.68	4.0	451	150	48.2
E-13		150.4	75.1	4.67	4.0	450	50	34.1
E-14		152.0	74.6	4.70	4.0	450	100	41.6
E-15	125x65x4	125.0	64.9	3.83	4.0	375	50	26.3
E-16	100x50x4	100.0	50.1	3.78	4.0	301	100	28.0
E-17		100.6	49.9	3.79	4.0	199	50	23.8 [*]
E-18		100.1	50.8	3.79	4.0	300	50	23.3
E-19		100.2	50.4	3.81	4.0	300	50	22.6 [#]
E-20		100.1	50.6	3.79	4.0	175	25	21.0 ^{**}
E-21		100.0	49.2	3.80	4.0	200	50	22.9 ^{##}
E-22	75x40x4	74.8	39.7	3.79	4.0	225	50	24.1

- Test E-19 is a repeat of Test E-18;

- Test E-21 is a repeat of Test E-17;

* - Corresponding Young and Hancock's [20] value is 24.8 kN;

** - Corresponding Young and Hancock's [20] value is 22.6 kN;

C - Combined flange crushing and web crippling;

+ - Test was stopped prematurely.

Table 7: Test specimen details and results for ITF load case

Test	Section	d (mm)	b _f (mm)	t _w (mm)	r _i (mm)	L (mm)	l _b (mm)	Ultimate load (kN)
I-1	250x90x6	251.2	89.6	5.98	8.00	750	150	144.7
I-2		249.2	90.7	5.99	8.00	875	150	154.2
I-3		250.4	90.1	6.02	8.00	1000	150	157.1
I-4		251.6	91.2	6.01	8.00	1250	150	160.5
I-5		250.4	90.4	6.01	8.00	1500	150	164.9
I-6	200x75x6	198.1	74.5	5.97	8.00	1000	150	155.0
I-7		200.8	75.7	5.88	8.00	1000	100	152.2
I-8	200x75x5	197.1	74.7	4.70	4.50	1000	150	105.2
I-9		201.5	75.9	4.70	4.50	1000	50	97.0 ^{C+}
I-10		199.1	75.1	4.68	4.50	1000	100	101.8
I-11	150x75x5	149.1	75.1	4.66	4.00	750	25	96.8 ^{C+}
I-12		149.5	75.1	4.68	4.00	750	50	100.3 ^C
I-13		152.5	75.0	4.66	4.00	750	100	102.7
I-14	125x65x4	123.3	64.6	3.84	4.00	625	100	72.7
I-15		123.8	64.8	3.80	4.00	625	50	73.7 ^C
I-16	100x50x4	100.1	50.5	3.81	4.00	499	100	66.1
I-17		99.8	50.8	3.84	4.00	350	50	59.0 [*]
I-18		99.8	49.7	3.79	4.00	500	50	63.1
I-19		100.2	50.0	3.82	4.00	325	25	62.3 ^{C**}
I-20	75x40x4	75.9	39.8	3.80	4.00	375	50	59.4

* - Corresponding Young and Hancock's [20] value is 58.3 kN;

** - Corresponding Young and Hancock's [20] value is 66.3 kN;

C - Combined flange crushing and web crippling;

+ - Test stopped prematurely.

Table 8: Mechanical properties of steel used in test specimens

Section	250x90x6	200x75x6	200x75x5	150x75x5	125x65x4	100x50x4	75x40x4
Yield strength (MPa)	470	477	477	468	494	449	480
Ultimate strength (MPa)	562	544	544	547	561	539	563

Elastic modulus = 200000 MPa

Table 9: Comparison of test results with predictions for ETF load case

Test	Section	L (mm)	I _b (mm)	Test ultimate load (kN)	Ultimate load ratios (Test/Predicted)					
					AS/NZS 4600	Prop. 1(a)	[20]	Prop. 2	Prop. 3	Prop. 4
E-4	250x90x6	750	50	50.8	0.88	1.06	1.10	1.19	1.02	1.03
E-7	200x75x6	600	50	48.1	0.86	1.00	1.11	1.12	0.99	1.00
E-8		600	100	53.9	0.79	0.95	0.85	1.06	0.94	0.95
E-9	200x75x5	600	150	39.6	0.73	0.92	0.53	0.91	0.94	0.96
E-10		600	50	31.6	0.81	0.99	0.81	0.97	0.99	1.01
E-11		600	100	35.4	0.74	0.93	0.62	0.93	0.95	0.97
E-12	150x75x5	451	150	48.2	0.89	1.08	0.58	0.90	1.07	1.09
E-13		450	50	34.1	0.89	1.02	0.84	0.90	1.04	1.05
E-14		450	100	41.6	0.87	1.03	0.66	0.90	1.05	1.07
E-15	125x65x4	375	50	26.3	0.92	1.08	0.93	1.06	1.12	1.13
E-16	100x50x4	301	100	28.0	0.89	1.04	0.69	0.99	0.98	0.99
E-18		300	50	22.9	0.89	1.01	0.91	1.03	0.99	1.00
E-22	75x40x4	225	50	24.1	0.88	0.95	0.92	1.08	0.95	0.95
Mean					0.85	1.00	0.82	1.01	1.00	1.01
COV					0.07	0.05	0.22	0.09	0.05	0.06

Table 10: Comparison of test results with predictions for ITF load case

Test	Section	L (mm)	l _b (mm)	Test ultimate load (kN)	Ultimate load ratios (Test/Predicted)					
					AS/NZS 4600	Prop. 1(a)	[20]	Prop. 2	Prop. 3	Prop. 4
I-4	250x90x6	1250	150	160.5	0.94	1.03	0.88	1.10	1.00	0.99
I-6	200x75x6	1000	150	155.0	0.87	0.97	0.89	1.00	0.93	0.92
I-7		1000	100	152.2	0.99	1.03	1.01	1.14	1.03	1.01
I-8	200x75x5	1000	150	105.2	0.78	1.01	0.69	0.88	1.00	0.99
I-10		1000	100	101.8	0.86	1.04	0.76	0.97	1.07	1.05
I-13	150x75x5	750	100	102.7	0.81	1.03	0.77	0.87	1.05	1.03
I-14	125x65x4	625	100	72.7	0.82	1.01	0.81	0.91	1.01	1.00
I-16	100x50x4	499	100	66.1	0.82	1.01	0.87	0.93	0.95	0.92
I-18		500	50	63.1	0.94	1.05	1.06	1.12	1.07	1.04
I-20	75x40x4	375	50	59.4	0.80	0.90	1.05	1.06	0.94	0.90
Mean					0.86	1.01	0.88	1.00	1.00	0.99
COV					0.08	0.04	0.15	0.10	0.05	0.05

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
ETF	AS/NZS 4600	2	0.11	0.37	0.01	0.85	0.07	0.76
	Proposal 1(a)	2.93	0.19	0.26	0.05	1.00	0.05	0.91
	Proposal 1(b)	3.05	0.19	0.26	0.05	0.97	0.05	0.87
ITF	AS/NZS 4600	13	0.47	0.25	0.04	0.86	0.08	0.76
	Proposal 1(a)	11	0.21	0.07	0.03	1.01	0.04	0.92
	Proposal 1(b)	11.6	0.21	0.07	0.03	0.96	0.04	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
ETF	Young and Hancock [20]	1.44	0.0133	0.6	N/A	0.82	0.22	0.58
	Proposal 2	0.706	0.011	2.5	N/A	1.01	0.09	0.88
ITF	Young and Hancock [20]	1.44	0.0133	N/A	1.4	0.88	0.15	0.71
	Proposal 2	1.5	0.021	N/A	1.5	1.00	0.10	0.86

Figure Captions

Figure 1: Cold-formed steel floor systems

Figure 2: Web crippling failure at a reaction point

Figure 3: Loading conditions for web crippling tests [2,3]

Figure 4: Young and Hancock's [20] web crippling test set-up

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

Figure 6: Uzzaman et al.'s [23,24] test set-up and failure modes

Figure 7: Mechanism model proposed by Young and Hancock [20]

Figure 8: Plastic hinge position and mechanism length, (N_m) assumed by Young and Hancock [20]

Figure 9: Web crippling test set-up for ETF load case

Figure 10: Web crippling test set-up for ITF load case

Figure 11: Web crippling failure modes under ETF load case

Figure 12: Web crippling failure modes under ITF load case

Figure 13: Combined flange crushing and web crippling (Test I-9)

Figure 14: Typical load versus deflection curves

Figure 15: Section deformation during the test

Figure 16: Comparison of web crippling capacities from tests and DSM based design equations

Figure 17: Simplified method to predict the web crippling capacities of DuraGal channels

(a) Duragal channel section

(b) Floor system

Figure 1: Cold-formed steel floor systems

Figure 2: Web crippling failure at a reaction point

Figure 3: Loading conditions for web crippling tests [2,3]

(a) ETF load case – front view

(b) ETF load case – end view

Figure 4: Young and Hancock's [20] web crippling test set-up

(a) ETF load case

(b) ITF load case

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

(a) ETF load case

(b) ITF load case

Figure 6: Uzzaman et al.'s [23,24] test set-up and failure modes

(a) One flange loading

(b) Two flange loading

Figure 7: Mechanism model proposed by Young and Hancock [20]

Figure 8: Plastic hinge position and mechanism length, (N_m) assumed by Young and Hancock [20]

Figure 9: Web crippling test set-up for ETF load case

Figure 10: Web crippling test set-up for ITF load case

(a) Test E-10

(b) Test E-6

(c) Test E-9

(d) Test E-13

Figure 11: Web crippling failure modes under ETF load case

(a) Test I-13

(b) Test I-5

(c) Test I-2

(d) Test I-20

Figure 12: Web crippling failure modes under ITF load case

Figure 13: Combined flange crushing and web crippling (Test I-9)

(a) ETF load case (Test E-8)

(b) ITF load case (Test I-7)

Figure 14: Typical load versus deflection curves

Figure 15: Section deformation during the test

(a) ETF load case

(b) ITF load case

Figure 16: Comparison of web crippling capacities from tests and DSM based design equations

(a) ETF load case

(b) ITF load case

Figure 17: Simplified method to predict the web crippling capacities of DuraGal channels