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# Experimental Studies on Web Crippling Behaviour of Hollow Flange Channel Beams under Two Flange Load Cases

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**Abstract:** This paper presents the details of an experimental study of a cold-formed steel hollow flange channel beam known as LiteSteel beam (LSB) subject to web crippling under End Two Flange (ETF) and Interior Two Flange (ITF) load cases. The LSB sections with two rectangular hollow flanges are made using a simultaneous cold-forming and electric resistance welding process. Due to the geometry of the LSB, and its unique residual stress characteristics and initial geometric imperfections, much of the existing research for common cold-formed steel sections is not directly applicable to LSB. Experimental and numerical studies have been carried out to evaluate the behaviour and design of LSBs subject to pure bending, predominant shear and combined actions. To date, however, no investigation has been conducted on the web crippling behaviour and strength of LSB sections. Hence an experimental study was conducted to investigate the web crippling behaviour and capacities of LSBs. Twenty-eight web crippling tests were conducted under ETF and ITF load cases, and the ultimate web crippling capacities were compared with the predictions from the design equations in AS/NZS 4600 and AISI S100. This comparison showed that AS/NZS 4600 and AISI S100 web crippling design equations are unconservative for LSB sections under ETF and ITF load cases. Hence new equations were proposed to determine the web crippling capacities of LSBs based on experimental results. Suitable design rules were also developed under the direct strength method (DSM) format.

*Keywords: Hollow Flange Channel Beams, Cold-formed Steel Beams, Web Crippling, ETF and ITF Load Cases, Direct Strength Method and Experiments.*

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## 1. Introduction

Cold-formed steel (CFS) structural members are widely used in modern construction due to the many advantages they offer in comparison with conventional hot-rolled steel sections. They are usually thin-walled members with large width-to-thickness ratios. Lightweight, high strength and stiffness, accurate section dimensions, easy prefabrication and mass production are some of the qualities of cold-formed steel members that create cost savings in construction.

Since early 1990s, Australian manufacturing companies [1] have introduced innovative cold-formed hollow flange sections, and one of them known as LiteSteel beams (LSB) is shown in Figure 1. The development of this hollow flange channel section was based on improving the structural efficiency by adopting torsionally rigid rectangular hollow flanges, minimising local buckling of plate elements by eliminating free edges, distributing material away from the neutral axis to afford greater bending stiffness than conventional cold-formed sections, and optimising manufacturing efficiency. The LSB sections were produced from a single steel strip using a combined dual electric resistance welding and automated continuous roll-forming process [1], primarily for use as floor joists and bearers in residential, industrial and commercial buildings. Table 1 shows the nominal dimensions of LSB sections.

The base steel used for LSB production has a yield strength of 380 MPa and a tensile strength of 490 MPa. However, due to cold-forming, the nominal yield strengths of the web and flange elements are 380 and 450 MPa, respectively [1]. The manufacturing process also introduces residual stresses and initial geometric imperfections which differ from those of common cold-formed and hot-rolled steel sections. Due to the geometry of the LSB, as well as its unique residual stress characteristics and initial geometric imperfections resultant of manufacturing processes, much of the existing research for common cold-formed steel sections is not likely to be directly applicable to the LSB.

Web bearing is a form of localized failure that occurs at points of transverse concentrated loading or supports of thin-walled steel beams (see Figure 2) [2]. LSB joists and bearers that are unstiffened against this type of loading are also vulnerable to web bearing/crippling failures (see Figure 3). The computation of the web bearing strength by means of theoretical analysis is quite complex as it involves many factors such as local yielding in the loading region, instability of the web element, and many others. Hence the current design rules in most cold-formed steel structures codes are empirical in nature developed based on more than 1200 tests of conventional cold-formed steel sections such as C-, Z- and hat sections and built-up sections [3-8] for the four types of web crippling loading conditions shown in Figure 4: End-One-Flange Loading (EOF), End-Two-Flange Loading (ETF), Interior-One-Flange Loading (IOF) and Interior-Two-Flange Loading (ITF). Since 2005, unified web bearing capacity equations have been developed that define specific web crippling coefficients for the key parameters influencing the web bearing capacity of C-, Z-, Hat and built-up sections, namely, 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 ($f_y$). However, these capacity equations are not applicable to the Litesteel beams (LSB) due to the presence of two rectangular hollow flanges instead of the conventional flange plate elements. Effects of the presence of hollow flanges including the higher rotational restraint at the LSB web-flange juncture have been successfully included in the shear capacity design rules of LSBs [9-11], However, such an approach has not been developed yet for the web crippling capacity of LSBs. Unlike other open cold-formed steel sections, LSBs will be subjected to web crippling and/or flange crushing failures.

Hollow flange channel sections such as LSBs can be used as flexural members in steel building systems, for example, floor joists and bearers. For them to be used as flexural members, their flexural, shear and web crippling capacities must be known. Recent research studies have investigated the flexural [12-15] and shear [9-11] behaviour and capacities of LSBs. However, no investigation has been conducted into the web crippling behaviour and strength of LSB sections. In this research web crippling behaviour and strength of LSBs under ETF and ITF load cases was investigated using an experimental study. This paper presents the details of this experimental study, and the results. Experimental web crippling capacities are compared with the predicted capacities using the current design rules. Currently direct strength method (DSM) based design rules are not yet available for web crippling capacities. Suitable design rules are therefore developed under the DSM format in this paper.

## 2. Literature Review

### 2.1. Web Crippling Test Method

Many research studies have been undertaken to investigate the web crippling behaviour of cold-formed steel channel sections. The new AISI standard test method [16] presents the details of suitable test procedures that should be adopted in web crippling studies. However, it is different to that used by past research studies [6,7] in relation to the specimen length and loading method used. The AISI standard test method [16] recommends the following test specimen lengths for the four loading cases shown in Figure 4.

EOF Loading: $L_{min}= 3d_1+$ bearing plate lengths

IOF Loading: $L_{min}= 3d_1+$ bearing plate lengths

ETF Loading: $L_{min}= 3d_1$

ITF Loading: $L_{min}= 5d_1$

where $d_1$ = Depth of the flat portion of the web measured along the plane of the web

Bearing capacities vary with specimen length as this will influence the yielding length. However, test specimen lengths used in the past research [6,7] are different to those recommended by the AISI standard test method [16]. There is a need to investigate the effects of using the specimen lengths given in the AISI standard test method on web bearing capacities. In this research on LSBs, test specimen lengths were based on [16].

### 2.2. AS/NZS 4600 and AISI S100 Design Equations

AS/NZS 4600 [17] is the governing standard in Australia and New Zealand for cold-formed steel members. This standard provides design guidelines for the web crippling capacity ($R_b$) of open cold-formed steel sections. These web crippling capacity guidelines take into consideration only 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 ($t_w$). They do not take into consideration the effects of hollow flanges in LSBs. AS/NZS 4600 design equation for web crippling capacity is based on Prabakaran [6], who performed an extensive statistical analysis of more than 1200 experimental web crippling capacities of a range of open single and built-up cold-formed steel sections and proposed a suitable unified design equation based on four web crippling coefficients (Equation 1). This equation has also been adopted in AISI S100 [18]. Suitable values of the four web crippling coefficients in Equation 1 are given in Table 2.

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

where

C = Coefficient

θ = Angle between the plane of the web and the plane of the bearing surface 45° ≤ θ ≤ 90°

$C_r$ = Coefficient of inside bent radius ratio ($r_i/t_w$)

$C_l$ = Coefficient of bearing length ratio ($l_b/t_w$)

$C_w$ = Coefficient of web slenderness ratio ($d_i/t_w$)

### 2.3. Past Research

Web crippling is one of the most important failure modes that must be considered in the design of cold formed steel members. Different design equations were used to predict the web crippling capacity [3-8], which started in 1939 at Cornell University [3]. Research and development in this area resulted in 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 [17] and AISI S100 [18]. In the older version of American Specification [19], different design expressions were used to predict the web crippling capacity. Each of these expressions 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 [17] and AISI S100 [18] is applicable to different types of open cold-formed sections and load cases (ETF, ITF, EOF and IOF).

Young and Hancock [7] conducted an experimental study to investigate the conservative and unconservative aspects of the AISI web crippling capacity equations [19]. A series of tests was carried out for the four loading conditions (EOF, IOF, ETF, ITF). They found that the design web crippling strength predictions given in the 1996 AISI specification [19] were unconservative for the unlipped channel sections tested. They proposed a simple plastic mechanism based expression to predict the web crippling strength of unlipped channels.

Macdonald et al. [8] conducted experimental and numerical studies to investigate the web crippling behaviour of lipped channel beams (LCBs) under ETF, ITF, EOF and IOF load cases. Figure 5 (a) shows the experimental set-up used in Macdonald et al.'s [8] tests while Figure 5 (b) shows the failure mode of LCBs under ITF load case. They found that the length of the load bearing plate, corner radii and clear height of web had an effect on the web crippling strength of LCBs, particularly for the IOF and EOF load cases.

Uzzaman et al. [20] investigated the effect of offset web holes on the web crippling strength of cold-formed steel lipped channel beams (LCBs) with flanges unfastened to support under ETF load case using experimental and numerical studies. Figure 6 (a) shows the experimental set-up used in Uzzaman et al.'s [20] tests while Figure 6 (b) shows the failure mode of LCBs under ETF load case. Uzzaman et al. [20] also did 12 web crippling tests of LCBs without web openings under the same load case. Table 3 shows the web crippling capacities of LCBs without web openings from their tests, which are compared with the predictions from the design equations based on AS/NZS 4600 [17] and AISI S100 [18]. The mean value of test to predicted web crippling capacities of LCBs by AS/NZ 4600 [17] is 0.60 while the corresponding coefficient of variation (COV) is 0.13. Table 3 results show that AS/NZS 4600 and AISI S100 design equations are considerably unconservative for LCB sections under ETF load case (mean ratio of 0.60).

Uzzaman et al. [21] also conducted experimental and numerical studies to investigate the effect of offset web holes on the web crippling strength of LCBs under ITF load case. Figure 6 (c) shows the failure mode LCBs under ITF load case. Uzzaman et al. [21] also did eight web crippling tests of LCBs without web openings under ITF load case. Table 4 shows the web crippling capacities of LCBs without web openings from their tests, which are compared with the predictions from the design equations based on AS/NZS 4600 and AISI S100. Table 4 results show that AS/NZS 4600 and AISI S100 design equations are very conservative for LCB sections under ITF load case. In summary both Table 3 and 4 results show that the current AS/NZS 4600 and AISI S100 web crippling capacity equations are unable to predict the capacities of LCBs under ETF and ITF load cases. These web crippling capacity equations do not cover the LiteSteel beams (LSBs). Hence further web crippling studies are needed for both LCBs and LSBs, and this paper presents the details of a study on LSBs.

### 2.4. Theoretical Method

Webs of cold-formed steel members can be idealized as simply supported rectangular thin plates along the edges, subjected to locally distributed in-plane edge compressive forces. The critical elastic buckling load can be calculated by relatively simple analytical equations. However, stiffened compression elements will not fail when the elastic buckling load is reached and will develop post-buckling strength by means of redistribution of stresses. The calculation of the post-buckling strength is somewhat complex. In addition, the boundary condition along the web-flange juncture further complicates the calculations.

The elastic buckling load of a simply supported rectangular plate under compression due to two equal and opposite partially distributed forces, as shown in Figure 7 (a), was investigated by Walker [5]. He developed the following equation with the plate buckling coefficients (k) as given in Figure 7 (b) to compute the elastic buckling load ($P_{cr}$).

$$P_{cr} = \frac{\pi^2 E k\, t_w^{\ 3}}{12\left[1-\upsilon^2\right] d_1} \tag{2}$$

where

$d_1$ = depth of the flat portion of the web measured along the plane of the web

t = web thickness

E = Young’s modulus of elasticity (200,000 MPa)

$\upsilon$ = Poisson’s ratio = 0.3

There are different methods regarding the theoretical elastic analysis of web crippling for cold-formed steel members subjected to different load conditions. 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. Boundary condition at the web-flange juncture of cold-formed steel beams is not purely simply supported nor an ideally clamped condition. Also, the critical elastic buckling load ($P_{cr}$) did not imply failure of the plate. Due to the difficulty associated with the theoretical analysis, most of the studies rely on experimental data in developing web crippling capacity equations for design.

The theoretical analysis of web crippling for cold-formed steel members is more complicated. Hence web crippling tests on real specimens are the most reliable approach for investigating the true web crippling behaviour of LSBs. The convenience of web crippling tests is recognised in investigating the post-buckling behaviour of LSBs where theoretical difficulties arise. Hence detailed experimental studies were conducted to investigate the web crippling behaviour of LSBs under ETF and ITF load cases and the results are presented next.

For the web crippling design of cold-formed web panels, their elastic buckling strength must be determined accurately including the potential post-buckling strength. Choy et al. [22] assumed that elastic buckling coefficients of web panels are determined by assuming that the web panels are simply supported at the junction between the flange and web elements.

Effects of the presence of hollow flanges including the higher rotational restraint at the LSB web-flange juncture have been included in the shear capacity design rules of LSBs [9-11], However, such a design method has not been developed yet for the web bearing capacity of LSBs. Therefore finite element analyses were carried out to determine the elastic buckling loads ($P_{cr}$) and used them in DSM equations (see Section 5). DSM needs the elastic buckling loads ($P_{cr}$) and the web yield loads ($P_y$) to compute the web crippling capacities of LSBs.

## 3. Web Crippling Tests –ETF and ITF Load Cases

It is vital that important parameters are chosen carefully in the design of a test program. In order to fully understand the web crippling behaviour of LSB sections, several important issues were considered when deciding these parameters. Test specimens were designed to fail in web crippling prior to reaching other section capacities.

### 3.1. Test Specimens and Test Set-up

Five LSB sections were chosen based on the commonly used sections in the building industry. Table 5 presents the details of the web crippling test specimens. It includes the measured web thicknesses ($t_w$), clear web heights ($d_1$), inside bent radii ($r_i$) and yield stresses

($f_y$) of the web elements of tested LSBs. Since the outside of the inner bent corners ($r_i$) is filled with weld material unlike in open cold-formed channel sections, the inner bent radius ($r_i$) of LSB was considered as zero (see Figure 1). Figures 8 (a) and (b) show the test set-up used in the web crippling tests of this research for ETF and ITF load cases, respectively, built based on the recommended AISI standard test method shown in Figure 4 (a) and (b).

It is stated in the AISI standard test method [16] that the specimen length should be at least equal to three times the flat portion of clear web height 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. Hence five times the section depth was selected for both ETF and ITF load cases. Single LSB section was considered as was used in Macdonald et al.'s [8] and Uzzaman et al.'s [20, 21] tests on ETF and ITF load cases. It should be noted that no signs of twisting were observed during experiments.

Twenty eight tests were conducted to investigate the web crippling behaviour of LSBs under ETF and ITF load cases. All the LSB tests were conducted using an Instron testing machine**.** Three different sizes of bearing plates (50 mm, 100 mm and 150 mm) were used to attain three types of testing conditions for both ETF and ITF load cases. The support system was designed to ensure that the test beam had pinned supports at the top and bottom. The applied load is the important parameter. The measuring system was set-up to record the applied load and associated test beam displacements. Two laser displacement transducers were located on the test beam near the loading point and the web panel to measure the vertical and lateral deflections, respectively (see Figure 8). The lateral deflection of test beam was measured at Point A on the web panel as shown in Figures 8 (a) and (b). The purpose of using a green strap is part of our laboratory safety procedure, whereby it prevents the test section from falling off. It is noted that the strap has no influence on the test results.

### 3.2. Test Procedure

The required LSB specimens were fabricated and their sizes, in particular, the clear web height ($d_1$), web thickness ($t_w$) and inside bent radius ($r_i$), were measured (Table 5). The specimen was placed in the Instron testing machine 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 the test beam failed.

### 3.3. Test Results and Analyses

The purpose of conducting tests is to experimentally establish the ultimate web crippling capacities of LSB sections under ETF and ITF load cases. These experimental results are important as they provide a point of comparison with which to gauge the performance of the web crippling design rules as well as presenting some data with which to verify finite element models of LSBs. Table 6 presents the web crippling capacities of LSBs as obtained from this experimental study.

Figures 9 to 11 show the web crippling failure modes of LSBs under ETF load case while Figures 12 to 14 show the web crippling failure modes of LSBs under ITF load case with 50 mm, 100 mm and 150 mm bearing plates, respectively. Figure 9 (b) shows that web yield zone extended to more than three times the flat portion of clear web height for LSBs under ETF load case while Figure 13 (a) shows that web yield zone extended to more than five times the flat portion of clear web height for LSBs under ITF load case.

As seen in Figures 9 to 14, web crippling failures occurred within the clear height of web (between the two hollow flanges). Slender LSB test specimens began to deflect out of plane and the beam reached its ultimate web crippling capacity. No flange crushing failures were observed in the tests. All the specimens displayed significant ductility at failure.

Figure 15 (a) shows the load-deflection curves for the web crippling test of 200x45x1.6 LSB section with 100 mm bearing length (ETF load case) while Figure 15 (b) shows the load-deflection curves for the web crippling test of 150x45x2.0 LSB section with 50 mm bearing length (ITF load case).

Figure 16 (a) shows the applied load versus lateral deflection curve for the web crippling test of 250x60x2.0 LSB section with 100 mm bearing length (ITF load case). It is difficult to discern a buckling load from experiments due to the presence of imperfections. Therefore elastic buckling load was calculated based on finite element analyses (FEA) and plotted in Figures 16 (a) and (b). In Figure 16 (a), at Point 1, the web began to buckle out of plane and the beam reached the ultimate web crippling capacity of 23.16 kN at Point 2. This shows that slender LSBs have a significant post-buckling strength in web crippling. Figure 16 (a) shows that there was considerable amount of post-buckling strength for slender LSBs subject to web crippling (250x60x2.0 LSB) while Figure 16 (b) shows that stocky LSBs (150x40x2.0 LSB) did not have post-buckling strength. Further FEA based research is continuing to investigate the post-buckling behaviour of LSBs subject to web crippling.

Experimental ultimate web crippling capacities are compared with the predictions from the design equation (Equation 1) based on AS/NZS 4600 [17] and AISI S100 [18] in Table 6. For the prediction of web crippling capacities, support and flange conditions were taken as Unfastened, Stiffened or partially stiffened flanges and Two-flange loading or reaction based on Table 2 and the corresponding web crippling coefficients are as follows.

Therefore

$C = 24$, $C_r = 0.52$, $C_l = 0.15$, $C_w = 0.001$ for ITF load case

$C = 13$, $C_r = 0.32$, $C_l = 0.05$, $C_w = 0.04$ for ETF load case

For ETF load case, the mean value of test to predicted web crippling capacity of LSB by AS/NZS 4600 is 0.76 while the corresponding coefficient of variation (COV) is 0.19. For ITF load case, the mean value of test to predicted web crippling capacity of LSB by AS/NZS 4600 is 0.31 while the corresponding COV is 0.21. Table 6 results show that AS/NZS 4600 [17] and AISI S100 [18] design equations are considerably unconservative for LSB sections, in particular under ITF load case.

Since AS/NZS 4600 [17] and AISI S100 [18] design equations were developed for open cold-formed steel sections, new web crippling capacity equations should be developed for LiteSteel beams (LSBs) with rectangular hollow flanges. Details of the proposed web crippling capacity equations for LSBs are given in the next section.

## 4. Proposed Web Crippling Capacity Equations

Since the currently available web crippling capacity equations are unsafe for LSBs, new design equations are proposed to predict the web crippling capacities of LSBs based on experimental results. This approach is similar to that used in the current cold-formed steel design codes [17, 18] in which Equation 1 is proposed with modified web crippling coefficients C, $C_r$, $C_l$ and $C_w$. Since the inside bent radius ($r_i$) was considered as zero, $C_r$ was taken as zero. Equations 3 and 4 show the proposed design equations for the web crippling capacities of LSBs ($R_b$) while Table 8 shows the associated, modified web crippling coefficients. Experimental ultimate web crippling capacities are compared with the predictions from the proposed Equations 3 and 4 in Table 7. For ETF load case, the mean value of test to predicted web crippling capacity ratio is 1.00 with a COV of 0.098. For ITF load case, these values are 1.00 and 0.135. It shows that the web crippling capacities predicted by Equations 3 and 4 agree well with the experimental web crippling capacities of LSBs under ETF and ITF load cases.

$$R_b = 12.5t_w^2 f_y\left(1+0.12\sqrt{\frac{l_b}{t_w}}\right)\left(1-0.07\sqrt{\frac{d_1}{t_w}}\right) \quad \text{for ETF load case} \qquad (3)$$

$$R_b = 25.7t_w^2 f_y\left(1+0.04\sqrt{\frac{l_b}{t_w}}\right)\left(1-0.06\sqrt{\frac{d_1}{t_w}}\right) \quad \text{for ITF load case} \qquad (4)$$

## Capacity Reduction Factor ($\phi_w$)

The North American Cold-formed Steel Specification [18] 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 5.

$$\phi_w = 1.52 M_m F_m P_m e^{-\beta_0\sqrt{\left\{V_m^2+V_f^2+C_pV_p^2+V_q^2\right\}}} \qquad (5)$$

where $M_m$, $V_m$ = Mean and coefficient of variation of the material factor = 1.1, 0.1

$F_m$, $V_f$ = Mean and coefficient of variation of the fabrication factor = 1.0, 0.05

$V_q$ = Coefficient of variation of load effect = 0.21

$\beta_0$ = Target reliability index = 2.5 for cold-formed steel members

$C_p$ = Correction factor depending on the number of tests = $\left[1+\frac{1}{n}\right]\left[\frac{m}{m-2}\right]$

$P_m$ = 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 5 with the mean and COV values in Table 7 gave capacity reduction factors ($\phi_w$) of 0.87 and 0.83 for ETF and ITF load cases. Therefore it is recommended to use $\phi_w$ factors of 0.85 and 0.80 for ETF and ITF load cases, respectively.

## 5. Direct Strength Method

The direct strength method (DSM) is an alternative to the traditional effective width method and has been adopted as an alternative design method in AS/NZS 4600 and AISI S100. However, no formal DSM provisions exist for web crippling of cold-formed steel beams. Hence suitable design rules were developed for the web crippling capacity of LSBs under the DSM format. They are proposed in a similar manner to those of the section capacity of columns in compression subject to local buckling (Equations 6 and 7) using test results. In these equations the DSM based nominal web crippling capacity ($P_u$) is proposed using the local buckling capacity equation ($N_{cl}$) where $N_{cl}$, $N_{ol}$ and $N_{ce}$ are replaced by $P_u$, $P_{cr}$ (elastic buckling capacity in web crippling) and $P_y$ (yield capacity in web crippling), respectively. In these equations, power coefficients of 0.78 and 0.75 are used instead of 0.4 based on the experimental results of LSBs for ETF and ITF load cases, respectively. Slenderness (λ) was calculated using Equation 8. Equations 6 and 7 show the proposed DSM based design equations for the web crippling capacity of LSBs under ETF and ITF load cases, respectively.

$$\frac{P_u}{P_y} = 0.50\left[1 - 0.05\left(\frac{P_{cr}}{P_y}\right)^{0.78}\right]\left(\frac{P_{cr}}{P_y}\right)^{0.78} \quad \text{for ETF load case} \qquad (6)$$

$$\frac{P_u}{P_y} = 0.56\left[1 - 0.05\left(\frac{P_{cr}}{P_y}\right)^{0.75}\right]\left(\frac{P_{cr}}{P_y}\right)^{0.75} \quad \text{for ITF load case} \qquad (7)$$

$$\lambda = \sqrt{\frac{P_y}{P_{cr}}} \qquad (8)$$

$$P_y = f_y t_w\left(l_b + \frac{d_1}{2}\right) \quad \text{for ETF load case} \qquad (9)$$

$$P_y = f_y t_w (l_b + d_1) \qquad \text{for ITF load case} \tag{10}$$

$$P_{cr} = \frac{\pi^2 E k\, t_w^{\ 3}}{12\left[1-\upsilon^2\right] d_1} \tag{11}$$

Equations 9 and 10 above 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. These equivalent web yield capacity expressions also agree with the yield-line model of Young and Hancock [24].

Equation 11 gives the elastic buckling capacity in web crippling provided a realistic buckling coefficient (k) is known. In order to obtain realistic buckling coefficients of LSBs under ETF and ITF load cases, finite element analyses (FEA) of LSBs subject to web crippling were undertaken for these load cases. Lagerqvist and Johansson [23] proposed a suitable equation for the buckling coefficient of plate girders under ITF load case. This equation was recalibrated to suit LSBs under ETF and ITF load cases based on the buckling results from finite element analyses. Based on this calibration, it is proposed that Equations 12 and 13 can be used to calculate the elastic buckling capacity in web crippling ($P_{cr}$) using Equation 11 for which the buckling coefficients ($k_{ETF}$) and ($k_{ITF}$) under ETF and ITF load cases are given by Equations 12 and 13, respectively. When the buckling coefficient predicted by these equations were compared with those from FEA, the mean value of FEA to predicted bucking coefficient was found to be closer to 1.0 with the corresponding COV of about 0.02 for both ETF and ITF load cases.

$$k_{ETF} = 0.435\left(1 + \frac{l_b}{0.8 d_1}\right)\left[2.5 + \left(\frac{d_1}{l}\right)^2 + 0.1\left(\frac{b_f}{d_1}\right)^{0.25}\right] \tag{12}$$

$$k_{ITF} = \left(1 + \frac{l_b}{4 d_1}\right)\left[2.5 + \left(\frac{d_1}{l}\right)^2 + 0.1\left(\frac{b_f}{d_1}\right)^{0.25}\right] \tag{13}$$

where l = Length of test specimen, $b_f$ = Flange width, $l_b$ = Bearing length, $d_1$ = clear height of web.

In order to investigate the accuracy of the proposed DSM based web crippling design equations for LSBs, experimental ultimate web crippling capacity results were processed within the DSM format and compared with the proposed design equations (6 to 13). They are shown in Figures 17 (a) and (b) for ETF and ITF load cases, respectively. These figures are in a non-dimensional format, ie. $P_u/P_y$ versus $\lambda = (P_y/P_{cr})^{0.5}$. It can be seen that the proposed DSM equations are able to predict the web crippling capacities of LSBs accurately. Further FEA based research is continuing to improve the proposed DSM equations using more web crippling capacity data.

## 6. Conclusions

This paper has presented the details of 28 web crippling tests conducted to investigate the web crippling behaviour and capacities of hollow flange channel beams known as LiteSteel beams (LSB) under ETF and ITF load cases. Comparison of the ultimate web crippling capacities from tests showed that AS/NZS 4600 [17] and AISI S100 [18] design equations are unconservative for LSB sections under both ETF and ITF load cases. New equations were therefore proposed to accurately predict the web crippling capacities of LSBs based on the test results from this study. Suitable design equations for the web crippling capacity of LSBs were also developed under the direct strength method format for ETF and ITF load cases. New equations were proposed to calculate the elastic buckling capacities of LSBs in web crippling for ETF and ITF load cases. Further finite element analyses are continuing to improve the DSM equations using more web crippling capacity data. A similar approach can be used to develop DSM based design equations from conventional open cold-formed steel sections.

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