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Abstract

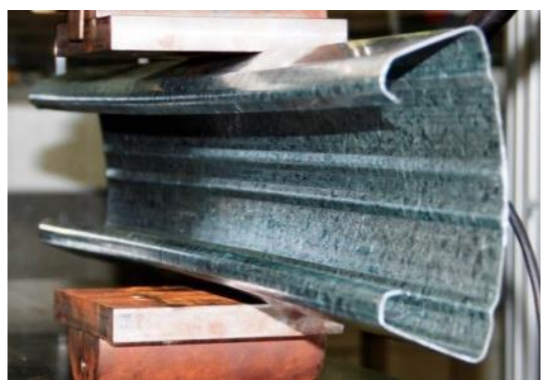
Lipped channel beams (LCBs) and SupaCee sections are commonly used as floor joists and bearers in the construction industry. SupaCee section is one of the cold-formed steel members, which is increasingly used in the building construction sector. It is characterized by unique ribbed web and curved lip elements, and is claimed to be more economical with extra strength than the traditional channel sections. These thin-walled LCBs and SupaCee sections are subjected to specific local and global failures, one of them being web crippling. Several experimental and numerical studies have been conducted in the past to study the web crippling behaviour and capacities of different cold-formed steel sections under different concentrated load cases. However, due to the nature of the web crippling phenomenon and many factors influencing the web crippling capacities, capacity predictions given by most of the cold-formed steel design standards are either unconservative or conservative. Hence both experimental and finite element studies were conducted to assess the web crippling behaviour and strengths of LCBs and SupaCee sections under ETF, ITF, EOF and IOF load cases. New equations were proposed to determine the web crippling capacities of LCBs and SupaCee sections based on the results from experiments and finite element analyses. Suitable DSM based web crippling design equations were also developed.

Keywords: Cold-formed Steel Beams, Web Crippling, Lipped Channel Beams, SupaCee Sections, Experiments, Finite Element Analyses, ETF, ITF, EOF and IOF Load Cases, Design Rules, Direct Strength Method

Introduction

Web bearing failure, generally known as web crippling, is a form of localized failure that occurs at points of transverse concentrated loading or supports of thin-walled steel beams. Lipped channel sections (LCB, Figure 1a) and SupaCee sections (Figure 1b) that are unstiffened against this type of loading are vulnerable to web crippling failures (Figure 1). The computation of web crippling strength using a theoretical analysis is quite complex as it involves many factors such as web slenderness, web thickness, yield strength and inside bent radius. Hence the current web bearing design rules found in most specifications for cold-formed steel structures are empirical in nature developed based on extensive testing of conventional cold-formed steel sections such as C-, Z- and hat sections and built-up sections in the past.

(a) LCB



(b) SupaCee

Figure 1: Web Crippling Failure

When subjected to concentrated loads and reactions under various loading conditions, thin-walled cold-formed steel members suffer from bearing failures. These loading conditions are defined in four categories, based on the location of load or reaction force through one flange or both flanges. Figure 2 shows the typical loading conditions specified in the AISI design specification AISI-S100 (AISI, 2012) and AS/NZS 4600 (SA, 2005). Many research studies have been conducted to investigate the web crippling behaviour of cold-formed steel sections. But these experimental studies appear to have inconsistencies in test set-up and selection of test specimen lengths. Therefore in 2008, American Iron and Steel Institute published a standard test method, AISI S909 (AISI, 2008) that presents the details of web crippling test set-ups and procedures for use in experimental studies. However, this AISI test procedure appears to be different from those used by past research studies. AISI S909 (AISI, 2008) recommends the following test specimen lengths for the four loading cases.

EOF Loading: $L_{min} = 3d_1 + 3\ell_b$
IOF Loading: $L_{min} = 3d_1 + 3\ell_b$
ETF Loading: $L_{min} = 3d_1$
ITF Loading: $L_{min} = 5d_1$

where;
L_{min} = Minimum specimen length
d_1= Depth of the flat portion of the web measured along the plane of the web
ℓ_b = Bearing length

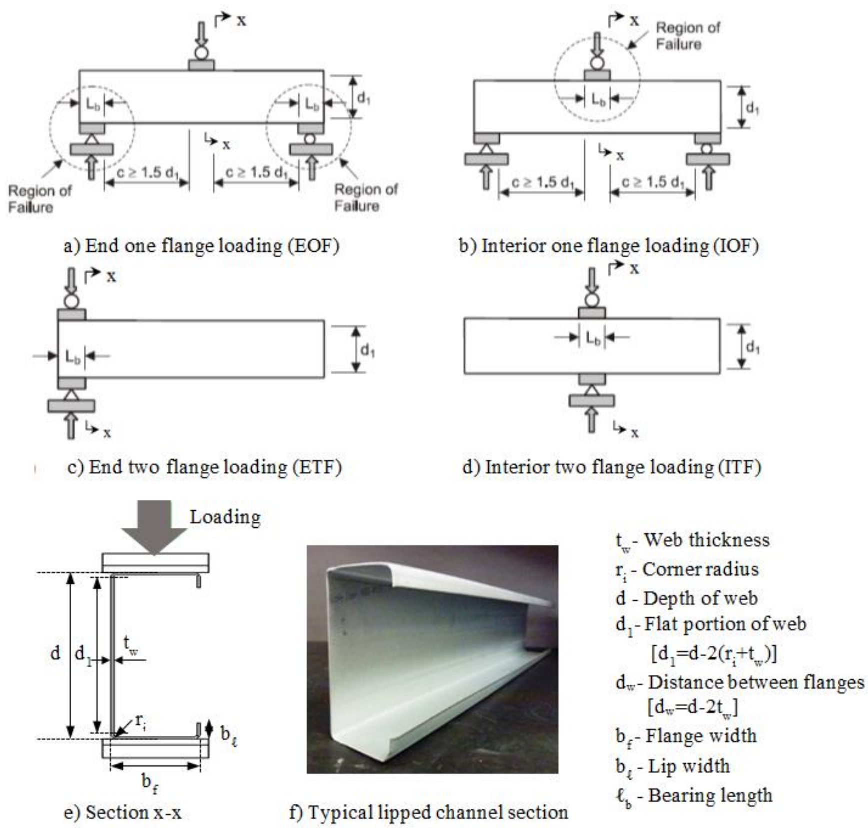


Figure 1: Web Crippling Loading Conditions and Common Parameters

This paper presents the details of the experimental and numerical studies of LCBs and SupaCee sections subject to web crippling under ETF, ITF, EOF and IOF load cases. Using the extensive web crippling capacity data obtained from both numerical and experimental studies, improved unified web crippling design equations were developed for LCBs and SupaCee sections. Suitable DSM based web crippling design equations were also developed.

Experiments

Six different lipped channel beam (LCB) and SupaCee sections (C10010 to C20024) were chosen from the list of commercially available sections to incorporate all the influencing parameters such as section depth, thickness and corner radius. They were made of high strength steels (G450, G500 and G550) with minimum yield strengths of 450, 500 and 550 MPa. Three different sizes of bearing plates (25, 50 and 100 mm) were used to attain three types of testing conditions for ETF, ITF, EOF and IOF load cases shown in Figure 2. Test specimens were not fastened to the supports. A series of experimental studies consisting of more than 150 web crippling tests was conducted for LCBs and SupaCee sections under ETF, ITF, EOF & IOF load cases using an Instron testing machine. The required specimens were fabricated and their sizes, including the section depth (d), web thickness (t_w) and inside bent radius (r_i), were measured. The support system was designed to ensure that the test beam had pin and roller supports using a half round, and a smooth surface between a half round and the testing table, respectively. All web crippling tests were conducted based on AISI S909 (AISI, 2008) test method. Further details of web crippling tests including test set-up and procedures and the results are reported in Sundararajah (2016).

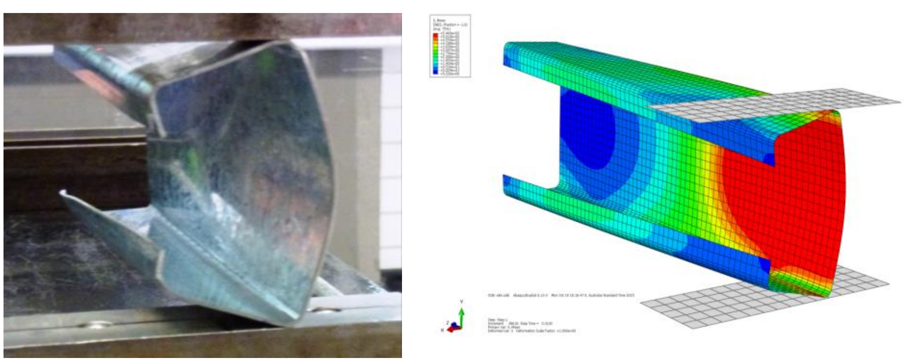
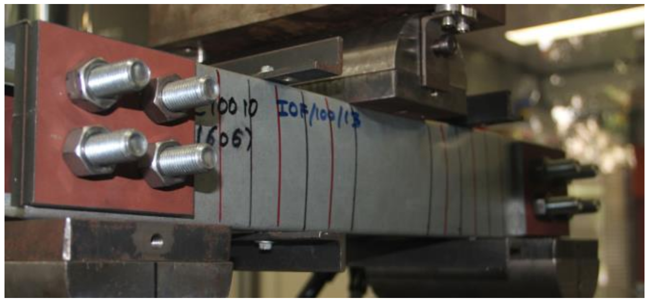
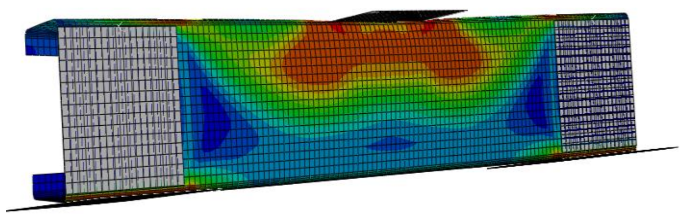


Figure 3: Failure Modes of ETF-C10015 Section with 50 mm Bearing Plate from Experiment and FEA



a) Test



b) FEA

Figure 4: Failure modes of IOF-C10010 Section with 100 mm Bearing Plate from Experiment and FEA

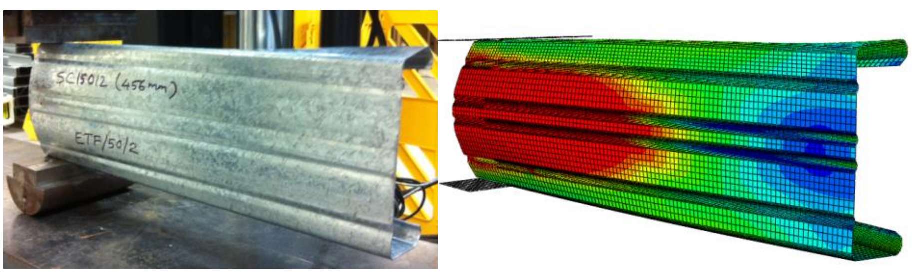


Figure 5: Failure Modes of ETF-SC15012 Section with 50 mm Bearing Plate from Experiment and FEA

Figures 3 to 5 shows the typical web crippling failure modes from selected experiments of LCBs and SupaCee sections. Experimental web crippling capacity results of LCBs and SupaCee sections and their comparisons with predictions from the leading cold-formed steel design standards (AISI S100 and AS/NZS

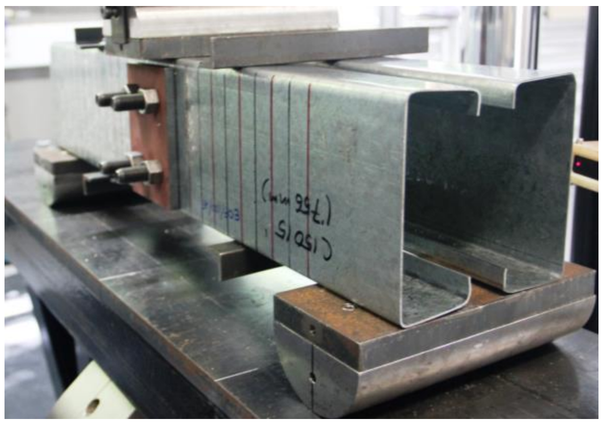
4600) revealed that the predictions are either unsafe or overconservative for LCBs and SupaCee sections under most load cases. These experimental results have highlighted the need to revise the existing web crippling design equations in these standards. Further details of comparison of web crippling tests and cold-formed steel design standards are reported in Sundararajah (2016).

Finite Element Analyses

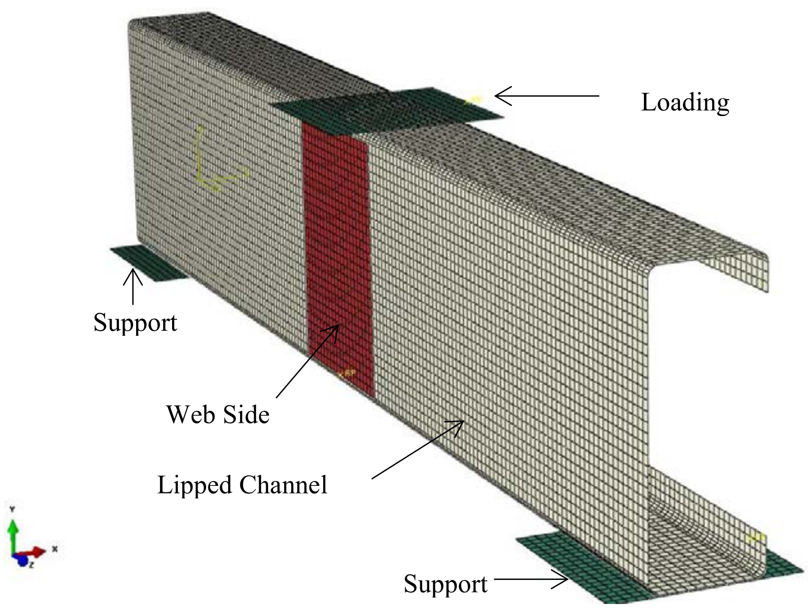
This section presents the details of the development of finite element models of LCBs and SupaCee sections subject to web crippling using ABAQUS Version 6.14. ETF, ITF, EOF and IOF web crippling tests were simulated using the measured section dimensions and mechanical properties. The measured dimensions of LCBs and SupaCee sections were converted to centreline dimensions in order to accurately represent the section in ABAQUS using middle surface shell offset definition. LCBs and SupaCee sections were created using 3D deformable shell elements while loading and support bearing plates were modelled with discrete rigid elements. All the shell elements used for LCBs and SupaCee sections were of type S4R, which is a linear four-node reduced integration shell element with finite strains.

Figures 6 show the developed finite element models of LCB under EOF load case. Element sizes of the web and flanges were kept to 5 mm × 5 mm. The material property of developed finite element model was defined based on the tensile coupon tests of samples taken in the longitudinal direction of the web. The elastic modulus and Poisson’s ratio of steel were considered as 200,000 MPa and 0.3, respectively. A single reference point can be assigned to represent the rigid body elements in ABAQUS. Boundary conditions were assigned to the reference points of loading and support bearing plates. Simply supported boundary conditions were assigned to finite element models. In this study surface-to-surface contact was assigned between shell finite element model representing LCBs and SupaCee sections and rigid plates.

Quasi-static analytical option was chosen in this study. Kaitila (2004), Natario et al. (2014) and Sundararajah et al. (2017a,b) also used quasi-static analysis method for web crippling as an alternative and economical analytical approach. The finite-element models developed for LCBs and SupaCee sections were validated by comparing their ultimate capacities, load-displacement curves and failure modes with those obtained from the web crippling tests. It was found that the developed finite element models simulated the web crippling behaviour of LCBs and SupaCee sections under ETF, ITF, EOF and IOF load cases observed in their experiments accurately as shown in Figures 3 to 6. Further details of the developed finite element models and the results are reported in Sundararajah (2016).



a) Experiment (EOF)



b) FE Model (EOF)

Figure 6: FE Model Simulating the EOF Load Case Test Set-up
(EOF-C15015 Section with 100 mm Bearing Plate)

4. Parametric Studies

This section presents the details of a parametric study into the web crippling behaviour of LCBs under ETF, ITF, EOF and IOF load cases using the validated finite element models described in the previous sections. The objectives of the parametric study are to investigate the web crippling behaviour of LCBs, develop an extensive web crippling capacity data base and then to use them to develop new and/or improved design rules so that their web crippling capacities can be used effectively to increase their range of applications in the construction industry.

All the tested specimens were considered with their nominal dimensions (t_w and d) in the parametric study. Table 1 shows the details of the parametric study conducted for LCBs under ETF, ITF, EOF and IOF load cases. In order to investigate the effect of inside bent radius (r_i), bearing length (ℓ_b) and yield stress (f_y) on web crippling capacities, different inside bent radius (r_i = 0,3,5 and 7), bearing lengths (ℓ_b = 50, 100 and 150 mm) and yield stresses (f_y = 300, 450 and 550 MPa) were considered in the parametric study. Further details of parametric study results are reported in Sundararajah (2016).

Table 1: Parametric Study of LCBs under ETF, ITF, 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
ETF, ITF	ETF-C10010	0,3,5,7	50,100,150	300,450,550	36
	ETF-C10015	0,3,5,7	50,100,150	300,450,550	36
	ETF-C15012	0,3,5,7	50,100,150	300,450,550	36
	ETF-C15015	0,3,5,7	50,100,150	300,450,550	36
	ETF-C20019	0,3,5,7	50,100,150	300,450,550	36
	ETF-C20024	0,3,5,7	50,100,150	300,450,550	36
			Test		18
			FEA-Test Validation		18
		Sub-Total			504
EOF, IOF	ITF-C10010	0,3,5,7	50,100,150	300,450,550	36
	ITF-C10015	0,3,5,7	50,100,150	300,450,550	36
	ITF-C15012	0,3,5,7	50,100,150	300,450,550	36
	ITF-C15015	0,3,5,7	50,100,150	300,450,550	36
	ITF-C20019	0,3,5,7	50,100,150	300,450,550	36
	ITF-C20024	0,3,5,7	50,100,150	300,450,550	36
			Test		18
			FEA-Test Validation		18
		Sub-Total			504
		Total			1008

5. Proposed Design Equations

Comparison of the ultimate web crippling capacities showed that the current AISI S100 (AISI, 2012) and AS/NZS 4600 (SA, 2005) design equations are unconservative for LCBs and SupaCee sections under ETF and EOF load case, but are overly conservative for ITF load case. For IOF load case, AS/NZS 4600 and AISI S100 predictions agree reasonably well with experimental and FEA web crippling capacities. Therefore, improvements were proposed to the currently used unified web crippling design equation based on experimental and numerical parametric study results.

Current web crippling design equation (Equation 1) presented in AISI S100 and AS/NZS 4600 was improved based on the extensive experimental and numerical studies conducted in this study. Table 2 provides the relevant web crippling coefficients for each section under all four load cases. Further details of the proposed design equations are reported in Sundararajah (2016).

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

where t_w = Web thickness, f_y = Web yield stress, ℓ_b = Bearing length, d = Section depth, d_1 = Flat portion of web depth [d_1=d-2(r_i+t_w)], θ = Angle between the plane of the web and the plane of the bearing surface, C = Coefficient, C_r = Coefficient of inside bent radius, r_i = Inside bent radius, C_ℓ = Coefficient of bearing length and C_w = Coefficient of web slenderness.

Table 2: Proposed Web Crippling Coefficients for Channel Sections

Section	Load Case	C	C_r	C_ℓ	C_w	Φ_w	No of Tests	Mean	COV
LCB	ETF	5.35	0.22	0.23	0.06	0.76	252	1.00	0.20
	ITF	17.00	0.19	0.05	0.03	0.82	252	1.00	0.15
	EOF	7.00	0.19	0.17	0.03	0.81	252	1.00	0.17
	IOF	13.10	0.22	0.13	0.01	0.80	252	1.00	0.17
SupaCee	ETF	5.05	0.22	0.23	0.06	0.85	42	1.00	0.12
	ITF	14.50	0.19	0.05	0.03	0.85	30	1.00	0.07
	EOF	5.95	0.19	0.17	0.03	0.87	42	1.00	0.10
	IOF	12.10	0.22	0.13	0.01	0.90	28	1.00	0.07

A new equation was also proposed in this study for low and high grade steel lipped channel beams under all four load cases to accurately predict the web crippling capacities (Equation 2) with corresponding web crippling coefficients presented in Table 3.

$$R_b = Ct_w^2 f_y \sin\theta \left(1 - C_r\sqrt{\frac{r_i}{t_w}}\right)\left(1 + C_\ell\sqrt{\frac{l_b}{t_w}}\right)\left(1 - C_w\sqrt{\frac{d_1}{t_w}}\right)\left(1 + C_f\sqrt{\frac{250}{f_y}}\right) \quad (2)$$

where C_f = Coefficient of yield stress and others as defined for Equation 1

Table 3: Proposed Web Crippling Coefficients for Lipped Channel Beams

Load Case	C	C_r	C_ℓ	C_w	C_f	Φ_w	No of Tests	Mean	COV
ETF	1.03	0.21	0.16	0.06	6.85	0.85	252	1.00	0.13
ITF	1.24	0.17	0.04	0.03	16.90	0.88	252	1.00	0.09
EOF	1.30	0.19	0.13	0.04	8.10	0.86	252	1.00	0.11
IOF	2.60	0.22	0.12	0.01	5.50	0.85	252	1.00	0.13

Direct Strength Method (DSM)

DSM based design equations proposed in this research to predict the web crippling capacities of LCBs and SupaCee sections under all four load cases (ETF, ITF, EOF and IOF) are given next. Equations pertaining to calculate the critical buckling load and yield/plastic load are also summarized.

Critical Buckling Load ($R_{b,cr}$)

Critical buckling load can be calculated using the standard buckling equation (Equation 3) with the proposed buckling coefficient equation (Equation 4) and corresponding coefficients provided in Table 4 for each section.

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

$$k_{Prop} = C_b\left(1 - C_{b,r}\sqrt{\frac{r_i}{t_w}}\right)\left(1 - C_{b,w}\sqrt{\frac{d_1}{t_w}}\right)\left(1 + C_{b,\ell}\sqrt{\frac{\ell_b}{t_w}}\right)\left(1 + C_{b,b}\sqrt{\frac{b_f}{t_w}}\right) \quad (4)$$

Table 4: Proposed Coefficients for Buckling Coefficient (k)

Section	Load Case	C_b	$C_{b,r}$	$C_{b,\ell}$	$C_{b,w}$	$C_{b,b}$	Mean	COV
LCB	ETF	0.58	0.01	0.05	0.30	0.05	1.00	0.06
	ITF	1.84	0.01	0.03	0.10	0.05	1.00	0.07
	EOF	0.80	0.01	0.05	0.46	0.03	1.00	0.06
	IOF	3.70	0.01	0.02	0.10	0.01	1.00	0.07
SupaCee	ETF	0.62	0.01	0.30	0.05	0.05	1.00	0.05
	ITF	1.90	0.01	0.10	0.03	0.05	1.00	0.08
	EOF	0.86	0.01	0.05	0.46	0.03	1.00	0.08
	IOF	3.96	0.01	0.02	0.10	0.01	1.00	0.07

Yield Load ($R_{b,y}$)

Yield load calculation is rather complicated due to the complex web crippling behaviour. A simplified plastic mechanism study presented in this study allowed reasonably accurate yield load predictions. Following yield load equations can be used for each section with relevant yield length equations presented next (Equations 5 and 6).

$$R_{b,y} = f_y N_m (\sqrt{4r_m^2 + t_w^{\ 2}} - 2r_m) \quad (5)$$

$$N_m = \ell_b + a(2.5r_{ext} + xd_1) \quad (6)$$

Table 5: Proposed Coefficients for Yield Length (N_m)

Section	Load Case	a	x
LCB & SupaCee	ETF	1	0.50
	ITF	2	0.75
	EOF	1	0.90
	IOF	2	0.90

DSM Equations

Web crippling capacities of lipped channel beams and SupaCees can be calculated using the following equation with the power coefficients presented in Table 6. The DSM based strength curve for the web crippling of channel beams is presented in Figure 7. Figure 8 shows the comparison of web crippling capacities of LCBs from test and parametric studies with DSM based design equation – ITF and EOF Load Cases.

Web crippling slenderness $\lambda = \sqrt{\frac{R_{b,y}}{R_{b,cr}}}$ (7)

When $\lambda \leq \lambda_y$ $R_b = R_{b,y}$ (8)

(Yield load $R_{b,y}$ can be calculated using Equations 5 and 6)

When $\lambda > \lambda_y$ $$\frac{R_b}{R_{b,y}} = \left[1 - n_1\left(\frac{R_{b,cr}}{R_{b,y}}\right)^{n_2}\right]\left(\frac{R_{b,cr}}{R_{b,y}}\right)^{n_2}$$ (9)

Table 6: Proposed Coefficients for DSM Equation

Section	Load Case	λ_y	n_1	n_2	Mean	COV	Φ_w
LCB	ETF	0.71	0.25	1.00	0.90	0.16	0.70
	ITF	0.94	0.10	0.86	1.01	0.16	0.80
	EOF	0.83	0.22	0.84	1.00	0.18	0.75
	IOF	0.78	0.23	0.85	1.00	0.23	0.70
SupaCee	ETF	0.72	0.25	0.98	0.99	0.16	0.80
	ITF	0.84	0.17	0.70	1.00	0.09	0.85
	EOF	0.58	0.25	0.60	1.01	0.15	0.80
	IOF	0.82	0.17	0.59	1.01	0.17	0.80

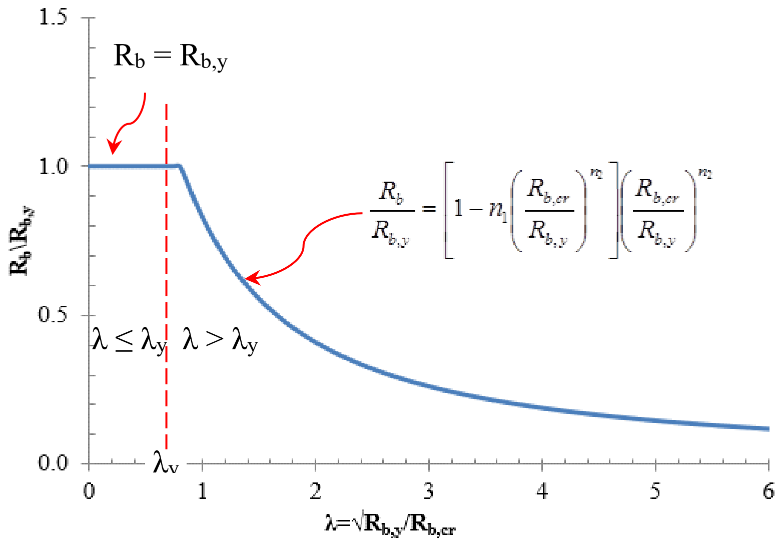
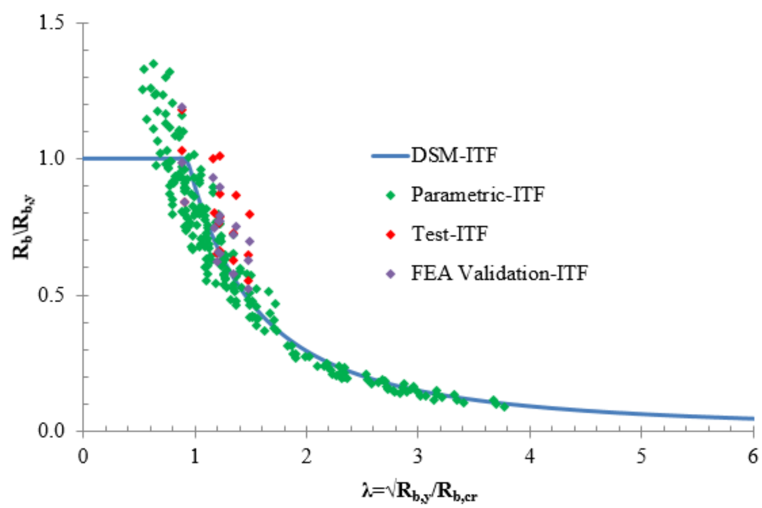
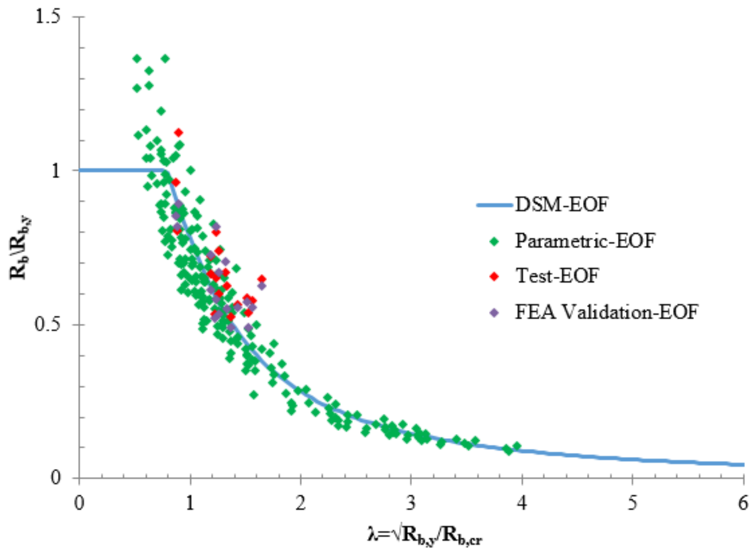


Figure 7: DSM Web Crippling Strength Curve for Channel Beams



(a) ITF load case



(b) EOF load case

Figure 8: Comparison of Web Crippling Capacities of LCBs from Tests and Parametric Studies with DSM based Design Equation – ITF and EOF Load Cases

Conclusions

This paper has presented the details of new web crippling design rules for cold-formed steel beams. More than 150 web crippling tests were first conducted based on the new AISI S909 standard test method for LCBs and SupaCee sections under ETF, ITF, EOF and IOF load cases, which were then simulated using ABAQUS and analysed using quasi-static analysis. Developed finite element models were validated using test results in terms of failure modes, load-deflection curves and ultimate capacities. Based on the validated finite element models, a detailed parametric study was conducted to develop an extensive web crippling capacity database for LCBs under ETF, ITF, EOF and IOF load cases.

Test and FEA results showed that the current AISI S100 (AISI, 2012) and AS/NZS 4600 (SA, 2005) design equations are unconservative for LCBs and SupaCee sections under ETF and EOF load case, but are overly conservative for ITF load case. For IOF load case, AS/NZS 4600 and AISI S100 predictions agree

reasonably well with experimental and FEA web crippling capacities. Therefore, improvements were proposed to the currently used unified web cri
ppling design equation based on experimental and numerical parametric study results. Only a few attempts have been made in the past to develop direct strength method (DSM) based design rules for web crippling and most of them were not developed in the standard DSM format. Therefore, in this study improved design equations in accordance with the standard DSM format were proposed for LCBs and SupaCees under ETF, ITF, EOF and IOF load cases. This study has also developed suitable equations to predict the critical buckling and yield loads of LCB and SupaCee sections, which are the two main components of DSM.

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