Numerical Modelling and Design of Lipped Channel Beams Subject to Web Crippling under One-Flange Load Cases

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Abstract
Web crippling failure governs the behaviour of thin cold-formed steel lipped channel beams (LCBs) used in floor systems. This paper describes a numerical modelling based research study undertaken to investigate the web crippling behaviour of LCBs under one-flange load cases and to develop improved design equations for possible inclusion in the cold-formed steel design standards. Finite element models were developed to simulate the web crippling behaviour of LCBs and their accuracy was verified using 36 web crippling tests of LCBs conducted under one-flange load cases using the new standard test method. A detailed numerical parametric study was then undertaken to investigate the web crippling behaviour of LCBs using the verified finite element models of LCBs. This numerical parametric study provided an extensive web crippling capacity database and improved the understanding of the effects of key web crippling parameters such as inside bent radius, bearing length and yield stress on the web crippling capacity. Using these results, new and improved web crippling design equations are proposed in this paper for LCBs under one flange load cases. They include both unified web crippling equations and the Direct Strength Method based equations. This paper has shown the improved accuracy of the proposed equations and the potential for their inclusion in the cold-formed steel design standards.

Keywords: Lipped channel beams, One-flange load cases, Web crippling, Flange crushing, Numerical modelling.

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1. Introduction

In recent times, the use of advanced manufacturing technologies and high strength steels has led to increased levels of cold-formed steel construction using a range of thin-walled steel sections. Many such thin cold-formed steel sections are used as floor joists, bearers, decks and purlins in residential, industrial and commercial buildings, where they are often subjected to concentrated, localised loads or reactions. These concentrated loads and reactions acting on flexural members cause localised bearing failures. This bearing failure, commonly known as web crippling, is one of the critical failure modes of thin cold-formed steel members. The commonly used unlipped and lipped channel sections are unstiffened against this type of loading and are thus vulnerable to web crippling failures. To investigate their web crippling failures and enable safe design against web crippling failures, past research studies have often used experimental studies, for example, Kaitila (2004), Prabakaran and Schuster (1998), Duarte and Silvestre (2014), Keerthan et al. (2014a,b, 2015) and Zhao and Hancock (1995). Such experimental studies provided useful web crippling capacity data although many of them did not use the AISI S909 standard test method (AISI, 2008). Unified web crippling design equations were developed using the experimental capacity data in Prabakaran and Schuster (1998) and were included in AISI S100 (AISI, 2012). However, the accuracy of such equations was limited since they were developed for selected cold-formed sections under specific loading and boundary conditions. Further, most of the past experimental studies were not based on the new AISI S909 standard test method.

To address the above shortcomings a detailed web crippling research study of lipped channel beams (LCB) was undertaken first based on experimental studies using the new AISI S09 standard test method for one-flange load cases (Sundararajah et al., 2017). Finite element models of the tested sections were developed and verified using the web crippling test results. The validated model was then used to undertake a detailed parametric study of a range of lipped channel sections to develop a large web crippling capacity data. The main purpose of this study is to develop improved web crippling design equations based on both the unified web crippling design method and the relatively new Direct Strength Method (DSM). Recently Natario et al. (2014a,2014b) have also developed finite element models of
LCBs subject to two-flange load cases and DSM based web crippling equations, but their study was not supported by web crippling tests based on AISI S909 test method and the DSM equations developed were not based on the standard format.

This paper presents the details of the finite element models developed for LCBs under one-flange (EOF and IOF) load cases including their verification and, proposes new and improved web crippling design equations developed using the results of the detailed finite element analysis based parametric study.

2. Numerical Study

This section presents the details of finite element (FE) models developed and used to simulate the web crippling behaviour of LCBs under one-flange load cases. The FE models were developed using ABAQUS Version 6.14 (Simulia 2013), and analysed using the quasi-static analysis method to avoid convergence and contact issues usually encountered in the non-linear analysis of complex web crippling failures. They also simulated well the displacement controlled loading process used in the experimental study. Other web crippling researchers (Kaitila O. 2004, Natário et al. 2014a, 2014b) also used the same analysis method for the same reasons.

Finite element models of six LCBs under one-flange (EOF and IOF) load cases with varying bearing lengths (25, 50 and 100 mm) were created and their accuracy was verified using the results from 36 web crippling tests. These web crippling tests were conducted using the recently introduced standard test method (AISI S909 2008) and their results are reported in Sundararajah et al. (2017). The tested LCBs were made of three high strength steels (G450, G500 and G550) and their thickness and depth varied from 1 to 2.4 mm and 100 to 200 mm, respectively. Tables 1 and 2 and Figure 1 provide the important details of the web crippling tests.
2.1. Model Description

In the numerical simulations of EOF and IOF web crippling LCB specimens, the measured dimensions of LCBs and mechanical properties of steel were used (Tables 1 and 2). The centreline dimensions determined based on the measured dimensions were used to accurately model the LCB section in ABAQUS.

Experimental studies were conducted using two identical LCB sections formed in a box shape. However, a single LCB section was modelled in ABAQUS to characterize the experimental test-up. Three-dimensional deformable shell elements (S4R) and four-noded rigid body elements (R3D4) were used to model LCB sections, and loading and support bearing and web side plates used in the experiments, respectively.

2.2. Element and Mesh Details

The LCB plate elements were modelled using 5mm x 5mm shell elements. The LCB section’s inside bent radius has a significant influence on its web crippling behaviour as shown in Prabakaran and Schuster (1998) and thus more elements are needed to model the corners. Hence, 1 mm x 5 mm shell elements were used to model the corners as shown in Figure 2. 10 mm x 10 mm rigid body elements were used to model the web side plates and loading and support bearing plates.

Cold-formed LCB sections can be represented using shell elements in FEA. Many shell elements, S4, S4R, S4RS and S4RSW, are available in ABAQUS. Higher order element types such as S4 shell elements are used for more accurate solutions. However, they need much more processing time and memory. A detailed study was conducted using the above shell elements to determine the most suitable shell element based on a reference section of C15015 with 100 mm bearing length. All four elements gave similar results, which agreed well with experimentally observed behaviour, while S4RSW elements predicted a lower capacity for EOF loading. In the case of IOF load case, each shell element type shows slightly different load-deflection behaviour. Since S4 element requires significantly more computing time, it was decided to use S4R elements in this study.
2.3. Material Definition

The material model utilised the tensile test results of the coupons taken from the LCB web element in the longitudinal direction (parallel to cold-forming direction) and, the average yield strengths are presented in Tables 1 and 2. In ABAQUS, a true stress versus logarithmic plastic strain relationship is required as input. It was derived from the engineering stress versus strain data obtained from tensile coupon tests including strain-hardening effects. Since analyses are based on quasi-static method, the modelled elements need to have mass or inertia values. Therefore, the typical steel density of 7850 kg/m$^3$ was used in this study (in Abaqus model: 7.85x10$^{-9}$ tonne/mm$^3$).

2.4. Boundary Conditions

Appropriate boundary conditions were applied to the loading and support bearing plates via their reference points. Figures 2 (a) and 2(b) illustrate these boundary conditions applied to LCBs subject to EOF and IOF load conditions. The loading plate at the top was assigned displacement control using smooth step amplitude to impose smooth loading on the LCB flange element. The loading plate was free to move in the vertical direction with a limit of 20 mm. Translations along both lateral and longitudinal axes and twist rotation of the loading plate were restrained. Simply supported condition was simulated at the bottom support plates by using pin and roller boundary conditions in the support bearing plates, ie. as shown in Figures 2(a) and 2(b), translations of support plate-1 in all three directions and rotation about the longitudinal axis were restrained to simulate pin support while translation of support plate-2 along lateral (z) and vertical (y) axis and rotation about longitudinal axis were restrained to simulate roller support conditions. Angle straps used to make a box shape test set-up was simulated by restraining lateral axis translation as nodal boundary conditions at quarter points. Web side plates in experiments were simulated by rigid plate and tie contact constraints were applied between the rigid plate and the LCB web element.
2.5. Contact Assignment

The connections between the bearing plates and the LCB flanges were simulated using contact surfaces to represent the real behaviour accurately as illustrated in Figure 3. The support bearing plates and the loading plate were located at a distance of half the LCB section thickness. This is because centreline dimensions were used for the shell FE model of LCB section. This separation between the LCB flange and the plates were assigned by using face to face position constraints in Abaqus to eliminate overclosure between rigid surfaces of loading and support bearing plates and LCB. Web side plates were modelled using discrete rigid elements and assigned with tie contact as shown in Figure 3. In the models used here, surface-to-surface contact was assigned between the shell FE model of LCB and the rigid plates representing bearing plates. Following the initial contact, separations were allowed between the contact surfaces. The friction between the contact surfaces was taken as 0.4 while the contact surfaces were assigned to hard surfaces using hard contact pressure overclosure.

2.6. Contact Properties

Different methods in Abaqus are used in defining the components of a mechanical contact property model. The “hard” and “softened” contact formulations are commonly used in Abaqus. The “softened” contact formulations are used to model a soft, thin layer on one or both surfaces. The “softened” linear contact formulations are defined by the slope k. The reference section of C15015 with 100 mm bearing plate was analysed using different k values and linear “softened” contact formulations for both one-flange load cases. Figures 4 and 5 compare the applied load versus vertical deflection plots for different softened contacts under EOF and IOF load conditions. The results obtained for different “softened” and “hard” contact formulations show that FE models with “softened” contact formulations can be used to investigate the EOF and IOF web crippling behaviour of LCBs. However, the effect of the rigid bearing plate deformation was negligible in the web crippling tests of LCBs. Therefore “hard” contact formulation was used in all the finite element models.
2.7. Load Rate Scaling

Load rate selection is important to minimise the inertial effects in achieving the solution. Load rate was changed by varying the step time (ST) in the analysis of the reference section C15015 with 100 mm bearing length. Figures 6(a) and 7(a) present the load versus deflection curves for different step times used in these analyses for EOF and IOF load conditions. Figures 6(b) and 7(b) show the ratio of kinetic energy to internal energy ($E_k/E_i$) versus deflection plots for respective models. Load rate implemented using small step time (0.1 s) created a high dynamic effect and gave an irregular and higher failure load. Comparison of $E_k/E_i$ ratios in Figures 6(b) and 7(b) also indicated the irregular dynamic effect occurring at a higher load rate. Hence step time of 1 second (ST = 1s) with smooth step load rate was selected in this study.

2.8. Mass Scaling

Reducing the analysis time period (load rate) or artificially increasing the model mass (mass scaling) is often useful to reach economical solutions in quasi-static analyses. To investigate the effect of mass scaling, quasi static analyses of the reference section C15015 section with 100 mm bearing plate were conducted with different mass scaling for one-flange load cases. Figures 8(a) and 9(a) compare the load versus vertical deflection plots with EOF and IOF load case test results. Figures 8(b) and 9(b) show the variation in the kinetic energy to internal energy ratio during the analyses. The results showed that the failure load for EOF load case was significantly affected by even a small mass scaling due to inflated kinetic energy. However, satisfactory results were obtained for IOF load case with mass scaling of 10, 100 and 1000 in comparison with the results for zero mass scaling and test results. Hence it was decided not to impose mass scaling to maintain consistency and obtain results with improved accuracy. Further details of finite element modelling for LCBs subject to web crippling are also available in Sundararajah et al. 2017.

2.9. Imperfection
In the nonlinear analysis, an initial geometric imperfection magnitude of 0.006 times the section depth was considered for the local plate imperfection. However, the ultimate web crippling capacities of lipped channel beams variations were negligible (< 3%).

3. Numerical Analysis Results

3.1. Verification

Tables 1 and 2 compare the web crippling capacities determined from finite element analyses (FEA) and experimental study ($R_{b,\text{FEA}}$ and $R_{b,\text{Exp}}$) for EOF and IOF load cases. For EOF loading, the mean and COV of the ratio of the web crippling capacities of LCB sections from experiments and FEA are 1.06 and 0.07, while they are 1.03 and 0.08 for IOF loading. These comparisons reveal that the FE models developed in this research study and analysed using quasi-static analysis method were able to accurately simulate the EOF and IOF web crippling test results.

Failure modes and load–deflection plots from FEA and experiments are compared in Figures 10 to 13. Figure 10 shows the experimental and FEA failure modes of EOF-C10010 sections with 25 mm bearing plate whereas Figure 11 shows the load-vertical deflection plots. Similarly, Figures 12 and 13 illustrate the failure modes and load-deflection plot comparisons for IOF-C10010 sections with 100 mm bearing plate. Figures 10 to 13 demonstrate that the FE models predict well the observed experimental EOF and IOF web crippling behaviour of LCBs.

3.2. Flange Crushing Mechanism

Flange crushing failure was also observed when LCB sections were used with small bearing lengths under IOF load case. Both FEA and experimental results exhibited similar flange crushing failure modes and associated load-deflection plots. Figure 14 shows the load-vertical deflection plots observed in FEA of IOF-C10015 LCB section with 25 mm bearing plate. As seen in this figure, until Point-b web crippled or deformed like an arc with increasing load. After Point-b, shortened web section was able to support higher loads, and thus led to web-flange juncture deformations. Figures 15(a) to 15(d) show the observed
failure modes at the points shown in Figure 14. Figure 16 shows the web crippling failure capacity with increasing bearing length. The higher web crippling capacity of LCBs observed with a 25 mm bearing plate was considered to have been caused by the combined web crippling and flange crushing actions. Figure 17 shows the failure shapes of LCB section under the applied load at Points (a) to (d) shown in Figure 14.

4. Parametric Study

The verified EOF and IOF finite element models of LCBs were used in a parametric study. This parametric study was aimed at investigating the web crippling behaviour of LCBs and developing an extensive web crippling capacity database so that new and/or improved design rules can be developed. All the tested specimens were considered in the study, but nominal dimensions (t_w and d) were used. The effect of inside bent radius (r_i), bearing length (ℓ_b) and yield stress (f_y) on the web crippling capacity of LCB was investigated by varying their values as follows: r_i = 0, 3, 5 and 7, ℓ_b = 50, 100, 150mm and f_y = 300, 450, 550MPa. Details of the study are given in Table 3.

5. Improved Web Crippling Design Equations

Both AISI S100 (2012) and AS/NZS 4600 (2005) present Equation 1 to calculate the web crippling capacities (R_b) of lipped channel beams (LCB). The web crippling coefficients to be used with Equation 1 are shown in Table 4. To investigate the accuracy of Equation 1, the web crippling capacities determined from both the numerical parametric study and web crippling tests were compared with the corresponding capacities calculated from Equation 1.

\[
R_b = C t_w^2 f_y \sin \theta \left( 1 - C_r \sqrt{\frac{r_i}{t_w}} \right) \left( 1 + C_\ell \sqrt{\frac{\ell_b}{t_w}} \right) \left( 1 - C_w \sqrt{\frac{d_1}{t_w}} \right) \tag{1}
\]

In Equation 1, t_w is the web thickness, f_y is the web yield stress, ℓ_b is the bearing length, d is the section depth, r_i is the inside bent radius, d_1 is the flat depth of web [d_1 = d - 2(r_i + t_w)], θ is the angle between the web and the bearing surface, C is the overall Coefficient and C_r, C_\ell
and $C_w$ are the relevant coefficients of the three important parameters, inside bent radius, bearing length and web slenderness, respectively.

Since the applicability of Equation 1 is limited to $r_i/t_w$ values less than 5, many numerical parametric study capacity results could not be used in the comparisons. For comparison purposes, the ratios of FEA and AS/NZS4600 web crippling capacities ($R_{b,\text{FEA}}/R_{b,\text{AS/NZS}}$) were calculated for each load case and their mean and COV values were calculated. The calculated mean and COV values are 0.89 and 0.20 for EOF loading, while they are 1.01 and 0.17 for IOF loading. The numerical parametric study produced 504 web crippling capacity data (Table 3), and thus the web crippling capacity comparisons could not be given in this paper for each case. Detailed comparisons are available in the first author’s PhD thesis (Sundararajah, 2016). The overall comparisons using the calculated mean and COV values reveal that the web crippling design equation in AS/NZS 4600 (2005) and AISI S100 (2012) is unconservative for LCBs under EOF loading while agreeing reasonably well with test and FEA predictions for IOF loading. Hence new web crippling coefficients were proposed using the 504 web crippling capacities obtained in this study.

When 25 mm bearing plates were used, combined web crippling and flange crushing failures were observed in LCBs and their web crippling capacity increased, contradicting the normal expectation for web crippling with decreasing bearing length. Hence the numerical parametric study was not conducted for 25 mm bearing plates in order to exclude flange crushing failures. Flange crushing failures were observed in some of the finite element models developed with 50 mm bearing plates and they were also omitted in the process of finding the new web crippling coefficients. However, the new coefficients can be used for LCB sections with smaller bearing lengths also, as they will give conservative predictions.

5.1. New Web Crippling Coefficients for Equation-1

The new web crippling coefficients for Equation 1 were determined using the numerical parametric study results of LCBs and are given in Table 4. The ratios of the web crippling capacities from FEA and experiments to the predicted web crippling capacities using the
new web crippling coefficients and their mean and COV values were calculated to evaluate
the improved accuracy of Equation 1. The mean and COV values are 1.00 and 0.17 for both
EOF and IOF loading conditions. Such improved mean and COV values demonstrate a good
agreement between the web crippling capacities ($R_b$) obtained using Equation 1 with the new
web crippling coefficients and those from FEA and web crippling tests.

The mean and COV values calculated as above were then used to determine the capacity
reduction factors ($\Phi_w$), which are 0.81 for EOF loading and 0.80 for IOF loading. Based on
these results, Equation 1 should be used with a $\Phi_w$ factor of 0.80 to determine the design
web crippling capacities of LCBs under one-flange load cases.

5.2. New Web Crippling Capacity Equation-2

The numerical parametric study results of LCBs made of steels of varying grade (G300 to
G550) show that the web crippling capacity increases significantly with increasing yield
strength. Hence Equation 2 was developed by including a new factor of $[1+ C_f \sqrt{(250/f_y)}]$ in
Equation 1 to improve the accuracy of predicting the web crippling capacity. Table 4 gives
the appropriate web crippling coefficients proposed for Equation 2. The web crippling
capacities obtained from Equation 2 were then compared with the corresponding capacities
from the numerical parametric study and web crippling tests.

$$R_b = C t_w^2 f_y \sin \theta \left(1 - C_r \sqrt{t_l/t_w} \right) \left(1 + C_f \sqrt{t_l/t_w} \right) \left(1 - C_w \sqrt{t_l/t_w} \right) \left(1 + C_f \sqrt{250/f_y} \right)$$

where $C_r$ = Yield stress coefficient

The comparisons gave the following mean and COV values for the ratio of the web crippling
capacities obtained from FEA and experiments to the web crippling capacities of LCBs
obtained from Equation 2: 1.00 and 0.11 for EOF loading and 1.00 and 0.13 for IOF loading.
These mean and COV values indicate an improved agreement between the FEA/Experiment
and Equation 2 predicted web crippling capacities in comparison with Equation 1. The COV
values have been reduced from 0.17 to 0.11 and 0.17 to 0.13 for the two load cases.
The above mean and COV values were then used to calculate the capacity reduction factors ($\Phi_w$), which are 0.86 for EOF loading and 0.85 for IOF loading. Based on these results, a capacity reduction factor of 0.85 is proposed for Equation 2 to determine the design EOF and IOF capacities of LCBs.

6. Direct Strength Method (DSM)

DSM is a more efficient design approach that is being adopted for metal structures in several design codes. However, none of the cold-formed steel design codes have yet included DSM based design equations for web crippling. In recent times, many researchers have addressed this issue through experimental and/or numerical studies and proposed DSM equations, for example, Duarte and Silvestre’s (2014) equations for plain channel sections, Keerthan et al.’s (2014a, 2014b) equations for hollow flange channel beams and Natario et al.’s (2016, 2017) equations for channel sections. However, past DSM studies have mostly concentrated on two-flange loading (ETF and ITF) and the equations given in these studies were not in proper DSM equation format. Hence this research study proposed suitable DSM based equations for LCBs under one-flange loading (EOF and IOF) using the extensive experimental and numerical parametric study data reported in the earlier sections of this paper. The web crippling results from 36 experiments and 468 FEA of LCBs under one-flange load conditions were used for this purpose. It included low and high strength steel LCBs (G300, G450 and G550) with varying geometric parameters: inside bent radius ($r_i$) in the range of 0 to 7 mm and bearing length in the range of 50 to 150 mm.

The two key parameters for the DSM web crippling design rules are the critical buckling load and the yield/plastic load. Finite element analyses can be used to investigate the elastic buckling behaviour and determine the associated critical buckling loads. However, such analyses are not needed if a simplified equation is available. In the first author’s PhD thesis (Sundararajah L. 2016), a simplified equation was developed to calculate the buckling coefficients ($k_{prop}$) for use with the critical buckling capacity equation (Equations 3 and 4 with the coefficients in Table 5 for EOF and IOF load conditions).
\[ k_{Pr,op} = C_b \left( 1 - C_{b,r} \sqrt{\frac{r}{t_w}} \right) \left( 1 - C_{b,w} \sqrt{\frac{d_1}{t_w}} \right) \left( 1 + C_{b,\ell} \sqrt{\frac{\ell_b}{t_w}} \right) \left( 1 + C_{b,b} \sqrt{\frac{b_f}{t_w}} \right) \]  

(3)

\[ R_{b,cr} = \frac{\pi^2 E k t_w^3}{12(1-\nu^2)d} \]  

(4)

In Equation 3, \( C_b \) is the general coefficient while the other four coefficients, \( C_{b,r}, C_{b,w}, C_{b,\ell} \) and \( C_{b,b} \), are included to consider the effects of the four important parameters: inside bent radius to thickness ratio, web slenderness ratio, bearing length to thickness ratio and flange width to thickness ratio.

However, the determination of the yield/plastic load (\( R_{b,y} \)) of the section is complicated. In this case, a plastic mechanism based study was undertaken by the first author (Sundararajah 2016), who proposed Equation 5 to calculate the yield capacity of LCB sections together with the yield length equations (Equation 6 and 7) for one-flange load conditions.

\[ R_{b,y} = f_y N_m \left( 4r_m^2 + t_w^2 - 2r_m \right) \]  

(5)

EOS Load Case

\[ N_m = \ell_b + \left( 2.5r_{ext} + 0.9d_1 \right) \]  

(6)

IOF Load Case

\[ N_m = \ell_b + 2\left( 2.5r_{ext} + 0.9d_1 \right) \]  

(7)

Figures 18 (a) and (b) illustrate the typical ultimate failure modes from FEA for EOF and IOF load conditions. The FEA results of EOF load case indicate the average yield mechanism length ratio (\( x \)) to be 0.92. Hence it was decided to use a yield mechanism length ratio (\( x \)) of 0.9 in Equation 6. Since the failure occurs in the middle of the web in a “yield arc” shape for IOF loading, the yield mechanism lengths measured along the web are too small. To magnify the yield arc in relation to yield mechanism length is difficult. Hence the same yield mechanism length ratio of 0.9 was used as for EOF loading (Equation 7).
In order to develop DSM equations, the critical buckling loads \( (R_{b,cr}) \) were determined using Equations 3 and 4 and their coefficients for EOF and IOF load conditions given in Table 5, whereas the yield loads \( (R_{b,y}) \) were determined using Equation 5 with the yield mechanism lengths for EOF and IOF load conditions based on Equations 6 and 7, respectively. Based on these loads, suitable DSM web crippling equations were proposed for LCBs subject to EOF and IOF load conditions and were calibrated using 36 web crippling test results and 468 FEA results from the numerical parametric study conducted in this study.

Equations 8 and 9 give the developed DSM based web crippling capacity equations while Equation 10 defines the web crippling slenderness \( (\lambda) \) required for DSM.

For \( \lambda \leq 0.83 \), \( R_b = R_{b,y} \)  

\[
R_b = \frac{R_{b}}{R_{b,y}} = \left[ 1 - 0.20 \left( \frac{R_{b,cr}}{R_{b,y}} \right)^{0.84} \right] \left( \frac{R_{b,cr}}{R_{b,y}} \right)^{0.84} \]  

EOF Load Case (8)

For \( \lambda > 0.83 \), \( R_b = R_{b,y} \)  

\[
R_b = \frac{R_{b}}{R_{b,y}} = \left[ 1 - 0.23 \left( \frac{R_{b,cr}}{R_{b,y}} \right)^{0.85} \right] \left( \frac{R_{b,cr}}{R_{b,y}} \right)^{0.85} \]  

IOF Load Case (9)

For \( \lambda \leq 0.78 \), \( R_b = R_{b,y} \)  

\[
\lambda = \sqrt{\frac{R_{b,y}}{R_{b,cr}}} \]  

(10)

For comparison purposes, the web crippling capacity data are compared in the DSM format with Equations 8 and 9 in Figures 19 and 21 for EOF and IOF load conditions. These figures, plotted using a non-dimensionalized format of \( R_b/R_{b,y} \) versus \( \lambda = \sqrt{(R_{b,y}/R_{b,cr})} \), reveal that the DSM equations presented above are reasonably well predicting the web crippling capacities of LCBs.
Due to the influence of many parameters on the web crippling failure mode that involves both buckling and yielding effects, the limits for pure yielding or pure buckling failure modes are difficult to define. However, the observations in Figure 19 for EOF loading indicate that the failure of compact LCBs with larger inside bent radius \( r_i = 7 \) was mainly in yielding (Region A), whereas that of slender LCBs with smaller or zero inside bent radius was mainly in buckling (Region B). Figure 20 shows the yielding and buckling failure mechanisms for EOF loading. For IOF loading, the compact LCBs with higher \( r_i \) of 7 mm failed mainly in yielding (Region A) and slender section with smaller or zero \( r_i \) failed mainly in buckling (Region B). Figure 22 shows the yielding and buckling failure mechanisms for IOF loading.

The EOF and IOF web crippling capacities of LCBs obtained from the proposed DSM equations were compared with those obtained from the numerical parametric study and web crippling tests (252 results in each load case). The ratios of FEA/test web crippling capacities to those obtained from DSM equations were used in these comparisons, which gave the following mean and COV values: 1.0 and 0.18 for EOF loading and 1.00 and 0.23 for IOF loading. These results demonstrate a closer agreement between the web crippling capacities from the proposed DSM Equations 8 and 9 and those from experiments and numerical parametric study.

Figure 21 shows that the proposed DSM equation over-estimates the web crippling capacity in the lower slenderness region for IOF load case. This is because the DSM equation was developed in the standard format with \( a = 1 \) (\( a \) is the coefficient outside square brackets) in Equation 9 (Keerthan and Mahendran, 2015; Schafer, 2008). Only if the 'a' value is other than 1.0, an improved-fit curve can be obtained. A reduced capacity reduction factor allows for this shortcoming.

The procedure given in AISI S100 was used to calculate the required capacity reduction factor \( (\Phi_w) \) for the proposed DSM equations. These factors were determined using the mean and COV values given in the last paragraph, which are 0.79 for EOF loading and 0.73 for
IOF loading. Therefore a suitable $\Phi_w$ factor is 0.75 for Equation 9 (EOF loading) while it is 0.70 for Equation 10 (IOF loading).

7. Conclusion

This paper has presented the details of a numerical study of cold-formed Lipped Channel Beam (LCB) sections subjected to one-flange web crippling loads (EOF and IOF load cases). In the study reported in this paper, finite element models capable of simulating the web crippling behaviour were first developed and their accuracy was investigated by comparing their results against those from the first author’s web crippling tests undertaken using the AISI S909 standard test method. This paper has shown that the developed web crippling finite element models are able to predict the experimental web crippling capacities, failure modes and load-deflection plots of LCBs under EOF and IOF load cases.

The developed one-flange web crippling models were then used in a detailed numerical parametric study to enhance the understanding of the EOF and IOF web crippling behaviour of LCBs and to develop 504 EOF and IOF web crippling capacity data without the need for time consuming and expensive experimental studies. When the web crippling capacities obtained from experimental and numerical studies were compared with the predictions of the unified web crippling design equations in AS/NZS 4600 and AISI S100, it was found that they are inconsistent for LCBs under one-flange load cases. Therefore, new web crippling design equations were proposed in the form of modified web crippling coefficients for the three important parameters of inside bent radius, bearing length and web slenderness ratio. A new parameter was also included to allow the use of the proposed web crippling equations for LCBs made of both low and high strength steels.

Finally, this study has proposed suitable Direct Strength Method (DSM) based web crippling design equations using the standard DSM format for LCBs under one-flange load cases. For this purpose, this paper has also developed suitable predictive equations for the two key parameters, elastic buckling load and plastic/yield load of LCBs under EOF and IOF load cases. The proposed web crippling equations in this paper can be considered for inclusion in the future versions of AISI S100 and AS/NZS 4600.
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Figure 1: FE Models Simulating EOF and IOF Tests

(a) Experiment and FE Model – EOF Load Case

(b) Experiment and FE Model – IOF Load Case

(c) Lipped Channel Beam (LCB)
**Figure 2: Boundary Conditions of FE Models**

- UT-Translation, UR-Rotation and 1, 2, 3 denotes the global axis x, y, z respectively
- Angle strap at quarter points were simulated by node points with UT1=0
Figure 3: Contact Surfaces and Constraint Assignment for FE Models
Figure 4: Comparison of Load versus Vertical Deflection Plots for Different Contact Formulations (EOF-C15015 Section with \( t_b = 100 \) mm)
Figure 5: Comparison of Load versus Vertical Deflection Plots for Different Contact Formulations (IOF-C15015 Section with $f_b = 100$ mm)
Figure 6: Effects of Different Load Rates for EOF Load Case
(C15015 Section with \( t_b = 100 \text{ mm} \))
Figure 7: Effects of Different Load Rates for IOF Load Case
(C15015 Section with \( h_b = 100 \) mm)
Figure 8: Effect of Different Mass Scaling Factors for EOF Load Case
(C15015 Section with $t_b = 100$ mm)
a) Load versus Vertical Deflection

b) Kinetic Energy ($E_k$) to Internal Energy ($E_i$) versus Vertical Deflection

Figure 9: Effect of Different Mass Scaling Factors for IOF Load Case
(C15015 with $t_b = 100$ mm)
Figure 10: Failure Modes of EOF-C10010 Section with 25 mm Bearing Plate from Experiment and FEA
Figure 11: Comparison of Load versus Vertical Deflection Plots of EOF-C10010 Section with 25 mm Bearing Plate from Experiment and FEA
Figure 12: Failure Modes of IOF-C10010 Section with 100 mm Bearing Plate from Experiment and FEA
Figure 13: Comparison of Load versus Vertical Deflection Plots of IOF-C10010 Section with 100 mm Bearing Plate
Figure 14: Load versus Vertical Deflection Plot of IOF-C10015 Section with 25 mm Bearing Plate
Figure 15: Failure Modes of IOF-C10010 Section with 25 mm Bearing Plate at Different Stages
Figure 16: Failure Load versus Bearing Length for IOF-C10015 Section under IOF Load Case.
Figure 17: Cross Section of IOF-C10015 with 25 mm Bearing Plate at Different Points
Figure 18: Yield Mechanism Length Observed with the Ultimate Failure Modes
Figure 19: Comparison of Web Crippling Capacities from Test and FEA Parametric Studies with DSM based Design Equation-EOF Load Case
Figure 20: Typical Web Crippling Failure Mechanisms Observed at the Ultimate Failure Stage - EOF Load Case
Figure 21: Comparison of Web Crippling Capacities from Test and FEA Parametric Studies with DSM based Design Equation-IOF Load Case
Figure 22: Typical Web Crippling Failure Mechanisms Observed at the Ultimate Failure Stage - IOF Load Case

a) Yielding Failure (C10015, \( r_l = 7 \), \( b = 100 \) & \( f_y = 550 \) MPa)

b) Buckling Failure (C20019, \( r_l = 0 \), \( b = 100 \) & \( f_y = 550 \) MPa)
## Table 1: Comparison of FEA and Experimental Web Crippling Capacities for EOF Load Case

| No | Member       | \( \ell_b \) (mm) | \( f_y \) (MPa) | \( t_w \) (mm) | \( r_i \) (mm) | \( b_f \) (mm) | \( b_g \) (mm) | \( d \) (mm) | \( L \) (mm) | \( R_{b,\text{Exp}} \) (kN) | \( R_{b,\text{FEA}} \) (kN) | \( R_{b,\text{Exp}}/R_{b,\text{FEA}} \) |
|----|--------------|------------------|----------------|--------------|--------------|--------------|--------------|--------------|--------------|----------------|----------------|----------------|
| 1  | EOF-C10010   | 25               | 581            | 1.03         | 3.5          | 50.4         | 14.5         | 101.0        | 381          | 3.92           | 4.01           | 0.98           |
| 2  | EOF-C10015   | 25               | 540            | 1.53         | 4.0          | 50.2         | 16.0         | 100.5        | 381          | 9.51           | 7.55           | 1.26           |
| 3  | EOF-C15012   | 25               | 556            | 1.21         | 4.0          | 61.6         | 19.9         | 151.1        | 531          | 5.10           | 4.92           | 1.04           |
| 4  | EOF-C15015   | 25               | 531            | 1.52         | 4.5          | 62.4         | 18.4         | 150.8        | 531          | 6.96           | 7.31           | 0.95           |
| 5  | EOF-C20019   | 25               | 506            | 1.91         | 5.0          | 76.8         | 22.0         | 203.1        | 688          | 10.50          | 10.25          | 1.02           |
| 6  | EOF-C20024   | 25               | 526            | 2.41         | 5.0          | 77.6         | 21.7         | 203.9        | 684          | 17.77          | 15.71          | 1.13           |
| 7  | EOF-C10010   | 50               | 581            | 1.03         | 3.5          | 49.9         | 14.0         | 100.6        | 456          | 4.22           | 4.25           | 0.99           |
| 8  | EOF-C10015   | 50               | 540            | 1.52         | 4.0          | 51.1         | 15.6         | 101.0        | 456          | 9.62           | 8.56           | 1.12           |
| 9  | EOF-C15012   | 50               | 556            | 1.21         | 4.0          | 61.6         | 19.3         | 151.1        | 606          | 5.16           | 4.98           | 1.04           |
| 10 | EOF-C15015   | 50               | 531            | 1.52         | 4.5          | 61.3         | 19.6         | 151.4        | 606          | 8.75           | 7.92           | 1.11           |
| 11 | EOF-C20019   | 50               | 506            | 1.91         | 5.0          | 76.3         | 20.4         | 203.5        | 759          | 11.18          | 10.98          | 1.02           |
| 12 | EOF-C20024   | 50               | 526            | 2.41         | 5.0          | 77.4         | 21.7         | 203.8        | 759          | 18.84          | 16.85          | 1.12           |
| 13 | EOF-C10010   | 100              | 581            | 1.03         | 3.5          | 50.0         | 14.3         | 100.4        | 606          | 5.14           | 4.74           | 1.09           |
| 14 | EOF-C10015   | 100              | 540            | 1.52         | 4.0          | 51.4         | 15.8         | 101.2        | 606          | 10.68          | 10.89          | 0.98           |
| 15 | EOF-C15012   | 100              | 556            | 1.21         | 4.0          | 62.8         | 18.2         | 151.2        | 756          | 6.01           | 5.49           | 1.09           |
| 16 | EOF-C15015   | 100              | 531            | 1.52         | 4.5          | 61.8         | 19.6         | 151.2        | 756          | 9.61           | 8.58           | 1.12           |
| 17 | EOF-C20019   | 100              | 506            | 1.91         | 5.0          | 76.4         | 19.8         | 203.4        | 909          | 12.39          | 11.59          | 1.07           |
| 18 | EOF-C20024   | 100              | 526            | 2.41         | 5.0          | 77.7         | 22.0         | 203.8        | 909          | 20.05          | 19.49          | 1.03           |

Mean 1.06
COV 0.07

Note: \( \ell_b \) = Bearing plate length, \( f_y \) = yield stress, \( L \) = specimen length and others are defined in Figure 1(c).
Table 2: Comparison of FEA and Experimental Web Crippling Capacities for IOF Load Case

| No | Member     | $\ell_b$ (mm) | $f_y$ (MPa) | $t_w$ (mm) | $r_i$ (mm) | $b_f$ (mm) | $b_f$ (mm) | $d$ (mm) | $L$ (mm) | $R_{b,Exp}$ (kN) | $R_{b,FEA}$ (kN) | $R_{b,Exp}/R_{b,FEA}$ |
|----|------------|---------------|-------------|------------|------------|-----------|-----------|----------|----------|-----------------|-----------------|---------------------|
| 1  | IOF-C10010 | 25            | 581         | 1.03       | 3.5        | 51.0      | 14.9      | 100.0    | 381      | 8.11            | 7.37            | 1.10                |
| 2  | IOF-C10015 | 25            | 540         | 1.52       | 4.0        | 50.4      | 15.4      | 101.0    | 381      | 15.52           | 15.75           | 0.99                |
| 3  | IOF-C15012 | 25            | 556         | 1.21       | 4.0        | 62.7      | 18.8      | 150.9    | 531      | 11.57           | 12.07           | 0.96                |
| 4  | IOF-C15015 | 25            | 531         | 1.52       | 4.5        | 61.1      | 19.4      | 151.0    | 531      | 15.41           | 17.16           | 0.90                |
| 5  | IOF-C20019 | 25            | 506         | 1.91       | 5.0        | 76.9      | 22.0      | 203.3    | 681      | 23.99           | 23.63           | 1.02                |
| 6  | IOF-C20024 | 25            | 526         | 2.41       | 5.0        | 77.6      | 22.2      | 203.7    | 684      | 37.32           | 32.51           | 1.15                |
| 7  | IOF-C10010 | 50            | 581         | 1.03       | 3.5        | 50.1      | 14.0      | 100.0    | 456      | 8.91            | 9.25            | 0.96                |
| 8  | IOF-C10015 | 50            | 540         | 1.52       | 4.0        | 51.3      | 16.0      | 100.8    | 456      | 15.05           | 13.61           | 1.11                |
| 9  | IOF-C15012 | 50            | 556         | 1.21       | 4.0        | 62.0      | 18.2      | 151.1    | 606      | 12.78           | 12.07           | 1.06                |
| 10 | IOF-C15015 | 50            | 531         | 1.52       | 4.5        | 62.8      | 18.1      | 151.6    | 606      | 13.32           | 14.13           | 0.94                |
| 11 | IOF-C20019 | 50            | 506         | 1.91       | 5.0        | 76.7      | 22.0      | 203.1    | 759      | 18.19           | 20.21           | 0.90                |
| 12 | IOF-C20024 | 50            | 526         | 2.41       | 5.0        | 76.8      | 20.4      | 203.8    | 759      | 28.94           | 30.49           | 0.95                |
| 13 | IOF-C10010 | 100           | 581         | 1.03       | 3.5        | 50.0      | 14.0      | 100.2    | 606      | 9.29            | 9.37            | 0.99                |
| 14 | IOF-C10015 | 100           | 540         | 1.52       | 4.0        | 51.4      | 15.8      | 101.0    | 606      | 19.81           | 16.60           | 1.19                |
| 15 | IOF-C15012 | 100           | 556         | 1.21       | 4.0        | 62.6      | 17.6      | 151.5    | 756      | 11.72           | 11.20           | 1.05                |
| 16 | IOF-C15015 | 100           | 531         | 1.52       | 4.5        | 61.8      | 19.6      | 151.2    | 756      | 16.84           | 15.68           | 1.07                |
| 17 | IOF-C20019 | 100           | 506         | 1.91       | 5.0        | 76.3      | 19.6      | 203.4    | 909      | 24.72           | 22.34           | 1.11                |
| 18 | IOF-C20024 | 100           | 526         | 2.41       | 5.0        | 77.7      | 22.0      | 203.8    | 909      | 37.65           | 35.81           | 1.05                |

Mean | 1.03

COV 0.08

Note: $\ell_b$ = Bearing plate length, $f_y$ = yield stress, $L$ = specimen length and others are defined in Figure 1(c).
Table 3: Parametric Study of LCBs under EOF and IOF load cases

| Load Case | Section  | Inside bent radius $r_i$ (mm) | Bearing length $l_b$ (mm) | Yield stress $f_y$ (MPa) | Number of Models |
|-----------|---------|-------------------------------|--------------------------|------------------------|-----------------|
| EOF       | EOF-C10010 | 0,3,5,7                       | 50,100,150               | 300,450,550            | 36              |
|           | EOF-C10015 | 0,3,5,7                       | 50,100,150               | 300,450,550            | 36              |
|           | EOF-C15012 | 0,3,5,7                       | 50,100,150               | 300,450,550            | 36              |
|           | EOF-C15015 | 0,3,5,7                       | 50,100,150               | 300,450,550            | 36              |
|           | EOF-C20019 | 0,3,5,7                       | 50,100,150               | 300,450,550            | 36              |
|           | EOF-C20024 | 0,3,5,7                       | 50,100,150               | 300,450,550            | 36              |
|           | Test      |                               |                          |                        | 18              |
|           | FEA-Test Validation |                   |                          |                        | 18              |
|           | Sub-Total |                               |                          |                        | 252             |
| IOF       | IOF-C10010 | 0,3,5,7                       | 50,100,150               | 300,450,550            | 36              |
|           | IOF-C10015 | 0,3,5,7                       | 50,100,150               | 300,450,550            | 36              |
|           | IOF-C15012 | 0,3,5,7                       | 50,100,150               | 300,450,550            | 36              |
|           | IOF-C15015 | 0,3,5,7                       | 50,100,150               | 300,450,550            | 36              |
|           | IOF-C20019 | 0,3,5,7                       | 50,100,150               | 300,450,550            | 36              |
|           | IOF-C20024 | 0,3,5,7                       | 50,100,150               | 300,450,550            | 36              |
|           | Test      |                               |                          |                        | 18              |
|           | FEA-Test Validation |                   |                          |                        | 18              |
|           | Sub-Total |                               |                          |                        | 252             |
|           | Total     |                               |                          |                        | 504             |
| Load Case | Equation       | C   | C_ℓ | C_l | C_w | C_f | Φ_w | Mean | COV |
|-----------|----------------|-----|-----|-----|-----|-----|-----|------|-----|
| EOF       | AS/NZS 4600    | 4.0 | 0.14| 0.35| 0.02| -   | 0.80| 0.89 | 0.20|
|           | Proposed-1     | 7.0 | 0.19| 0.17| 0.03| -   | 0.81| 1.00 | 0.17|
|           | Proposed-2     | 1.3 | 0.19| 0.13| 0.04| 8.1 | 0.86| 1.00 | 0.11|
| IOF       | AS/NZS 4600    | 13.0| 0.23| 0.14| 0.01| -   | 0.90| 1.01 | 0.17|
|           | Proposed-1     | 13.1| 0.22| 0.13| 0.01| -   | 0.80| 1.00 | 0.17|
|           | Proposed-2     | 2.6 | 0.22| 0.12| 0.01| 5.5 | 0.85| 1.00 | 0.13|
Table 5: Proposed Coefficients for Buckling Coefficient in Equation 4

| k_{Prop} | C_b | C_{b,r} | C_{b,w} | C_{b,l} | C_{b,b} |
|----------|-----|---------|---------|---------|---------|
| k_{EOF}  | 0.8 | 0.01    | 0.05    | 0.46    | 0.03    |
| k_{IOF}  | 3.7 | 0.01    | 0.02    | 0.10    | 0.01    |