Northumbria Research Link

ICSESM2019-44

WEB CRIPPLING BEHAVIOR OF COLD-FORMED STAINLESS STEEL LCB WITH NON-CIRCULAR WEB OPENING UNDER ETF LOAD CASE

M.F.M. Ishqy*[1,2], K.S. Wanniarachchi[1], P. Keerthan[2], S. Gunalan[3], P. Gatheeshgar[2] and R. Heshachanaa[4]

[1]*Department of Civil and Environmental Engineering, University of Ruhuna, Sri Lanka*
[2]*Faculty of Engineering & Environment, Northumbria University, Newcastle upon Tyne, UK*
[3]*Griffith University, Queensland, Australia*
[4]*Department of Civil Engineering, Sri Lanka Institute of Information Technology, Sri Lanka*
**Correspondence E-mail: ishqyfareed@cee.ruh.ac.lk, TP: +94777073752*

Abstract: Cold-formed stainless steel beams are often subjected to concentrated, localised loads or reactions. These concentrated forces acting on flexural members cause localised bearing failures. This bearing failure, generally known as web crippling, is one of the critical failure modes of cold-formed stainless steel members. The provision of web opening at an appropriate location in such section is also important to avoid holes being cut at an inappropriate location during the construction stage. Different shapes and sizes of web openings are made on the web panel of such sections to facilitate building services. The scope of this study is however limited to stainless steel Lipped Channel Beams (LCB) with square and rectangular web openings. Presence of opening in the web directly influences the web crippling behaviour and also considerably reduces web crippling strength of stainless steel LCBs, but very limited researches have been undertaken to predict the web crippling capacity of stainless steel LCBs. Hence, a detailed finite element analysis was undertaken to investigate the web crippling behaviour and web crippling strength of cold-formed stainless steel LCBs with centered non-circular web opening under the exterior-two-flange (ETF) loading condition. Finite element models of cold-formed stainless steel beams with web opening under web crippling actions were developed to investigate the ultimate web crippling strength behaviour of cold-formed stainless steel beams with web opening including their elastic and post-buckling characteristics. They were validated with currently available web crippling test results. A detailed parametric study based on validated finite element model was undertaken to develop an extensive web crippling strength database and were then used to develop the new design equations for the reduction factor of web crippling capacities of cold-formed stainless steel beams with non-circular (i.e. Square or rectangle) web opening. Appropriate web crippling design rules within the framework of European and International Standards were developed based on obtained FEA results.

Keywords: Finite element modelling; Cold-formed Stainless Steel Beam; Non-circular web opening; Web crippling; Design rules

1. Introduction

Over the past decades, usage of stainless steel over the normal carbon steel has exponentially increased due to its remarkable benefits over the carbon steel. Stainless steel is an alloy material containing chromium thus it produces chromium oxide in presence of oxygen and it protects the steel from corrosion attack. In addition to the corrosion-resistant, it shows some other prominent favourable characteristics, recycling options, enhanced strength, superior durability, attractive surface and retain strength in high temperatures. Cold-formed steel sections are preferred over the hot-rolled sections due to its beneficial identities such as lightweight, high durability, enhanced strength, ease of fabrication, ease of transportation and higher strength to weight ratio. Cold-formed steel sections made out of stainless steel materials produce the best solution for the lightweight structures in aggressive environment by adopting both advantages mentioned above. Until recently, normal carbon cold-formed steel LCBs have been used on a large scale in the construction industry. But nowadays, cold-formed stainless steel LCBs are gaining popularity because of their auspicious mechanical and physical properties.

(a) (b)

Figure 1:

a) Pedestrian bridge at Cheung Kong Center, Hong Kong, stainless steel

b) Structural stainless steel with web opening used as load bearing element

Figure 1a shows one of the applications of cold-formed stainless steel sections in the building industry. The non-linear stress-strain behaviour of stainless steel, which is the main difference with carbon steel, makes the standards for conventional carbon steel not always acceptable in the stainless steel design. But, due to the lack of existing design rules for stainless steel, the rules for carbon steel have been generally adopted in the stainless steel design. Since stainless steel constraints with high cost, proper distinctive studies on stainless steel is essential to avoid too conservative or unsafe design. There are few international design standards for stainless steel that are published and yet under the development stage. The European standard (Eurocode EN1993-1-4:

General Rules – Supplementary Rules for Stainless Steels) can be used for both hot-rolled and cold-formed stainless steel section, whereas American standard (SEI/ASCE 8-02: Specification for the Design of Cold-Formed Stainless Steel Structural Members) and Australian/New Zealand standard (AS/NZS 4673: Cold-formed Stainless Steel structures) are restricted to cold-formed steel sections only.

Cold-formed stainless steel lipped channel sections are commonly used as main structural element such as support for walls and railings in building construction, floor joist or bearer and many other load bearing components. However, these sections are susceptible to various failure modes such as shear, bending and web crippling when they get subjected to concentrated loads. Web crippling is one of the most critical failure mode of cold-formed stainless steel members. Openings in the web of such sections have become a common practice in the construction industry in order to avoid inappropriate cuttings during the construction. Various shapes of web openings as shown in figure 1b are commonly deployed in the channel section beams used in buildings to facilitate various building services systems such as plumbing, electrical, fire extinguisher services, heat and ventilation. Due to the openings in the web panels, web crippling behavior of channel sections are changed and become more susceptible to web crippling failure thus it can cause a reduction in web crippling capacity tremendously. Many parameters affect the web crippling behaviour of cold-formed stainless steel LCBs with web openings. Past researches (Keerthan et. al. 2014), Yousefi & Lim (2017) and Ishqy et. al. (2019) have reported that the most influential parameters for the web crippling capacity of hollow flange channel and lipped channel beam with web opening are shape, size, location of the web openings, slenderness of the web element and size of the loading plate.

Many research studies have been conducted on the web crippling behaviour of normal carbon cold-formed channel beams without web openings under interior and exterior load conditions (Keerthan & Mahendran, 2014, Gunalan & Mahendran, 2015 and 2019 Sundararajah et al., 2017a & 2017b and Janarthnanan et al., 2015 and 2019). In recently, Alsanat et al. (2019) investigated the web crippling capacity of Aluminium LCBs without web opening under two flange load cases. But very limited research studies have been investigated to study the behaviour of cold-formed stainless steel LCBs with web openings. Yousefi et al. (2017) focused on the stainless steel unlipped channel beam with circular web opening but not on the beam with non-circular web openings such as square and rectangular. Again, Ishqy et al. (2019) focused on the cold-formed stainless steel unlipped channel beam with rectangular and square shape of web opening for the interior two flange load cases.

Numerical studies on the web crippling behaviour of cold-formed stainless steel lipped channel section showed that the currently available design equations to predict the web crippling capacity of conventional carbon cold forms lipped channel beams with web openings are deficient to determine the web crippling strength of the CFSS LCBs with rectangular and square shapes of web opening. Hence, detailed finite element analyses were undertaken and a unified strength reduction factor equation for the web crippling strength of cold-formed stainless steel lipped channel sections with square and rectangular web opening under ETF load case was developed.

2. Finite element modelling

2.1 FE model development

FEM is becoming progressively popular. This is due in part to the increased freedom one has in terms of geometry and distribution, interface, and mechanical properties, and in part due to progressive development in computational power and graphical user-friendly interfaces. With modern computers, elastic models containing many thousands of elements can be constructed and solved quickly. For this study, commercially available FE package ABAQUS was used to develop the FE models with suitable geometric and material properties and loading and boundary conditions to simulate the web crippling test conditions as in Asraf et al. (2012). Initially, a bifurcation buckling analysis was executed to obtain the Eigenvectors to incorporate the geometric imperfections into the non-linear FE analysis. Then, non-linear dynamic explicit analyses were employed to study the web crippling behaviour of cold-formed stainless steel lipped channel beam with rectangular and square web opening.

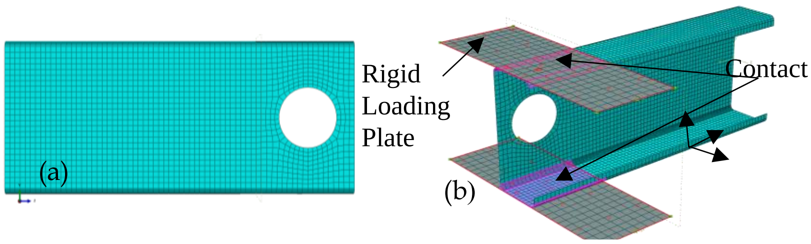

Figure. 2: Geometry and finite element mesh
(a) Mesh (b) Boundary condition and contact

In this analysis, adequate numbers of elements were chosen for both flanges and web, based on detailed convergence studies in order to obtain sufficient accuracy of results without excessive use of computing time. Available Quad-structured S4R shell element type was assigned to the FEM beam to simulate the thin deformable section behaviour. In the vicinity of the web openings, Quad-free S4R shell element type with medial axis algorithm to minimize the mesh transition was assigned to obtain the proper meshing with consistent element shape. Finite element mesh size of 5 mm × 5 mm (see Figure. 2(a)) was assigned to reach convergence with reasonably good accuracy and reasonable time in channel sections. 10mm x 10mm mesh sized R3D4 rigid element type was assigned for bearing plates. Simply supported boundary conditions were simulated to the bearing plates in the finite element models of channels with unreinforced rectangular and square web openings.

2.2 Material modeling and boundary conditions

Stress-strain curve of stainless steel explicit distinctive nonlinear material behaviour in which no clearly defined yield point can be observed, unlike the normal carbon steel where it shows linear and perfect plastic behaviour. Nonlinear strain hardening material behaviour was adopted in the model by using the Romberg-Osgood Equation (1) for stainless steel type of Austenitic. Where E_0 is initial elastic modulus, σ_u and ε_u are the ultimate stress and strain respectively, $\sigma_{0.2}$ is the proof stress corresponding 0.2% of plastic strain, $\varepsilon_{0.2}$ is the total stain at 0.2% proof stress and $E_{0.2}$ is the elastic tangent modulus at 0.2% proof stress. Elastic modulus and Poisson's ratio of austenitic stainless steel grade were taken as 197,333 MPa and 0.3 respectively. During the material modelling, corner regions (defined in Figure (3) and flat portion of the LCB sections were differentially modelled to incorporate the strength enhancement (Equation 2) within the corner regions

$$\varepsilon = \begin{cases} \dfrac{\sigma}{E_0} + 0.002\left(\dfrac{\sigma}{\sigma_{0.2}}\right)^n & \text{for } \sigma \le \sigma_{0.2} \\ \varepsilon_u + \dfrac{\sigma - \sigma_{0.2}}{E_{0.2}} + \varepsilon_u\left(\dfrac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^m & \text{for } \sigma > \sigma_{0.2} \end{cases} \tag{1}$$

$$\sigma_{0.2,pb,c} = \frac{1.673\sigma_{0.2,mill}}{\left(\dfrac{r_i}{t}\right)^{0.126}} \tag{2}$$

due to the cold-working process by press bark operation($\dot{\sigma}_{0.2,pb,c}$) during the manufacturing of cold-formed channel sections (Cruise and Gardner, 2008). Where t is thickness and r_i is internal corner radius.

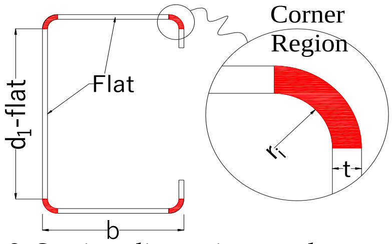

Figure 3: Section dimensions and corner region

In this FEM, “hard” contact model (see Figure 2(b)), which is the default contact formulation in ABAQUS (2017), was assign within the bearing plate and contact surface of flanges of LCBs to simulate the simply supported boundary conditions and roller supports were assigned at the two flanges. Details of boundary conditions used are elaborated below. The ux, uy and uz are the translational degree of freedom (d.o.f) while θx, θy and θz are rotational d.o.f in the x, y and z direc-

Bottom support condition:		Top loading point condition:	
u_x = restrained	θ_x = free	u_x = restrained	θ_x = free
u_y = restrained	θ_y = free	u_y = Displacement	θ_y = free
u_z = free	θ_z = retrained	u_z = restrained	θ_z = retrained

tions, respectively.

In thin stainless-steel sections such as LCBs, some residual stress might get induced during their manufacturing process. Nevertheless, the impact of these residual stresses has not been taken into consideration, as previous research (Keerthan & Mahendran (2012)) shows that the influence of residual stress on the shear capacity of LCB sections is about 1 percent, and is therefore negligible.

2.3 FE model validation and parametric study

Developed FE models should be validated to ensure the reliability of the model to be used in further non-linear analyses of cold-formed stainless steel lipped channel beams with rectangle and square web openings subjected to web crippling under ETF load case. So, developed models were fully validated against the experimental test results by using failure mode, load versus displacement graph and ultimate web crippling capacity. Web crippling experimental test results of cold-formed steel lipped channel beam with circular web opening under ETF loading condition were used for modelling and validation. Models of cold-formed stainless steel unlipped channel beams with centered circular web openings were also developed and validated against available test results for web crippling under ETF load case. Validated cold-formed steel lipped channel beams with openings and cold-formed stainless steel unlipped channel beam with openings were further used for the parametric study.

In this study, four sections with different parameters were used to develop the database and selection was done based on industrially available sectional specifications. Normal dimensions of web thickness (t_w) around 1 mm - 2 mm, web heights (d_1) from 175 mm to 250 mm, web yield stress (f_{yw}) = 259.3 MPa (EN 1.4301) and bearing plate width from 90mm to 150mm were used in the analyses. For the validation, 21 web crippling ETF test results of cold-formed LCBs with and without web openings from Asraf *et al*. (2012) and 11 web crippling ETF test results of cold-formed stainless steel unlipped channel beam with and without web opening from Yousefi *et al*.(2017) were assessed. Cold-formed LCB specimens of 142x60x13x1.3, 172x65x13x1.3, 202x65x13 and 262x65x13x1.6 and Cold-formed stainless steel unlipped channel beam specimens of 175x60x15x1.2, 200x75x1.2 and 200x100x1.2 were used for validation. Figure 4 depicts the good agreement of failure mechanism between the experimental test specimen and FEA model.

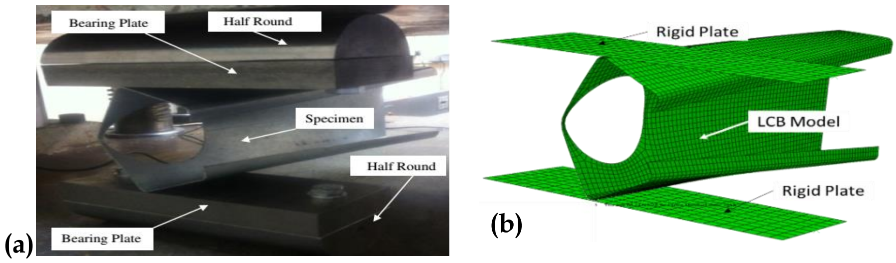

Figure 4: web crippling failure mode of stainless steel section 142x60x15x1.3
a) Experiment (Asraf *et al.*, 2012); b) FEA

Table 1 and Table 2 shows the validation results of web crippling capacities under ETF load case for cold-formed LCB with circular web openings and cold-formed stainless steel unlipped channel beams with circular web openings respectively where d_1, d_{wh} and t_w are the clear web height, depth of web opening and web thickness of the section, respectively. Hence it shows that the FE models were able to predict the ultimate web crippling capacities of tests with good accuracy. The respective mean and coefficient of variance (COV) of the results in Table 1 are 1.01 and 0.046 and Table 2 are 0.985 and 0.039.

2.3 Parametric study

Validated cold-formed LCB models were used for the further detailed parametric study to investigate the web crippling behaviour of cold-formed stainless steel LCB with non-circular web opening by developing an extensive web crippling strength database for lipped channel sections with unreinforced rectangular and square web opening. In the parametric study, web openings were located only at middle of the section depth and center of the bearing plate, different sizes, opening depths(d_{wh}), web opening widths (b_{wh}) and loading plate width (N) were considered for ETF load case (see Figure. 5) to predict the web crippling strength.

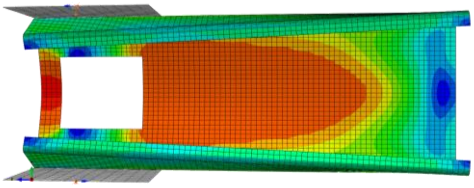

Figure 5: Web crippling failure mode of 80x80 square web opening 172x65x13x1.2 CFSS LCB

The ultimate web crippling capacities of stainless steel lipped channel sections with web openings and the corresponding web crippling capacity reduction factors (R_c) defined as the ratio of web crippling capacity of CFSS LCB with web opening (P_{nl}) to the web crippling strength of CFSS LCB without web opening (P_n) were obtained for varying ratios of d_{wh}/d_1, N/ b_{wh} and d_{wh}/b_{wh}. The ultimate web crippling capacities of the selected sections without web openings (P_n) were also obtained from FEA. Web opening depth to beam height ratio (d_{wh}/d_1) of 0, 0.2, 0.4, 0.6, 0.8and 0.95, bearing plate width (N) of 50, 100 and 150 and web opening depth to width ratio (d_{wh}/b_{wh}) of 1.0, 0.8, 0.7, 0.6, 0.5, 0.4 and 0.3 were studied.

Table 1: Comparison of web crippling strength predicted from finite element analysis with experiment results for cold formed LCB under ETF Load case

Specimen	d (mm)	d_{wh}/d_1 (mm)	P_{EXP} (kN)	P_{FEA} (kN)	P_{EXP} / P_{FEA}
ETF142-60-16-t13N90MA0	142.2	0.00	2.21	2.28	0.97
ETF142 60 16-t1.3N90MA0.2	142.2	0.20	1.98	2.03	0.98
ETF142 60 16-t1.3N90MA0.4	142.2	0.39	1.62	1.68	0.96
ETF142 60 16-t1.3N90MA0.6	142.2	0.59	1.32	1.38	0.96
ETF142-60-16-t1.3N120MA0	141.8	0.00	2.35	2.45	0.96
ETF142 60 13-t1.3N120MA0.2	141.8	0.20	1.95	2.02	0.97
ETF142 60 13-t1.3N120MA0.4	141.3	0.39	1.78	1.82	0.98
ETF142 60 13-t1.3N120MA0.6	141.3	0.59	1.49	1.42	1.05
ETF172 65 13-t1.3N120MA0	172.8	0.00	2.37	2.44	0.97
ETF172 65 13-t1.3N120MA0.4	172.3	0.39	1.70	1.67	1.02
ETF172 65 13-t1.3N120MA0.6	172.6	0.59	1.36	1.47	0.93
ETF202 65 13-t1.4N120MA0	202.1	0.00	2.70	2.80	0.96
ETF202 65 13-t1.4N120MA0.2	202.7	0.20	2.41	2.50	0.96
ETF202 65 13-t1.4N120MA0.4	202.4	0.39	1.88	1.76	1.07
ETF202 65 13-t1.4N150MA0	202.1	0.00	2.84	2.67	1.06
ETF202 65 13-t1.4N150MA0.4	202.7	0.39	2.19	2.28	0.96
ETF202 65 13-t1.4N150MA0.6	202.4	0.59	1.77	1.84	0.96
ETF262 65 13-t1.6N120MA0	263.4	0.00	2.55	2.63	0.97
ETF262 65 13-t1.6N120MA0.2	263.4	0.20	2.29	2.36	0.97
ETF262 65 13-t1.6N120MA0.4	262.8	0.39	1.77	1.68	1.05
ETF262 65 13-t1.6N150MA0	263.4	0.00	2.82	2.82	1.00
ETF262 65 13-t1.6N150MA0.4	262.8	0.39	2.04	2.12	0.96

3. Comparison of web crippling capacities with current design predictions

The numerical results, ultimate web crippling capacities of cold-formed stainless steel LCB with non-circular web opening obtained from FEA parametric study were analysed and compared with the predictions from the currently available web crippling design equations for ETF load case. Figure 7 illustrates the comparison of the obtained FEA results with currently available design equations to predict the web crippling capacity of cold-formed channel and hollow section, with circular web openings under ETF load case. Web crippling reduction factor (R_c) for cold-formed LCBs with circular web opening under ETF load case published in Asraf *et al*. (2012) and R_c for Aluminum hollow square sectiopn with web opening published in Zhou & Young (2010) are not concentrated on stainless steel elements and their predictions shows anomalous deviation. Since the stainless steel material shows a complex material behaviour, having enhanced strength due to the material strain hardening and corner strength enhancement due to the cold working, conventional cold-formed design equations gave an over-conservative result. Due to the lack of existing design rules for stainless steel, the rules for carbon steel have been generally adopted in the stainless steel design. However, the prominent non-linear behaviour of stainless steel, which is the main difference with carbon steel, makes the standards for carbon steel not always acceptable in the stainless steel design.

In term of cold-formed stainless steel, Krovink & van den Berg (1994) equations are focused on one flange load cases thus it shows aberrant deviation. R_c proposed by Yousefi *et al.* (2017) concentrated on circular web opening there for its prediction leads to unsafe design. In very recently, R_c proposed by Ishqy *et al*. (2019) for stainless steel unlipped channel beams with noncircular web opening also slightly deviated on LCB section. Hence the predictions provide too conservative or unsafe results and failed to precisely predict the web crippling of CFSS LCB with rectangular and square opening. Therefore, new web crippling design equations are necessary to predict the web crippling capacities of channel sections with rectangular and square web openings.

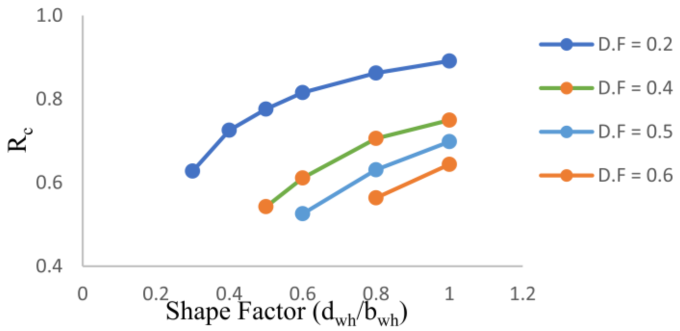

Figure 6: web crippling capacity reduction with shape factor for stainless steel section 142x60x15x1.3

4. Proposed Equations for web crippling strength of CFSS LCB with rectangular and square web openings

Eurocode 3: EN 1993-1-4 (2006) gives supplementary provisions for the design of stainless steels for both hot-rolled and cold-formed sections. Even so, for the ultimate resistance design of cold-formed stainless steel members, the specifications given in EN 1993-1-3 (2006) which are conceived for carbon steel, are still applied. Over the lasts decades, numerous research studies have been conducted in this field in order to achieve a better understanding of the cold-formed stainless steel behaviours, as well as to check the reliability and applicability of the existing design specifications, and to obtain new design rules to provide the designers with more economical and efficient ways of designing. In extend to that, in this study web crippling behaviour of cold-formed stainless steel LCBs with unreinforced non-circular web opening is investigated and a new design equation is introduced.

The comparison of the ultimate web crippling strength of CFSS LCBs with rectangular and square web openings and with that of sections of solid web ascertain that web bearing capacity significantly reduces with increased of opening depth.It also observed that with the increase of the breadth of the opening we crippling capacity of CFSS LCB reduces slightly. Figure (6) clearly depicts the influence of shape factor (d_{wh} /b_{wh}) and depth factor (d_{wh}/d_1) denoted as D.F on the web crippling reduction factor (R_c). The numerical results showed that the ratios depth factor, shape factor and N/ b_{wh} are the basic parameters which impact the web crippling strength of the sections with unreinforced non-circular web openings. Therefore, based on the numerical results obtained from this study, strength reduction factor equation (R_c) is proposed as a function of the depth factor (d_{wh}/d_1), shape factor (d_{wh} /b_{wh}) and the ratio of bearing plate width to clear web height (N/d_1). Equation 4 is the proposed design equations for CFSS LCBs with cantered rectangular and square web openings for ETF load case. The mean value of the numerical results over the results from the proposed both equations are equal to 1.003, with the coefficient of variation (COV) of 0.046 for ETF load case.

$$P_{nl} = R_c P_n \qquad (3)$$

P_n- Nominal web crippling strength of cold-formed stainless steel sections, refer Equations 3.3.4-1 to 3.3.4-22 of SEI/ASCE 8-02: 2002

$$R_c = 0.656 + 0.032\frac{N}{b_{wh}} + 0.24\frac{d_{wh}}{b_{wh}} - 0.545\frac{d_{wh}}{d_1} \qquad (4)$$

R_c - for rectangular and square cantered unreinforced web opening under ETF load case.

5.0 Conclusions

Web crippling behaviour and strength of CFSS LCBs with rectangular and square web openings under ETF load case have been investigated and presented in this paper by using finite element modelling and analyses. Obtained results from this study were used for the comparative study of currently available design equations to predict the web crippling capacity of perforated cold-formed channel and hollow section under ETF load case with the proposed equation. It is evident that, most of the currently available design equations are focused on circular web openings and convention carbon cold-formed steel and thus it makes the design either too conservative or unsafe for stainless steel LCBs with rectangular and square centered web opening. In this study, existing design equations were improved by incorporating shape factor d_{wh}/b_{wh}. The obtained FEA results were perfectly matched with the proposed design rules. Hence, the proposed design equations from this study are competent to predict the web crippling strength of CFSS LCBs with rectangular and square web openings precisely.

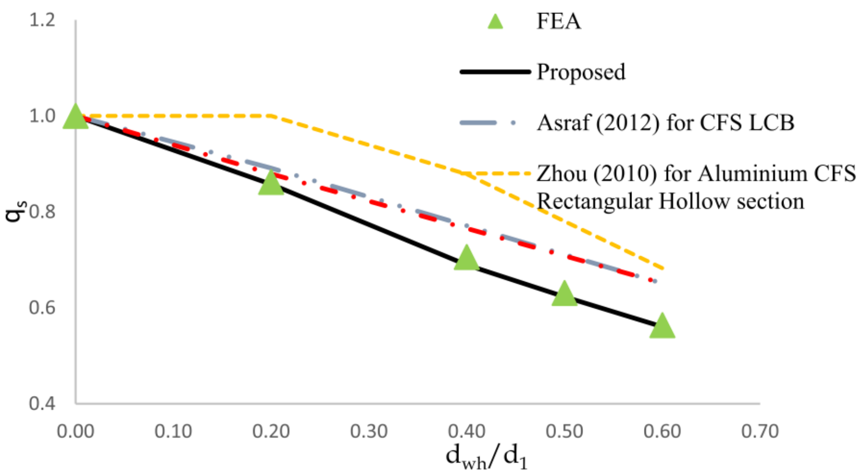

Figure 7: Comparison of web crippling capacity of stainless steel 172x65x13x1.3 LCBs with rectangular web openings with shape factor of 0.8 from FEA with current design equations

References

Abaqus/CAE Standard 2017, "Abaqus/CAE, User's Guide", Dassault Systems Simulia Corp, Providence, RI, USA

Alsanat, H., Gunalan, S., Keerthan, P., Guan, H. and Tsavdaridis, K.D., 2019. Web crippling behaviour and design of aluminium lipped channel sections under two flange loading conditions. *Thin-Walled Structures*, *144*, p.106265.

BSI. *Eurocode 3: Design of Steel Structures – Part 1–4: General Rules – Supplementary Rules for Stainless Steels.* Brussels: British Standards Institution, 2006.

Cruise, R. B. and Gardner, L. (2008) 'Strength enhancements induced during cold forming of stainless steel sections', 64, pp. 1310–1316. doi: 10.1016/j.jcsr.2008.04.014.

Fareed, I., Somadasa, W., Poologanathan, K., Gunalan, S., Corradi, M. and Sivapalan, S., 2019. Finite Element Analyses of Cold-formed Stainless Steel Beam with Web Openings in Shear. *ce/papers*, *3*(3-4), pp.907-912. https://doi.org/10.1002/cepa.1168

Fareed, I., Somadasa, W., Poologanathan, K., Gunalan, S., Beatini, V. and Sivabalan, S., 2019. Web Crippling Behaviour of Cold-formed Stainless Steel Beams with Non-Circular Web Opening. *ce/papers*, *3*(3-4), pp.937-942. https://doi.org/10.1002/cepa.1170

Gunalan S, Mahendran M. Web crippling tests of cold-formed steel channels under two flange load cases. J Const Steel Res 2015;110:1-15.

Ishqy, M.F.M., Wanniarachchi, K.S., Keerthan, P., Gunalan, S. and Corradi, M., numerical analyses of cold-formed stainless steel lip-channel beams (lcb) with non-circular web openings subjected to shear. *Stainless steel*, *1*, pp.1-4404.

Janarthanan, B., Sundararajah, L., Mahendran, M., Keerthan, P. and Gunalan, S., 2019. Web crippling behaviour and design of cold-formed steel sections. *Thin-Walled Structures*, *140*, pp.387-403.

Keerthan, P., Mahendran, M. and Steau, E., 2014. Experimental study of web crippling behaviour of hollow flange channel beams under two flange load cases. *Thin-Walled Structures*, *85*, pp.207-219

Specification for the Design of Cold-Formed Stainless Steel Structural Members [SEI/ASCE 8-02], [Standards No. 02-008], American Society of Civil Engineers, 2002.

Sundararajah, L., Mahendran, M. & Keerthan, P. 2017a. New design rules for lipped channel beams subject to web crippling under two-flange load cases. Thin-Walled Structures, 119, 421-437.

Sundararajah, L., Mahendran, M. and Keerthan, P., 2017b. Web crippling experiments of high strength lipped channel beams under one-flange loading. *Journal of Constructional Steel Research*, *138*, pp.851-866.

Sundararajah, L., Mahendran, M. and Keerthan, P., 2019. Numerical Modeling and Design of Lipped Channel Beams Subject to Web Crippling under One-Flange Load Cases. *Journal of Structural Engineering*, *145*(10), p.04019094.

Uzzaman, A., Lim, J.B., Nash, D., Rhodes, J. and Young, B., 2012. 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*, *56*, pp.38-48.

Yousefi, A.M., Lim, B.P., 2017. Web bearing capacity of unlipped cold formed stainless steel channels with perforated web subject to end two flange loading. *Engineering Structures*, *152*, pp.804-818

Zhou, F. and Young, B., 2010. Web crippling of aluminium tubes with perforated webs. *Engineering Structures*, *32*(5), pp.1397-1410.