Northumbria Research Link

ICSESM2019-43

SHEAR CAPACITY OF COLD-FORMED STAINLESS-STEEL BEAM WITH ELLIPTICAL WEB OPENINGS: NUMERICAL ANALYSES

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 sections are increasingly being used in the construction industry, for both architectural and structural applications. The excellent combination of mechanical properties and corrosion resistance makes stainless steel a very good material for structural applications. Due to the lack of design rules for stainless steel, the design 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 accurate in the stainless-steel design. The provision of web openings at appropriate locations in such sections is also important to avoid cutting holes at an inappropriate location during the implementation stage. The type of section and the shape of opening were primarily chosen based on the application. The scope of this study is however limited to stainless steel Lipped Channel Beams (LCB) with elliptical web openings. The provision of openings in web affects the shear behaviour and shear capacity of LCB sections, but only very limited researches have been conducted so far. Hence, a numerical analysis was undertaken to investigate the shear behaviour and strength of cold-formed stainless steel LCB section with elliptical web openings. Finite element models of cold-formed ferritic stainless steel LCB with centered web openings were developed under the simply supported loading condition. They were validated with currently available shear test results and a detailed parametric study was undertaken to develop an extensive shear strength database. Numerical results showed that the currently available reduction factor equations of circular web opening are either conservative or unsafe to use for the non-circular openings. Hence, numerical results were then used to develop a reduction factor to the shear capacities of cold-formed stainless steel LCBs with elliptical web opening.

Keywords: Finite element modelling; Cold-formed stainless steel; Shear; Lipped channel sections; Non-circular web openings

1. Introduction

Stainless steel is arousing as a popular construction material around the world because of its excellent material properties. It differs from carbon steel mainly due to its chromium content (Minimum 10.5%) and thus protects steel structures from corrosion. Stainless steel spontaneously forms chromium oxide protective layer which is tightly adhered to the surface and thus it makes the stainless-steel structural components can be exposed to corrosive environment without any additional protective coatings. Nowadays, Stainless steel structures are highly recommended because they are attractive and highly corrosion resistant, whilst at the same time having good strength, toughness and fatigue properties alongside low maintenance requirements. They can be fabricated using a wide range of commonly available engineering techniques. There are 5 types of stainless steel available and among them, ferritic stainless steel is having outstanding performance compared to other types. Austenitic stainless steels provide a good combination of corrosion resistance, forming and fabrication properties, with design strengths from 220 MPa to 430 MPa. The most commonly used grades EN 1.4301 (widely known as AISI 304) and EN 1.4401 (widely known as AISI 316) are used in this study. Grade EN 1.4301 is cheaper and suitable for rural, urban and light industrial sites whilst grade EN1.4401 is of higher alloy content and will perform well in marine and industrial sites.

In recent, cold-formed steel sections are highly recommended for primary load-bearing members in building construction industries instead of hot-rolled steel sections due to their higher strength to weight ratio, economy of transportation, ease of fabrication and handling, trouble-free replacement and uncomplicated installation. The use of cold-formed stainless steel members over the normal carbon cold-formed steel members are preferred because of their additional advantages.

Figure 1: Structural cold-formed steel sections with perforated web.

Stainless steel structural members behave similar to carbon steel members, although there are some significant differences arising from the material's distinctive strength, stiffness and physical properties. The major difference between the mechanical properties of carbon and stainless steel is the stress-strain relationship: stainless steel has a continuous, but non-linear relationship between stress and strain, whereas carbon steel has a clearly defined yield point. Cold-Formed Stainless Steel (CFSS) LCB are commonly used as building frames, floor joist or bearers and many other load-bearing elements in low rise buildings. In many applications of CFSS LCB such as roof and floor systems, include web openings in order to facilitate building services such as electrical, plumbing, heating and ventilation system within them (as shown in Figure 1) and it became acceptable practice to preclude inappropriate cutting of web holes by service engineers. Openings in such CFSS LCB's web panels affect the structural behaviour of LCB due to the reduction in the web area and thus significantly reduce the shear strength and capacity. In contrast, the effect of web openings on the flexural capacity is negligible as the web openings are normally located at the centre of the web. (Keerthan and Mahendran, 2012)

Sufficiently many researches have been conducted the shear and combined bending and shear behaviour of cold-formed steel channel section with solid web (Keerthan & Mahendran, 2011a, 2011b, 2013 & 2015, Keerthan, Hughes & Mahedran., 2014). Past researches (Keerthan & Mahendran, 2012 & 2014 and Wanniarachchi et al., 2017) have studied and identified the parameters which affect the shear capacity of cold-formed steel LCBs with web openings. They are the shape, size and location of the web openings and the slenderness of the web element. Keerthan et al, (2014) has reported that the most influential parameter for the shear capacity of cold-formed steel (LCB) with unreinforced circular web openings is the ratio of the depth of web opening (dwh) to clear height of web (d1) and thus developed their shear capacity reduction factors in terms of dwh/d1. The main objective of this study is to investigate the effect of elliptical web opening of varying breadth and depth on the shear capacity of stainless steel LCB using Finite Element Analyses (FEA) using ABAQUS. Numerical results of shear capacity of CFSS LCBs with elliptical web openings are compared with the predicted results using currently available design equations for both normal carbon cold-formed steel LCBs with non-circular web opening and CFSS LCBs with circular web opening. Suitable design equations are also developed based on FEA results.

2. Shear capacity of cold-formed LCBs with web openings.

Over the past decades, many research studies have been undertaken on the shear behaviour and strength of cold-formed steel lipped channel beams and hollow flange channel beams with web openings. Currently available shear design equations for cold-formed steel LCBs with web openings are based on a reduction factor (q_s) defined as the ratio of shear capacity with web opening (V_{nl}) to the shear strength without web opening (V_v). (Wanniarachchi et al., 2017)

Initially, Shan et al. (1997) introduced the application of shear reduction factor (q_s) to the solid web strength of the shear element to calculate the shear capacity of cold-formed lipped channel beams with unreinforced web openings. Later on, Eiler's(1997) modified version of Shan's (1997) shear strength reduction factor equations have been adopted in AISI S100 and AS/NZS 4600 (both are identical) design standards for cold-formed steel structures.

Keerthan and Mahendran (2013, 2014) conducted experimental and finite element analyses to investigate the shear behaviour of cold-formed steel lipped channel beams with circular unreinforced web openings and developed improved design equations for the prediction of their shear strength. Wanniarachchi et al. (2017) conducted experimental and numerical analyses to predict the shear capacity of cold-formed steel LCBs with non-circular including rectangle, square and ellipse web opening and developed q_s as a function of the ratio of depth of web opening to clear web height (d_{wh}/d_1) and as well as q_s as a function of the ratio qa (area reduction factor) of web opening area to shear panel area (A_h/A_f). But these findings are concentrated on normal carbon cold-formed steel only and until now, very few researches have been conducted on CFSS LCBs.

In terms of stainless steel, currently available design standards for stainless steel such as EN-1993-1-4, SEI/ASCE-8-02 and AUS/NZ 6359 have not yet included the web opening effect on shear capacity. In recent, a few researches were carried out in CFSS sections. Sonu and Singh (2017) investigated the shear characteristics of Lean Duplex Stainless Steel (LDSS) rectangular hollow beams using numerical studies. Recently, Ishqy et al. (2019) investigated a numerical study on the shear behaviour of CFSS LCB with unreinforced circular web opening and new shear reduction factor (q_s) is proposed as provided in Equations 1-4.

$$V_{nl} = q_s V_v \quad (1)$$

$$for\ 0.2 > \frac{d_{wh}}{d_1}, \qquad q_s = 1 - 0.473 \times \frac{d_{wh}}{d_1} \quad (2)$$

$$for\ 0.2 \leq \frac{d_{wh}}{d_1} < 0.8, \qquad q_s = 1.130 - 1.151 \times \frac{d_{wh}}{d_1} \quad (3)$$

$$for\ 0.8 \leq \frac{d_{wh}}{d_1} \leq 0.95, \qquad q_s = 0.743 - 0.655 \times \frac{d_{wh}}{d_1} \quad (4)$$

However, yet no any researches have studied the shear behaviour and strength of conventional stainless steel lipped channel beams with elliptical web openings. Hence, in this study detailed finite element analyses were undertaken to investigate the shear behaviour and strength of austenitic stainless steel LCBs with circular and elliptical web openings.

3. Shear capacity of Stainless-Steel LCB without web opening.

The design of cold-formed stainless-steel section is more complicated than that of carbon cold-formed steel because of the distinction between their material properties. Due to the stainless steel's strain hardening effect, it shows a non-linear stress-strain behaviour which is beneficial in design of cold-formed stainless-steel member elements due to the enhancement of strength. The following equations (5-6) to predict the shear resistance are referenced from SEI/ASCE 8-02: Specification for the Design of Cold-Formed Stainless Steel Structural Members where, Φ_v is resistance factor for shear; V_n is nominal shear strength of beam; h is depth of flat portion of web measured along plane of web; t is web thickness and G/G0 is plasticity reduction factor.

$$V = \phi_v V_n \quad (5)$$

$$\phi_v = 0.85$$

$$V_n = \frac{4.84 E_o t^3 (G_s/G_0)}{h} \quad (6)$$

In 2006, European standard on stainless steel Eurocode 3: Part 1.4 (EN 1993-1-4): Design of steel structures: General rules. Supplementary rules for stainless steels was published with the following equations (7-9) by including the web and flange effect on shear capacity where, f_y is yield strength, η is the parameter that approximates the influence of strain hardening, b_f is overall the flange width, Y_{M1} is partial safety factor, χ_w is web shear buckling reduction factor, M_{Ed} is coexistent design bending moment, $M_{f,Rd}$ is moment resistance of the cross section C is the distance which defines the location of the plastic hinges.

$$V_{b,Rd} = V_{bw,Rd} + V_{bf,Rd} \leq \frac{\eta f_{yw} h_w t_w}{\sqrt{3}\,\gamma_{M1}} \quad (7)$$

$$V_{bw,Rd} = \frac{\chi_w f_{yw} h_w t_w}{\sqrt{3}\,\gamma_{M1}} \quad (8)$$

$$V_{bf,Rd} = \frac{b_f t_f^2 f_{yf}}{c\,\gamma_{M1}}\left[1-\left(\frac{M_{Ed}}{M_{f,Rd}}\right)^2\right] \quad (9)$$

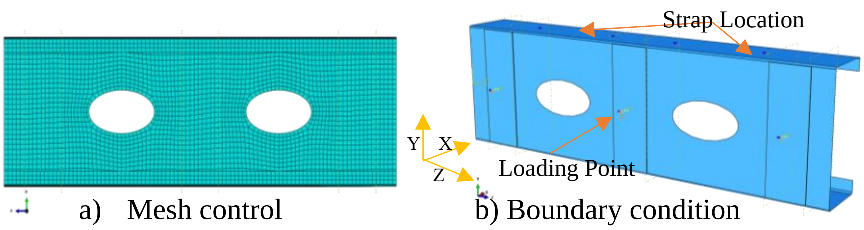
4. FE analyses of LCB

4.1. FE model development

This section presents the development of the finite element (FE) models which were used to study the shear behaviour of cold-formed stainless-steel lipped channel beams with web openings. with unreinforced rectangular and square web opening.

For the FE modelling, the commercially available general-purpose finite element software ABAQUS CAE 2017 was accessed. Geometric and material properties, loading and boundary conditions were suitably adopted to simulate the shear test conditions of austenitic type of stainless-steel lipped channel beams. In FEA, a bifurcation buckling analysis was initially performed to obtain the eigenvectors for the inclusion of geometric imperfections in the non-linear analysis. Then, non-linear general Riks analyses were employed to investigate the shear strength and behaviour of stainless steel LCBs with circular and elliptical web opening up to shear failure.

In the experiments, back-to-back beam setup was used to avoid any torsional effects induced due to eccentricity of shear centre. Three full height rigid web plates, each 45 mm wide were used at the two support ends and at the mid span loading point. To get the pure shear load condition by minimising the bending effect, all considered LCB sections were having an aspect ratio (shear span (a) / clear web height (d_1)) of



a) Mesh control b) Boundary condition

Figure 2: Finite element model of 200×75×15×1.5 stainless steel LCB

1.0. Keerthan and Mahendran (2011) carried out shear tests on cold-formed Lite Steel Beam (LSB) and their results showed that shear strength of back to back cold-formed LSBs and single cold-formed LSBs with a shear centre loading are similar in shear behaviour. Hence in this study, FE model of single LCB sections with shear centre loading (see Figure 2b) was used instead to preclude any torsional effect due to the eccentricity of load and to simulate the back to back shear test of LCB. ABAQUS contains several element types and shell element was selected out of them due to its ability to imitate the elastic buckling and non-linear shear behaviour of thin steel sections such as Lipped channel beams. Available S4R shell element type which is thin, isometric quadrilateral shell with 4 nodes and 5 degrees of freedom (d.o.f) and shear flexible is used to imitate the thin section behaviour under shear. All the LCB sections were drawn using the centreline dimensions. 5 mm × 5 mm sized mesh (see Figure 2a.) was reasonable and able to reach convergence with good accuracy. The size of the mesh was choose based on the convergence study. In corner regions, at least 5 elements were used to transfer the load from web to flange and 10 mm x 10 mm sized meshes were assigned to web side plate.

4.2. Material modelling and Boundary conditions

Carbon steel and stainless steel differ mainly by their behaviour of the stress-strain curve. Unlike the carbon steel, which depicts a linear elastic, perfectly plastic behaviour, stainless steel respond in non-linear rounded and anisotropic way. So, Elastic and non-linear hardening material model was used in the FE model. Similar method was followed as proposed previously (Ishqy et al., 2019b) when developing the material model. Elastic modulus and Poisson's ratio of all the stainless-steel grades were taken as 197,333 MPa and 0.3 respectively. In order to incorporate the strain hardening effect into the material model, Ramberg-Osgood equation (Equation 11) with second order of n was used in this study. Where E_0 is initial elastic modulus or Young's 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.

$$\varepsilon = \begin{cases} \dfrac{\sigma}{E_0} + 0.002\left(\dfrac{\sigma}{\sigma_{0.2}}\right)^n & \text{for } \sigma \le \sigma_{0.2} \\ \varepsilon_u + \dfrac{\sigma-\sigma_{0.2}}{E_{0.2}} + \varepsilon_u\left(\dfrac{\sigma-\sigma_{0.2}}{\sigma_u-\sigma_{0.2}}\right)^m & \text{for } \sigma > \sigma_{0.2} \end{cases} \qquad (11)$$

The strength enhancement in the corner regions of the cold-formed stainless steel section due to plastic deformation has been studied in (Cruise and Gardner, 2008) and produced the predicted 0.2% proof stress at corner ($\sigma_{0.2,pb,c}$) presented in Equation 12 for press-braked cold-formed stainless steel section was produced where r_i is internal corner radius and $\sigma_{0.2,mill}$ is 0.2% proof stress given in mill certificate.

$$\sigma_{0.2,\mathrm{pb,c}} = \frac{1.673\sigma_{0.2,\mathrm{mill}}}{\left(\frac{r_i}{t}\right)^{0.126}} \quad (12)$$

Simply supported boundary condition is implemented by assigning pin and roller support conditions at the two supports. To simulate the effect of equal angle straps, suitable boundary conditions were assigned at strap locations on the flange. Details of boundary conditions used are elaborated below. The u_x, u_y and u_z are translations and θ_x, θ_y and θ_z are rotations in the x, y and z directions, respectively while 0 denotes free and 1 denotes restrained conditions.

Left support: $u_x=1$ $u_y=1$ $u_z=1$ $\theta_x=0$ $\theta_y=0$ $\theta_z=1$

Right support: $ux=1$ $u_y=1$ $u_z=0$ $\theta_x=0$ $\theta_y=0$ $\theta_z=1$

Mid span loading point: $u_x=1$ $u_y=0$ $u_z=1$ $\theta_x=0$ $\theta_y=0$ $\theta_z=1$

Strap locations: $u_x=1$ $u_y=0$ $u_z=0$ $\theta_x=0$ $\theta_y=0$ $\theta_z=1$

The experimental test conditions were simulated by single point concentrated nodal forces in the FE model. Both concentrated displacement control point load and simply support conditions were applied at the shear centre of LCB using a fixed reference point of the web side plate. The manufacturing process of LCBs may induce some residual stresses in thin stainless-steel sections. However, the effect of these residual stresses was not taken into account, as previous research (Keerthan, P. and Mahendran, M., 2014) has found that the effect of residual stress on the shear capacity of LCB sections is about 1%.

4.3 FE model validation

Validation of the developed FE models is imperative for non-linear analyses of LCBs with web openings subjected to shear. For this purpose, FE models were developed to simulate 11 shear tests on cold-formed steel specimens of 200x75x15x1.9 LCBs and 160x65x15x1.9 LCBs with unreinforced circular web openings published by Keerthan and Mahendran's (2012) and 7 shear tests on stainless steel LCB specimens published by Ishqy et al. (2019).

Firstly, Non-linear models were analysed, and their results were compared with those from tests, with particular attention given to the ultimate loads, load-deflection curves and failure mechanisms. Table 1 shows the validation results for cold-formed steel beams with circular web openings while Table 2 shows the validation results for cold-formed stainless steel lipped channel sections where d1, d_{wh} and t_w are the clear web height, depth of web opening and web thickness of the section, respectively and f_{yw} and f_u are the yield stress and ultimate stress of the steel grade, respectively.

Table 1: Comparison of ultimate shear capacities of LCBs with circular web openings

No.	**LCB Section**	**As-pect Ratio**	**d_{wh} (mm)**	**d_{wh}/d_1**	**V_{nl} (kN)**		**Test/FEA**
					Test	***FEA***	
1	200x75x15x1.9	1.0	0	0.00	75.80	80.02	0.95
2	200x75x15x1.9	1.0	30	0.15	74.83	76.42	0.98
3	200x75x15x1.9	1.0	60	0.30	63.35	62.93	1.01
4	200x75x15x1.9	1.0	100	0.51	38.83	42.08	0.92
5	200x75x15x1.9	1.0	125	0.63	29.38	29.65	0.99
6	200x75x15x1.9	1.5	0	0.00	63.36	61.30	1.03
7	200x75x15x1.9	1.5	30	0.15	57.09	57.63	0.99
8	200x75x15x1.9	1.5	60	0.30	53.09	54.04	0.98
9	200x75x15x1.9	1.5	100	0.51	37.15	36.23	1.03
10	200x75x15x1.9	1.5	125	0.63	28.82	26.38	1.09
11	160x65x15x1.9	1.0	60	0.38	47.10	49.60	0.95

Tables 1 and 2 show that the FE models were able to predict the ultimate shear capacities of tests with good accuracy. The mean and coefficient of variance (COV) of the results are 1.00 and 0.047 for the cold-formed steel beams with web openings and 0.99 and 0.084, for the cold-formed stainless steel LCB sections. Figure 3 shows the shear failure mode of stainless steel 200×75×15×1.5 LCB section as captured during the experiment and from the corresponding FE model and it depicts a good correspondence and thus further affirm the adequacy of the validated models in predicting the load-deflection curve and failure modes of CFSS LCBs with elliptical web opening

Table 2. Validation results for stainless steel sections

No.	**LCB section**	**d_1 (mm)**	**t_w (mm)**	**f_{yw} (MPa)**	**f_u (MPa)**	**Shear Capacity (kN)**		**Test/ FEA**
						Test	***FEA***	
1	200×75×15×1.2	197.0	1.18	230	540	23.0	22.3	1.03
2	150×65×15×1.2	147.0	1.18	230	540	21.6	19.6	1.10
3	200×75×15×1.5	197.5	1.50	230	240	26.8	28.1	0.96
4	150×65×15×1.5	147.0	1.50	230	540	26.3	27.1	0.97
5	200×75×15×2.0	196.0	1.99	230	540	47.1	47.7	0.99
6	150×65×15×2.0	146.5	1.99	230	540	43.6	40.7	1.07
7	100×50×15×2.0	97.5	1.99	230	540	36.0	34.2	1.05

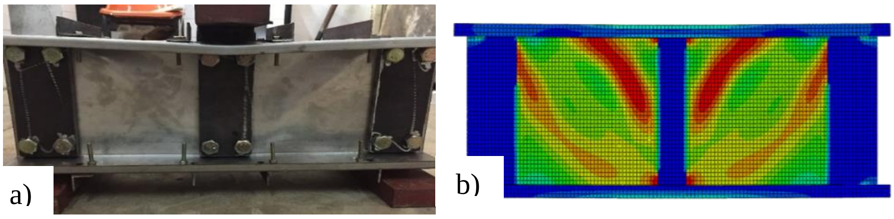


Figure 3: Shear failure mode of 200×75×15×1.5 stainless steel LCB: a) Experiment; b) FE model

4.4 Parametric study and comparison of results with available design rules.

Following the validation of the developed FE models, a detailed parametric study (Total of 72 FEA) was undertaken using the validated model to develop an extensive shear capacity database for CFSS LCBs with unreinforced elliptical web openings. For example, Figure 4 shows the shear failure mode of cold-formed stainless steel 200 x 75 x 15 x 1.5 LCB with 40 x 60 mm elliptical web openings.

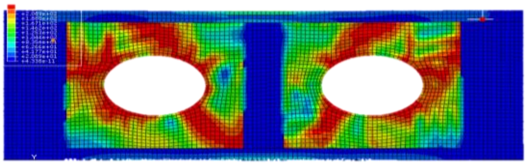


Figure 4: Shear failure mode of CFSS 200 x 75 x 15 x 1.5 LCB with 40x20 mm elliptical web openings

It was then used to evaluate the current design rules and to develop improved design equations. In this study, aspect ratio of 1.0 was used with seven LCB sections, 200x75x15x1.2LCB, 150x65x15x1.2LCB, 200x75x15x1.5LCB, 150x65x15x1.5LCB, 200x75x15x2.0LCB, 150x65x15x2.0LCB and 100x50x15x1.5LCB, to represent the commonly used LCBs. Nominal dimensions (t_w of 1.2 mm, 1.5 mm and 2.0 mm and d1 of 100 mm, 150 mm and 200 mm), yield stress (f_{yw} of 253.9 MPa) and ultimate stress (f_u of 725 MPa) were used in the analyses. The corner radius was assumed to be 2mm in the analyses with the given dimensions taken as centreline dimensions. In this parametric study, web opening depth to clear web height ratio (d_{wh}/d_1) of 0,0.2,0.4,0.6,0.8 and 0.95 and web opening width to height ratio (b_{wh}/d_{wh}) of 0, 0.2, 0.3,0.5,0.7,0.8 and 1.0 are considered. The ultimate shear capacities of CFSS LCB with elliptical opening (V_{nl}) and the corresponding q_s for varying ratios of d_{wh}/d_1 and b_{wh}/d_{wh} were obtained from parametric studies. Further it shows that the q_s having a higher weightage on d_{wh}/d_1 than b_{wh}/d_{wh}.

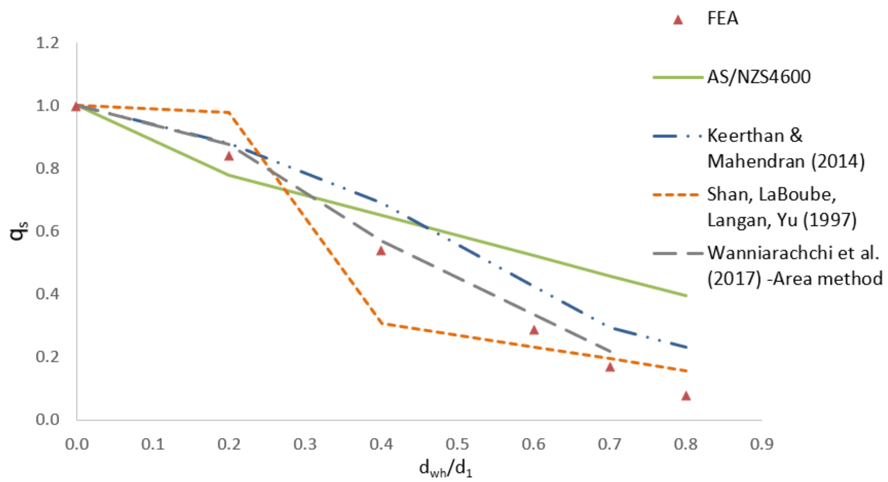


Figure 5: Comparison of shear capacity of stainless steel 150x75x15x2.0 LCBs with circular web openings from FEA with current design equations.

The comparison of shear capacity reduction factors (q_s) from FEA and current design equations shows (see Figure 5) that AS/NZS 4600 and AISI S100 design equations are very conservative for stainless steel lipped channel beam with web opening. Keerthan & Mahendran's (2014) reduction factor equations are unconservative for the opening with d_{wh}/d_1 ratio larger than 0.2. Wanniarachchi et al's (2017) equations to predict the shear capacity of cold-formed normal carbon LCBs with square and rectangular web openings are bit close to the FEA value but unconservative and unable to predict the exact shear capacities of cold-formed stainless steel LCB sections with elliptical web openings. Ishqy et al. (2019) reduction factor equations were produced without including the strength enhancement in the corner regions of CFSS LCB thus it varies by 5% from the FEA results and underestimates the actual shear strength of CFSS LCBs with web openings. Currently there are no shear design equations to predict the shear capacities of cold-formed steel beams with web openings and cold-formed stainless steel beams with web openings in Eurocode 3.

5. Shear design rules for CFSS beams with web openings.

Since the currently available shear capacity reduction factor equations are either conservative or unsafe, new shear design equations are proposed to predict the shear capacity of CFSS LCBs with elliptical web openings based on FEA results. It is proposed that the shear capacity of cold-formed stainless steel LCBs with web openings (V_{nl}) can be calculated using a reduction factor qs applied to the shear capacity of LCBs without web openings (V_v). Shear capacity equations for cold-formed stainless steel LCBs without web openings (V_V) is presented in Eurocode 3 (7) and SEI/ASCE 8-02. In this section, new equations are provided for shear capacity reduction factor (q_s) based on FEA results. Here shear capacity reduction factor (q_s) was proposed as a function of the ratio of the depth of web opening to clear web height (d_{wh}/d_1) and the shape factor defined ratio of depth of the web opening to width of the web opening (d_{wh}/b_{wh}). Equations 13 to 14 show the proposed design equations for cold-formed stainless steel LCBs with elliptical web openings.

Figure 6 shows the non-dimensional curve of qs versus d_{wh}/d_1 for CFSS LCBs with unreinforced elliptical web openings with the shape factor of 1.0 based on the proposed equations (Equations 13 to 15) and compares it with the corresponding FEA shear capacity reduction factors. It illustrates that the shear capacity reduction factors predicted by Equations 13 to 15 agree well with FEA shear capacity reduction factors of CFSS LCB with elliptical web opening.

$$V_{nl} = q_s V_v \quad (13)$$

$$for\ 0.2 > \frac{d_{wh}}{d_1}, \quad \mathrm{q_s} = 1 - 1.941 \times \frac{d_{wh}}{d_1} + 0.333 \times \frac{d_{wh}}{b_{wh}} \quad (14)$$

$$for\ 0.2 \leq \frac{d_{wh}}{d_1} \leq 0.8, \ \mathrm{q_s} = 0.862 - 1.172 \times \frac{d_{wh}}{d_1} + 0.3 \times \frac{d_{wh}}{b_{wh}} \quad (15)$$

The mean of predicted value to FEA value and the coefficient of variation (COV) are 1.003 and 0.0615 respectively. Normally cold-formed steel beams with elliptical web openings are used up to the shape factor of 1.0 in the building industry thus derived equations cover up to the maximum ratio d_{wh}/b_{wh} of 1.0.

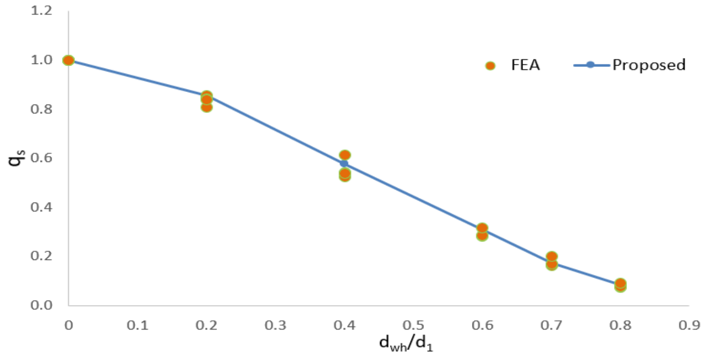


Figure 6: comparison of shear capacity reduction factor q_s versus d_{wh}/d_1 for CFSS LCBs with elliptical web openings with from FEA and proposed.

6. Conclusions

This paper has presented a detailed investigation into the shear behaviour and strength of cold-formed stainless steel LCB with unreinforced elliptical web openings using FEA. FE models of CFSS LCBs with web openings were developed and validated using available shear test results. The developed models predicted the shear capacities and imitated the failure modes with good agreement. Results from numerical analyses showed that the current shear design rules in cold-formed structures design standards are either too conservative or unsafe for stainless steels LCBs. New shear design equations were proposed based on a shear capacity reduction factor using the ratios of web opening height to clear web depth (i.e. d_{wh}/d_1) and web opening height to web opening width (i.e. d_{wh}/b_{wh}) known as shape factor. Hence, the proposed design equations are able to predict the shear capacity of cold-formed stainless steel LCBs with unreinforced elliptical web openings accurately. Further it is evident that the shear capacity of CFSS LCBs with web opening depth factor beyond 0.7 reaches upto 80% of reduction. In order to preclude such detrimental reduction of shear capacity, further shear improvement technique studies are being carried out with stiffened web opening using plate and stud stiffeners.

References

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

American Iron and Steel Institute (AISI) (2012), North American Specification for the Design of Cold-formed Steel Structural Members, AISI, Washington, DC, USA.

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., Gardner, L., 2008. Strength enhancements induced during cold forming of stainless-steel sections 64, 1310–1316.

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.

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.

Ishqy, M.F.M., Wanniarachchi, K.S., Keerthan, P., Gunalan, S. and Corradi, M., 2019. 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

Keerthan, P. & Mahendran, M. 2011b. Numerical Modelling of Lite Steel Beams Subject to Shear. Journal of Structural Engineering, 137, 1428-1439.

Keerthan, P. & Mahendran, M. 2013. Shear buckling characteristics of cold-formed steel channel beams. International Journal of Steel Structures, 13, 385-399.

Keerthan, P. & Mahendran, M. 2015. Experimental investigation and design of lipped channel beams in shear. Thin-Walled Structures, 86, 174-184.

Keerthan, P. and Mahendran, M., 2011a. New design rules for the shear strength of LiteSteel beams. Journal of Constructional Steel Research, 67(6), pp.1050-1063.

Keerthan, P. and Mahendran, M., 2012. New design rules for the shear strength of Lite Steel beams with web openings. Journal of Structural Engineering, 139(5), pp.640-656.

Keerthan, P. and Mahendran, M., 2014. Improved shear design rules for lipped channel beams with web openings. Journal of Constructional Steel Research, 97, pp.127-142.

Keerthan, P., Hughes, D. & Mahendran, M. 2014. Experimental studies of hollow flange channel beams subject to combined bending and shear actions. Thin-Walled Structures, 77, 129-140.

LaBoube, R.A., Yu, W.W., Langan, J.E. and Shan, M.Y., 1997. Cold-formed steel webs with openings: Summary report. Thin-walled structures, 27(1), pp.79-84.

Sonu, J.K. and Singh, K.D., 2017, May. Shear characteristics of Lean Duplex Stainless Steel (LDSS) rectangular hollow beams. In Structures (Vol. 10, pp. 13-29). Elsevier.

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.

Standards Australia/Standards New Zealand (2005), Australia/New Zealand Standard AS/NZS4600 Cold-Formed Steel Structures, Sydney, Australia.

Wanniarachchi, K.S., Mahendran, M. and Keerthan, P., 2017. Shear behaviour and design of Lipped Channel Beams with non-circular web openings. Thin-Walled Structures, 119, pp.83-102.