Ninth International Conference on
THIN-WALLED STRUCTURES – ICTWS2023
Sydney, Australia, Nov 29 – Dec 1, 2023

WEB CRIPPLING BEHAVIOUR OF COLD-FORMED STEEL SUPACEE SECTIONS WITH WEB OPENINGS

Hasini Weerasinghe*, Chaminda Konthesingha*, Anura Nanayakkaraand Keerthan Poologanathan*****

* Department of Civil Engineering, University of Sri Jayewardenepura, Colombo 10250, Sri Lanka
e-mails: hasiniweerasinghe@sjp.ac.lk, konthesingha@sjp.ac.lk

** Department of Civil Engineering, University of Moratuwa, Colombo 10400, Sri Lanka
e-mail: sman@civil.mrt.ac.lk

*** Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne NE1 8ST, UK
e-mail: keerthan.poologanathan@northumbria.ac.uk

Keywords: Cold-formed steel; SupaCee sections; Web crippling; Web openings; End Two Flange loading condition; Design equation.

Abstract. *With enhanced bending and shear capacities, web-stiffened Cold-Formed Steel (CFS) SupaCee sections have been widely used as flexural members in the construction industry. These sections are often fabricated with web openings to allow easy installation of service lines. Despite the enhanced bending and shear performance, SupaCee sections tend to display reduced web crippling capacities. However, no detailed investigation has been conducted on the web crippling behaviour of CFS SupaCee sections with web openings. Hence, this study intends to numerically investigate the web crippling behaviour of CFS SupaCee sections with web openings. Developed finite element models were validated with web crippling experiments available in the literature. An extensive parametric study was conducted considering different section geometries, bearing lengths and opening ratios. Following the comparison of numerical results with current design predictions, a new design equation was derived for predicting the web crippling capacity of CFS SupaCee sections with web openings subjected to End Two Flange (ETF) loading condition.*

1 INTRODUCTION

In recent decades, Cold-Formed Steel (CFS) sections have gained extensive popularity in the construction industry as primary and secondary structural members. Cold-Formed (CF) sections are available in a variety of geometries, such as plain C and Z sections, hat sections, hollow sections, sigma sections and SupaCee sections. These sections are often fabricated with web openings facilitating easy installation of service lines. SupaCee sections with their longitudinal web stiffeners and curved lips possess enhanced bending and shear capacities making them ideal for flexural members [1–4]. Hence, these sections are often used as roof purlins, girts, floor joists and bearers in lightweight steel buildings. Despite the enhanced bending and shear performance, SupaCee sections are vulnerable to web crippling failure when subjected to transverse concentrated loading.

Web crippling is a localized failure observed in the web element of a thin-walled channel section subjected to transverse concentrated loading. Web crippling failure can occur via web buckling, web yielding, flange crushing, or a combination of these failure modes (Figure 1). Cold-formed sections are often subject to web crippling failures due to their high slenderness ratios and the eccentric loading caused by rounded section corners. Hence, a considerable amount of studies have been conducted on the web crippling behaviour of CF channel sections [5–14].

Identifying the effect of web crippling on SupaCee sections, Sundararajah et al. [15–17] conducted a series of combined experimental and numerical investigations on the web crippling behaviour of SupaCee channel sections subjected to End Two Flange (ETF), Interior Two Flange (ITF), End One Flange (EOF) and Interior One Flange (IOF) loading conditions. These studies revealed a notable reduction in the web crippling capacities of SupaCee channel sections when compared with similar lipped CFS channel sections. This capacity reduction was observed to be a result of the localized failures observed along the longitudinal web stiffeners of the SupaCee section [18]. Upon identifying the unsuitability of existing web crippling design guidelines, Sundararajah et al. [15,17] proposed modifications to the AS/NZS 4600 [19] and AISI S100 [20] design guidelines for predicting the web crippling capacity of SupaCee sections. However, the web crippling behaviour of web-perforated CFS SupaCee sections is yet to be investigated. In some recent studies, Thirunavukkarasu et al. [3,4] numerically investigated the shear and flexural performance of web-perforated CFS SupaCee channel sections. Based on the shear performance, Thirunavukkarasu et al. [3] proposed to replace CFS lipped channel sections with web-perforated CFS SupaCee sections having a web opening ratio of 0.2 (i.e. web opening depth to clear depth ratio is 0.2). Thirunavukkarasu et al. [4] identified the superior flexural performance of web perforated SupaCee sections (beyond web opening ratio of 0.6) in comparison to that of lipped CFS sections. Hence, these two studies suggest the replacement of conventional CFS lipped channel sections with web-perforated SupaCee sections. Nevertheless, commercial usage of CFS SupaCee sections with web openings has been limited due to the inadequate understanding of its web crippling behaviour.

Bridging the existing research gap, under this study a numerical investigation was conducted on the web crippling response of CFS SupaCee sections with web openings, subjected to ETF loading condition. Circular openings were considered in this study. The numerical investigation was conducted considering the general-purpose Finite Element (FE) program ABAQUS [21]. Upon validating the developed model with past experimental data, a detailed parametric study was conducted considering different section geometries, bearing lengths and opening ratios. The suitability of existing design equations in predicting the web crippling capacity of CFS SupaCee sections with web openings was evaluated. Based on the findings a modified design equation was developed for predicting the web crippling capacity of CFS SupaCee sections with web openings, thus encouraging their commercial usage.

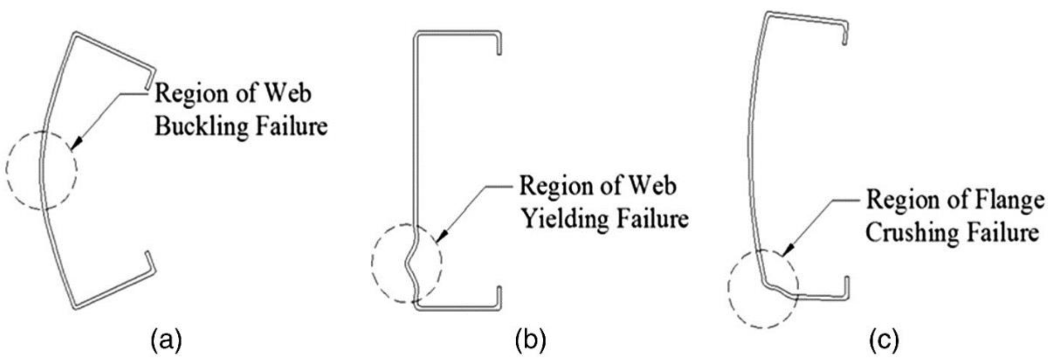


Figure 1: Web Crippling failure modes [22] (a)Web buckling, (b)Web yielding, (c) Flange crushing

2 NUMERICAL INVESTIGATION

2.1 General

This section describes the FE model developed for simulating the web crippling response of web-perforated CFS SupaCee channel sections under the ETF loading condition. Unfastened flange condition was considered in this study. The model comprises of four components: web-perforated SupaCee channel section, loading plate, bearing plate and contacts between the channel section and the loading/bearing plate. Models were developed considering the non-linear general-purpose FE software ABAQUS, version 6.14 [21]. Considering the slow loading rates observed in past experimental investigations [14,16,23], quasi-static analysis technique was used to simulate the loading behaviour. Based on the potential converging issues observed in using the ABAQUS/Implicit solver [8,24] and considering the proven computational efficiency of the ABAQUS/Explicit solver [8], the latter was used in this study. Initial geometrical imperfections were disregarded in this model due to their negligible effect on web crippling behavior [12,24].

2.2 Section geometry and Material properties

SupaCee sections with web openings were modelled considering centerline dimensions and mid-surface shell offset definition. Openings were located at the mid-depth of the web to be centered beneath the loading plate. Considering the ETF loading condition extrusion length of the channel sections was maintained to be $3d_1$ [25]. Here, d_1 represents the flat depth of the channel section. Lengths of the loading and bearing plates were selected to match the past experimental data, while the width was maintained to be B + 20 mm, where B is the width of the channel section.

The stress-strain behaviour of CFS was modelled considering the elastic perfectly plastic material model with a nominal yield strength. Based on the findings of past research studies [4,26], the effect of the material strength enhancement around the section corners and the effect of residual stresses were not taken into account in this study. Density of steel was taken as 7850 kg/m^3, while the elastic modulus and poisson's ratio values of steel were taken as 200 GPa and 0.3, respectively.

2.3 Element type and Mesh control

SupaCee sections were modelled considering general purpose three-dimensional deformable shell element S4R, while the bearing and loading plates were modelled using three-dimensional discrete rigid element R3D4. To ensure the accuracy of numerical results and to optimize the computational time, a mesh size of 5 mm x 5 mm was used for the flat regions of the channel section [17]. The medial axis algorithm along with the minimize mesh transition option was used to improve the mesh quality around the web openings. A finer mesh size of 1 mm x 5 mm was used for the corner regions of the channel section, while a comparatively coarser mesh size (10 mm x 10 mm) was opted for the loading and bearing plates (Figure 2).

2.4 Contact behaviour, Boundary and Loading conditions

Contact between the SupaCee section and the loading and bearing plate were modelled considering surface-to-surface contact interaction. The bottom surface of the loading plate and the top surface of the bearing plate were modelled as master surfaces, while the contact surfaces of the SupaCee section were modelled as slave surfaces. A "Hard" pressure-overclosure relationship was considered to minimize the penetration of the slave surface into the master

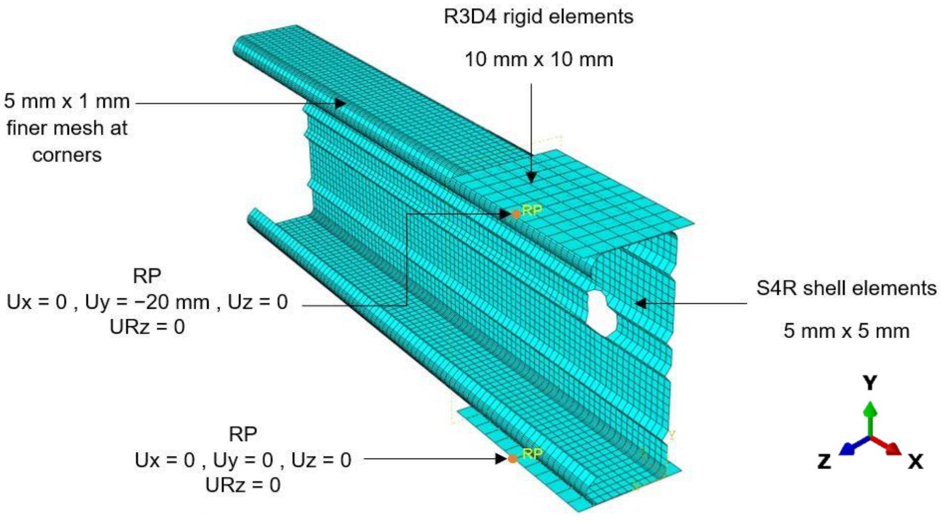


Figure 2: Element types, mesh sizes and boundary conditions used in the FE model [27]

surface [8]. A friction coefficient of 0.4 was assumed to accommodate for the friction between contact surfaces [12,15,28].

Boundary conditions were assigned via the reference points (RP) of the loading and bearing plates. Simulating the experimental behaviour all translational movements of the bearing plate, translational movements of the loading plate along the X and Z axes and the rotational movements of both plates about the Z axis were restricted. Displacement controlled loading mechanism was simulated by enabling translational movements of the loading plate along the Y axis, with a maximum displacement of 20 mm (Figure 2). The load was applied considering smooth step amplitude curves, thus excluding undesirable inertia effects at the beginning of the simulation [8,24,29].

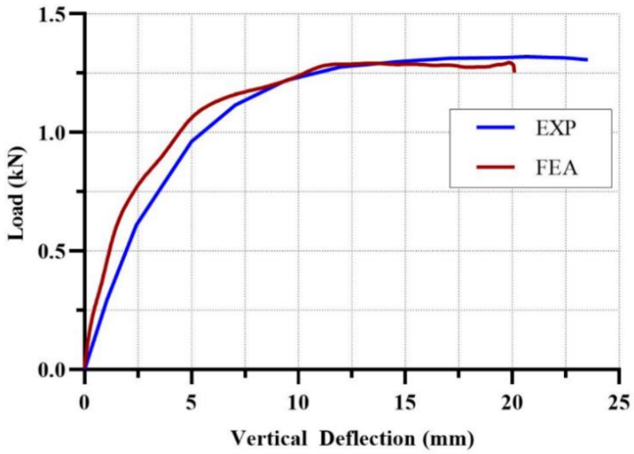
2.5 Model validation

To ensure the reliability of the parametric study, the developed FE model was validated considering past experimental data. Due to the absence of past experimental data on the web crippling behaviour of web-perforated SupaCee sections, model validation was conducted in two stages. The model was initially validated using experimental data from Sundararajah et al.'s [16] study on the web crippling behaviour of SupaCee sections without web openings. Table 1 shows the comparison between experimental and FE results. A fair agreement between the two results was observed with a mean value of 0.97 and a Coefficient of Variation (COV) value of 0.05. Further, as shown in Figure 3, the load vs deflection curves and the failure modes of the FE results were compared with the experimental results. Both comparisons show good agreement between the two results, thus validating the reliability of the FE model in simulating the web crippling behaviour of CFS SupaCee sections.

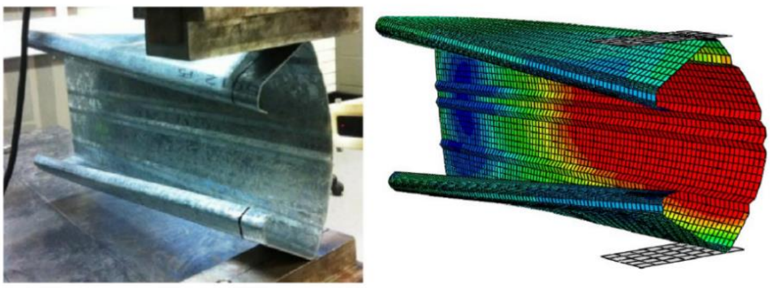
Subsequently, the model was validated to ensure its reliability in simulating the web crippling response of CFS sections with web openings. Results of the experimental study conducted by Uzzaman et al. [30] on the web crippling response of CFS lipped channel sections with and without web openings were considered in this stage. The authors presented the results of this model validation in their previous research work [28]. There a reasonable agreement was observed between the experimental and FE results with a mean value of 0.95 and a COV value of 0.04 [28]. Based on these results, the developed FE model was selected for simulating the web crippling response of web-perforated CFS SupaCee sections under the ETF loading condition.

Table 1: Comparison between experimental [16] and FE results

Specimen	Dimensions of the SupaCee Channels (mm)						Bearing length (mm)	Yield strength (MPa)	Experimental web crippling strength (KN)	Web crippling strength from FEM (KN)	Exp/FEM
	Depth of the web	Flange width	Lip width	Web thickness	Corner radius	Length					
ETF-SC15010	152.7	56.7	19.6	1.03	5	456	50	624	1.32	1.3	1.01
ETF-SC20012	201.4	69.6	24.5	1.22	5	609	50	580	1.62	1.71	0.95
ETF-SC15010	153.4	56.35	19.9	1.03	5	456	100	624	1.39	1.44	0.97
ETF-SC15015	152.3	60.5	20.1	1.53	5	456	100	534	3.84	3.98	0.96
ETF-SC15015	153.1	60.8	19.7	1.53	5	456	150	534	4.43	4.24	1.04
ETF-SC20012	202.5	70.4	24.4	1.22	5	609	150	580	1.89	2.1	0.90
Mean Value											0.97
COV											0.05



a) Load versus Vertical Deflection Curves



b) Failure Modes

Figure 3: Comparison of FEA and experimental [16] results for the section SC15010 (Bearing length of 50 mm)

3 PARAMETRIC STUDY

Upon validating the FE model, a comprehensive parametric study was conducted to investigate the web crippling behaviour of web-perforated CFS SupaCee sections under the ETF loading condition. Considering the critical parameters affecting the web crippling behaviour of CFS sections, two SupaCee sections of different sections depths (150 mm and 200 mm), two web thickness values (1 mm, 2 mm), two bearing length values (100 mm, 120 mm), two inside corner radius values (3 mm, 5 mm) and four web opening ratio values (0,0.2,0.4,0.6) were chosen for this study. Only one yield strength value (220 Mpa) was considered in this study, despite the significant impact it has on the web crippling behavior of CFS sections. Dimensions of the SupaCee sections considered in this study are presented in Table 2, while Figure 4 illustrates the definitions of the symbols used. Web opening diameter is referred to as d_{wh}. Table 3 shows the summary of the parametric study conducted in this study.

Altogether 60 FE models were generated in this study. Table 4 shows the results of the parametric study. Based on the results, it can be stated that there is a significant reduction in the web crippling strength along with increasing web opening diameter values. Compared to CFS SupaCee sections without web openings, web crippling strength reductions of 14.6%, 22.8%, and 35.2% were observed in SupaCee sections with web opening ratios of 0.2, 0.4, and 0.6, respectively. An average strength increment of 6.2% was observed with the increase in the bearing length to thickness ratio. Similarly, a considerable web crippling strength enhancement was observed with the increase in the bearing length to flat web depth ratio (l_b/d_1). Moreover, it was evident that both r_i/t_w and d_1/t_w ratios show a negative relationship with the web crippling capacity of web-perforated CFS SupaCee sections. These results are consistent with the findings of past research studies conducted on CFS SupaCee sections without web openings [15,16]. Similar to previous research findings on the web crippling behaviour of CFS lipped channel sections with web openings [30,31], d_{wh}/d_1 and l_b/d_1 ratios were found to have a direct influence on the strength reduction caused by the openings.

Table 2: Dimensions of the SupaCee sections in millimeters

Section	D	B	L_1 and L_2	r_i and r_L	Length	S1	S2	S_h	Sd
A	150	50	12	3,5	$3d_1$	40	20	10	5
B	200	65	15	3,5	$3d_1$	40	70	10	5

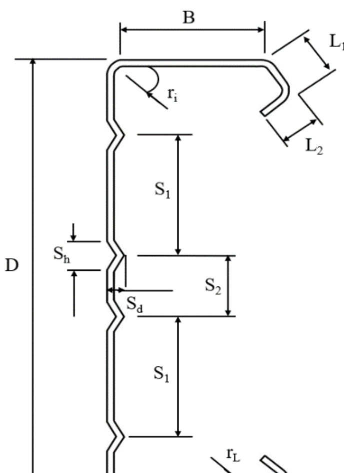


Figure 4: Cross sectional view of a SupaCee section

Table 3: Summary of the parametric study

Sections	Thickness (mm)	Bearing length (mm)	Inside corner radius, r_i (mm) and r_L (mm)	Yield strength (Fy)	d_{wh}/d_1	Total
A	1,2	100,120	3,5	220	0,0.2,0.4,0.6	32
B	1,2	100	3,5	220	0,0.2,0.4	12
	1,2	120	3,5	220	0,0.2,0.4,0.6	16
Total FE models						60

4 APPLICABILITY OF EXISTING DESIGN GUIDELINES

North American specification for design of cold-formed steel structural members (AISI S100-16) [32], Australian/New Zealand standard for cold-formed steel structures (AS/NZS 4600) [33] and Eurocode 3 Part 1-3 (EN1993-1-3) [34] are the three main design standards used for predicting the web crippling behaviour of CFS sections. Among these standards, AISI S100-16 [32] and AS/NZS 4600 [33] provide identical design rules for predicting the ultimate web crippling strength of CFS sections with and without web openings [28]. Design equations provided in EN1993-1-3 [34] only cover the web crippling behaviour of CFS sections without web openings. However, neither of these design standards provides web crippling design guidelines specific for CFS SupaCee sections with web openings.

Under this section, the results of the parametric study were compared with the predictions from the design guidelines, to assess their applicability in predicting the web crippling capacity of SupaCee sections with web openings (Figures 5 and 6). It was observed that on average all three AISI S100-16 [32], AS/NZS 4600 [33] and EN1993-1-3 [34] guidelines overestimate the web crippling capacity of CFS SupaCee sections with web openings.

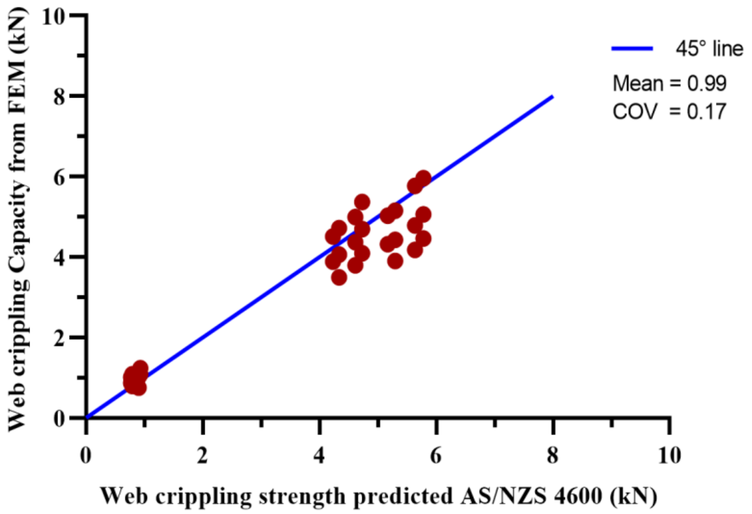


Figure 5: Comparison of the FE results with AS/NZS 4600 [33] and AISI S100-16 [32] design predictions

Table 4: Results of the parametric study

Section	Specimen	Thickness (mm)	Bearing length (mm)	Depth of the web D (mm)	Inside corner radius r_i (mm)	Web crippling strength values predicted via FEA (kN) d_{wh}/d_1			
						0	0.2	0.4	0.6
A	D150Fy220T1N100R3	1	100	150	3	1.531	1.022	1.141	0.750
	D150Fy220T1N120R3	1	120	150	3	1.662	1.085	1.239	0.785
	D150Fy220T1N100R5	1	100	150	5	1.229	1.078	0.955	0.842
	D150Fy220T1N120R5	1	120	150	5	1.331	1.158	1.026	0.903
	D150Fy220T2N100R3	2	100	150	3	6.265	5.773	4.785	4.178
	D150Fy220T2N120R3	2	120	150	3	6.601	5.965	5.065	4.460
	D150Fy220T2N100R5	2	100	150	5	4.723	4.994	4.373	3.798
	D150Fy220T2N120R5	2	120	150	5	5.954	5.371	4.693	4.095
B	D200Fy220T1N100R3	1	100	200	3	1.184	1.010	0.873	-
	D200Fy220T1N120R3	1	120	200	3	1.273	1.091	0.938	0.799
	D200Fy220T1N100R5	1	100	200	5	1.049	0.940	0.818	-
	D200Fy220T1N120R5	1	120	200	5	1.101	0.991	0.865	0.740
	D200Fy220T2N100R3	2	100	200	3	5.789	5.031	4.323	-
	D200Fy220T2N120R3	2	120	200	3	5.936	5.158	4.430	3.901
	D200Fy220T2N100R5	2	100	200	5	5.103	4.515	3.891	-
	D200Fy220T2N120R5	2	120	200	5	5.312	4.718	4.066	3.496

5 PROPOSED DESIGN GUIDELINE

Based on the inadequacies of existing design guidelines, a new design guideline was proposed by modifying the existing AISI S100-16 [32] or AS/NZS 4600 [33] design guidelines to predict the web crippling capacities of CFS SupaCee sections with web openings under ETF loading condition. The effect of web openings on the web crippling strength was incorporated by introducing an additional factor $[1- C_A\sqrt{d_{wh}/d_1} + C_N\sqrt{l_b/d_1}]$ to the existing design guideline. Equation 1 shows the proposed modified design guideline.

$$R = Ct_w^2 f_y Sin\emptyset \left(1 - C_R\sqrt{\frac{r_i}{t_w}}\right)\left(1 + C_L\sqrt{\frac{l_b}{t_w}}\right)\left(1 - C_W\sqrt{\frac{d_1}{t_w}}\right)\left(1 - C_A\sqrt{\frac{d_{wh}}{d_1}} + C_N\sqrt{\frac{l_b}{d_1}}\right) \quad (1)$$

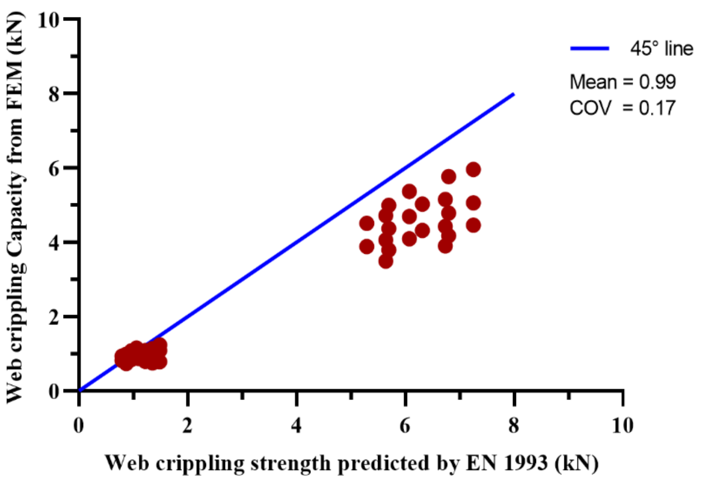


Figure 6: Comparison of the FE results with EN 1993-1-3 [34] design predictions

Here,

R	Ultimate web crippling capacity
t_w	Web thickness
f_y	Yield strength of the section material
Ø	Angle between the plane of the web and the plane of the bearing surface
r_i	Inside bent radius
l_b	Bearing length
d_1	Flat depth of the web
d_{wh}	Opening depth (diameter)
C	Coefficient
C_R	Coefficient of inside bent radius to thickness ratio
C_L	Coefficient of bearing length to thickness ratio
C_W	Coefficient of web slenderness
C_A	Coefficient of web opening depth to flat depth of the web ratio
C_N	Coefficient of bearing length to flat depth of the web ratio

Coefficients C, CR, CL, CW, CA and CN (Table 5) were derived to minimize the COV value while ensuring the mean value of the ratio between web crippling predictions from the proposed modified design guideline and finite element results remains equal to one. Generalized Reduced Gradient (GRG) nonlinear solving technique was considered in this analysis. Figure 7 compares the results of the parametric study with the web crippling capacities predicted by the proposed modified design guideline. The comparison of results indicates that the proposed modified design guideline effectively predicts the web crippling capacities of CFS SupaCee sections with web openings, subjected to ETF loading condition.

Table 5: Coefficients of Equation 1

Section/Loading condition	C	C_R	C_L	C_W	C_A	C_N	Mean	COV
CFS SupaCee sections/ ETF	42.97	0.16	0.19	0.04	0.66	0.20	1.00	0.06

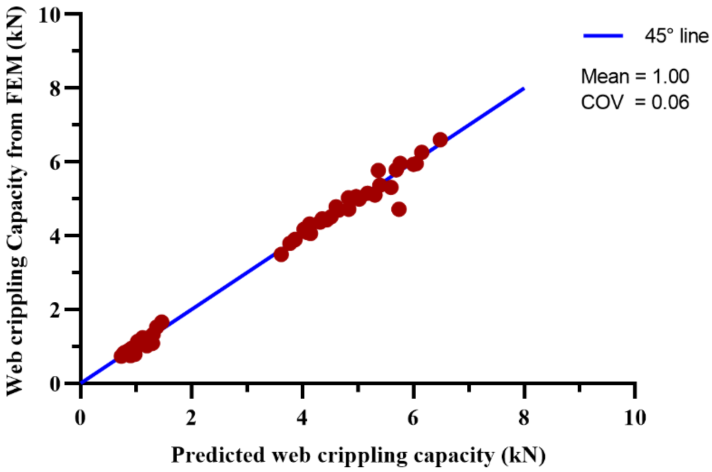


Figure 7: Comparison of the parametric study results with the predictions from Equation 1

6 CONCLUSION

This paper has presented the details of a comprehensive numerical investigation conducted on the web crippling behaviour of CFS SupaCee sections with web openings under the ETF loading condition. FE models were developed to simulate the web crippling response of CFS SupaCee sections with web openings. The model was validated using experimental data from past literature. A detailed parametric study was then conducted, considering various section geometries, bearing lengths, web thicknesses, corner radius values, and opening ratios for SupaCee sections. In total, 60 FE models were generated. These results were utilized to assess the applicability of existing design standards in predicting the web crippling response of web-perforated CFS SupaCee sections under ETF loading conditions. Based on the identified inconsistencies in the current design guidelines, a modified design equation was developed to predict the web crippling strength of CFS SupaCee sections with web openings under the ETF loading condition. Further numerical investigations are currently underway to develop the proposed design equation to be applicable for cold-formed steel, stainless steel, and aluminium SupaCee channel sections with web openings.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support provided by the University of Sri Jayewardenepura and Northumbria University and the financial assistance provided by the University research grant, University of Sri Jayewardenepura (ASP/01/RE/ENG/2021/85).

REFERENCES

[1] Pham, C.H.; Hancock, G.J. Experimental Investigation and Direct Strength Design of High-Strength, Complex C-Sections in Pure Bending. *J. Struct. Eng.* **2013**, 139, 1842–1852, doi:10.1061/(ASCE)ST.1943-541X.0000736.

[2] *Shear Buckling of Thin-walled Channel Sections with Complex Stiffened Webs*; Pham, S.H.; Pham, C.H.; Hancock, G.J., Eds. 21 st International Specialty Conference on Cold-Formed Steel Structures, Aug 24th - Aug 25th; Missouri University of Science & Technology, St Louis, Missouri, 2012.

[3] Thirunavukkarasu, K.; Kanthasamy, E.; Poologanathan, K.; Tsavdaridis, K.D.; Gatheeshgar, P.; Hareindirasarma, S.; McIntosh, A. Shear performance of SupaCee sections with openings: Numerical studies. *Journal of Constructional Steel Research* **2022**, 190, 107142, doi:10.1016/j.jcsr.2022.107142.

[4] Thirunavukkarasu, K.; Kanthasamy, E.; Poologanathan, K.; Gunalan, S.; Gatheeshgar, P.; Tsavdaridis, K.D.; Corradi, M. Flexural behaviour and design rules for SupaCee sections with web openings. *Journal of Building Engineering* **2023**, 63, 105539, doi:10.1016/j.jobe.2022.105539.

[5] Keerthan, P.; Mahendran, M.; Steau, E. Experimental study of web crippling behaviour of hollow flange channel beams under two flange load cases. *Thin-Walled Structures* **2014**, 85, 207–219, doi:10.1016/j.tws.2014.08.011.

[6] McIntosh, A.; Gatheeshgar, P.; Gunalan, S.; Kanthasamy, E.; Poologanathan, K.; Corradi, M.; Higgins, C. Unified approach for the web crippling design of cold-formed channels: Carbon steel, stainless steel and aluminium. *Journal of Building Engineering* **2022**, 51, 104134, doi:10.1016/j.jobe.2022.104134.

[7] Beshara, B.; Schuster, R.M. *Web Crippling Data and Calibrations of Cold Formed Steel Members*, 2000.

[8] Cain, D.E.; LaBoube, R.A.; Yu, W. *The effect of flange restraint on web crippling strength of cold-formed steel Z- and I-sections*, 1995.

[9] *Web Crippling of Single Web Cold Formed Steel Members Subjected to End One-flange Loading*; Gerges, R.R.; Schuster, R.M., Eds. International Specialty Conference on Cold-Formed Steel Structures, 1998.

[10] Sundararajah, L.; Mahendran, M.; Keerthan, P. New design rules for lipped channel beams subject to web crippling under two-flange load cases. *Thin-Walled Structures* **2017**, 119, 421–437, doi:10.1016/j.tws.2017.06.003.

[11] Winter, G.; Pian, R. *Crushing strength of thin steel webs*; Cornell University, 1946.

[12] Young, B.; Hancock, G. Design of Cold-Formed Channels Subjected to Web Crippling. *Journal of Structural Engineering* **2001**, 127, 1137–1144.

[13] Uzzaman, A.; Lim, J.B.; Nash, D.; Rhodes, J.; Young, B. Web crippling behaviour of cold-formed steel channel sections with offset web holes subjected to interior-two-flange loading. *Thin-Walled Structures* **2012**, 50, 76–86, doi:10.1016/j.tws.2011.09.009.

[14] McIntosh, A.; Gatheeshgar, P.; Poologanathan, K.; Gunalan, S.; Navaratnam, S.; Higgins, C. Web crippling of cold-formed carbon steel, stainless steel, and aluminium channels: Investigation and design. *Journal of Constructional Steel Research* **2021**, 179, 106538, doi:10.1016/j.jcsr.2021.106538.

[15] *Web Crippling Capacity of Cold-formed Channel Sections with and without Longitudinal Web Stiffeners Subject to Two Flange Load Cases*; Sundararajah, L.; Mahendran, M.; Keerthan, P., Eds. 7th International Conference on Coupled Instabilities in Metal Structures, Baltimore, United States, November 7-8, 2016.

[16] Sundararajah, L.; Mahendran, M.; Keerthan, P. Web crippling studies of SupaCee sections under two flange load cases. *Engineering Structures* **2017**, 153, 582–597, doi:10.1016/j.engstruct.2017.09.058.

[17] Sundararajah, L.; Mahendran, M.; Keerthan, P. Design of SupaCee Sections Subject to Web Crippling under One-Flange Load Cases. *J. Struct. Eng*. **2018**, 144, 4018222,doi:10.1061/(ASCE)ST.1943-541X.0002206.

[18] Sundararajah, L. Web Crippling Studies of Cold-Formed Steel Channel Beams. PhD thesis; Queensland University of Technology, 2017.

[19] AS/NZS 4600. *Cold formed steel structures*; Standards Australia/ Standards New Zealand: Wellington, New Zealand, 2005.

[20] AISI S100. *Specifications for the cold-formed steel structural members, cold-formed steel design manual*; American Iron and Steel Institute: Washington, DC, USA, 2012.

[21] Dassault Systemes Simulia Corp. *ABAQUS/CAE*; Providence, RI, USA, 2014.

[22] Sundararajah, L.; Mahendran, M.; Keerthan, P. Experimental Studies of Lipped Channel Beams Subject to Web Crippling under Two-Flange Load Cases. *J. Struct. Eng.* **2016**, 142, doi:10.1061/(ASCE)ST.1943-541X.0001523.

[23] Gunalan, S.; Mahendran, M. Web Crippling Tests of Cold-formed Steel Channels under Two Flange Load Cases. *Journal of Constructional Steel Research* **2015**, 110, 1–15.

[24] Alsanat, H.; Gunalan, S.; Keerthan, P.; Guan, H.; Tsavdaridis, K.D. Web crippling behaviour and design of aluminium lipped channel sections under two flange loading conditions. *Thin-Walled Structures* **2019**, 144, 106265, doi:10.1016/j.tws.2019.106265.

[25] AISI S909-17. *Test Standard for Determining the Web Crippling Strength of Cold-Formed Steel Flexural Members*, 2017 Edition; American Iron and Steel Institute: Washington, DC, USA, 2018.

[26] Schafer, B.W.; Li, Z.; Moen, C.D. Computational modeling of cold-formed steel. *Thin-Walled Structures* **2010**, 48, 752–762, doi:10.1016/j.tws.2010.04.008.

[27] *Web crippling behaviour of cold-formed steel, stainless steel and aluminium channel sections with web openings*; Weerasinghe, H., Ed. 25th Young Researchers Conference, 23 March; The Institution of Structural Engineers: London, United Kingdom, 2023.

[28] Weerasinghe, H.; Konthesingha, C.; Nanayakkara, A.; Poologanathan, K.; Perampalam, G.; Kanthasamy, E. Web Crippling Behaviour of Cold-Formed Carbon Steel, Stainless Steel, and Aluminium Lipped Channel Sections with Web Openings. *Buildings* **2022**, 12, 1820, doi:10.3390/buildings12111820.

[29] Natário, P.; Silvestre, N.; Camotim, D. Web crippling failure using quasi-static FE models. *Thin-Walled Structures* **2014**, 84, 34–49, doi:10.1016/j.tws.2014.05.003.

[30] Uzzaman, A.; Lim, J.B.; Nash, D.; Rhodes, J.; Young, B. Cold-formed steel sections with web openings subjected to web crippling under two-flange loading conditions—part I: Tests and finite element analysis. *Thin-Walled Structures* **2012**, 56, 38–48, doi:10.1016/j.tws.2012.03.010.

[31] Uzzaman, A.; Lim, J.B.; Nash, D.; Rhodes, J.; Young, B. Cold-formed steel sections with web openings subjected to web crippling under two-flange loading conditions—Part II: Parametric study and proposed design equations. *Thin-Walled Structures* **2012**, 56, 79–87, doi:10.1016/j.tws.2012.03.009.

[32] AISI S100-16. *North American Specification for the Design of Cold-Formed Steel Structural Members (Reaffirmed 2020) with Supplement 2*; American Iron and Steel Institute: Washington, DC, USA, 2016.

[33] AS/NZS 4600. *Cold formed steel structures;* Standards Australia/ Standards New Zealand: Wellington, New Zealand, 2018.

[34] EN 1993-1-3. Eurocode 3: *Design of steel structures* - *Part 1-3: General rules* - *Supplementary rules for cold-formed members and sheeting*; European Committee for Standardisation, 2006.