Northumbria Research Link

Northumbria
University
NEWCASTLE

ICSESM2019-106

FLEXURAL BEHAVIOUR OF OPTIMISED COLD-FORMED STEEL BEAMS WITH SLEEVE STIFFENED WEB OPENINGS

P Gatheeshgar[1*], K Poologanathan[1], S Gunalan[2], KD Tsavdaridis[3], B Nagaratnam[1]

[1]*Faculty of Engineering and Environment, Northumbria University, Newcastle, UK.*
[2]*School of Engineering and Built Environment, Griffith University, Gold Coast, Australia.*
[3]*School of Civil Engineering, Faculty of Engineering and Physical Sciences, University of Leeds, Leeds, UK.*

**Correspondence E-mail: g.perampalam@northumbria.ac.uk*

Abstract: *CFS beams are often provided with web openings to accommodate building services. However, the area reduction in the web affects their load-bearing capacities. The reduction of bending capacity can be regained through providing suitable stiffeners in the vicinity of the web openings and through providing the web openings to the optimised CFS beams. Many research studies have been conducted for the former but no research studies have been reported for the latter. This paper presents an investigation on providing reinforced web openings to optimised CFS beams to restore the original flexural capacity. A computational analysis was carried out. The Finite Element (FE) elements were validated against experimental data from the literature and then used in conducting detailed parametric studies (80 FE models). The influence of the rectangular openings with four different sizes (hole height-to-web depth ratios: 0.2, 0.4, 0.6 and 0.8) and four different sleeve stiffening lengths (5, 10, 15 and 20 mm) on the bending capacity subject to distortional buckling was investigated in the parametric study. The results indicated that introducing web openings to the optmised CFS along with sleeve stiffening arrangement is a satisfactory approach to restore the original bending capacity. In addition, the optimum sleeve length was found and updated direct strength-based design equations are proposed to predict the bending capacity of the CFS beams with sleeve stiffened rectangular web openings subject to distortional buckling.*

Keywords: *Cold-formed steel; Optimised beams; Rectangular web openings; Bending capacity; Distortional buckling; Sleeve stiffener.*

1. Introduction

Cold-Formed Steel (CFS) beams are employed as floor/ceiling joists and roof purlins in light gauge steel and modular building constructions. Discrete web openings are commonly placed in these CFS beams to facilitate the installation of the services (electrical, plumbing and heating conduits). Without these openings, the services need to be placed under the floor joist, which increases the floor depth. Such web openings reduce the ability to withstand the full load due to the substantial reduction of the cross-sectional area. Many research studies have investigated the different load-bearing capacities of CFS beams without web openings under bending, shear, combined bending and shear and web crippling actions (Keerthan and Mahendran, 2013b, Keerthan et al., 2014a, Keerthan and Mahendran, 2015, Sundararajah et al., 2017a, Sundararajah et al., 2017b). However, limited research has been carried out to investigate the influence of the web holes on the load-carrying capacities of CFS beams. Among that notably, researchers have investigated the influenced of web openings in steel members in bending (Moen et al., 2013, Zhao et al., 2019, Tsavdaridis and D'Mello, 2012), shear (Keerthan and Mahendran, 2013a, Keerthan and Mahendran, 2012, Degtyareva et al., 2019), web-post buckling (Tsavdaridis and D'Mello, 2011, Tsavdaridis and Galiatsatos, 2015). The reduction of these capacities due to the discrete web holes present in the CFS beams need to be restored as the member losses the original capacity. This can be achieved using stiffening arrangements around the openings. Even though different types of reinforcing schemes have been proposed through research studies such as plate stiffeners, sleeve stiffeners, transverse stiffeners and stud stiffeners (Mahendran and Keerthan, 2013), the most common application is the sleeve stiffening method (see Figure 1) and to date, no research has been reported to calculate the optimum sleeve stiffener length. Therefore, this study considers the sleeve stiffening method to regain the bending capacity loss.

Figure 1: LCB with sleeve stiffened web openings

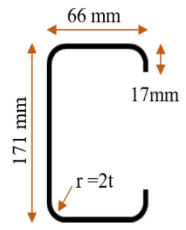
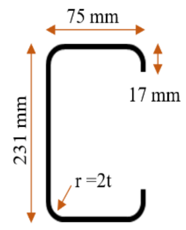
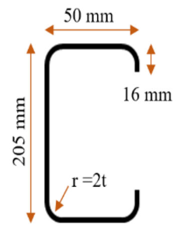
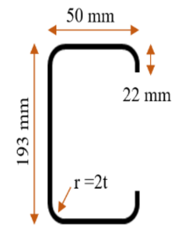
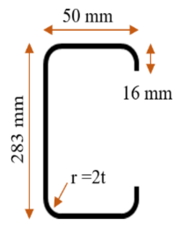
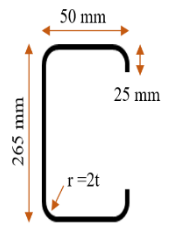
To compensate the bending capacity loss due to the web openings, optimised CFS beams should be employed. The optimisation framework performed in previous research studies (Perampalam et al., 2019, Ye et al., 2016) showed up to 30 % of the capacity enhancement compared with the available standard section Lipped Channel Beams (LCBs) using the same amount of material. Therefore, it is suggested to use web openings with the optimised CFS sections and balance the capacity loss. No research has been performed up to date on this subject area.

Consequently, this study explores the concept of providing web openings to the optimised LCBs along with the sleeve stiffening reinforcing scheme. A computational investigation was carried out and the developed FE models were validated against available test data. Subsequently, parametric studies were performed including different rectangular opening sizes, sleeve stiffening length, and CFS channel coil lengths. The benefits of using optimised LCBs together with rectangular web openings were captured. Moreover, Direct Strength Method (DSM) based design equations were proposed to predict the flexural capacity of the CFS LCBs with rectangular web openings and sleeve stiffeners.

2. Optimised LCB channels and web openings

The optimisation of CFS beams has resulted substantial bending capacity enhancements and it has been identified that with the same amount of material usage, up to 30 % of bending capacity can be achieved for LCB sections compare to the standard LCB sections (Perampalam et al., 2019, Ye et al., 2016). In this study, two commercially available standard sections having 337 mm and 415 mm coil lengths (L) with 1mm and 2 mm thicknesses (t) were selected for the optimisation (see Table 1). The optimisation was performed using the particle swarm optimisation algorithm through developing section moment capacity equations. During the optimisation, the coil length was maintained constant and practical, and manufacturing constraints were applied to ensure the optimised sections applicable. The change in LCB dimensions was noticed during the optimisation, when the thickness changes. Also, negligible change in the dimensions was noticed when the yield strength (F_y) changes from 350 MPa to 550 MPa. F_y=450 MPa was considered in this study. The lower bound of the flange width and lip length was set to be 50 mm and 15 mm, respectively. Table 1 also provides the optimised dimensions and corresponding bending capacities obtained from FE analysis in terms of percentage. Subsequently, the rectangular web openings were provided to the optimised LCBs with varying web opening height and a constant opening width of 150 mm. The web openings were analysed with and without sleeve stiffeners around the web opening edges.

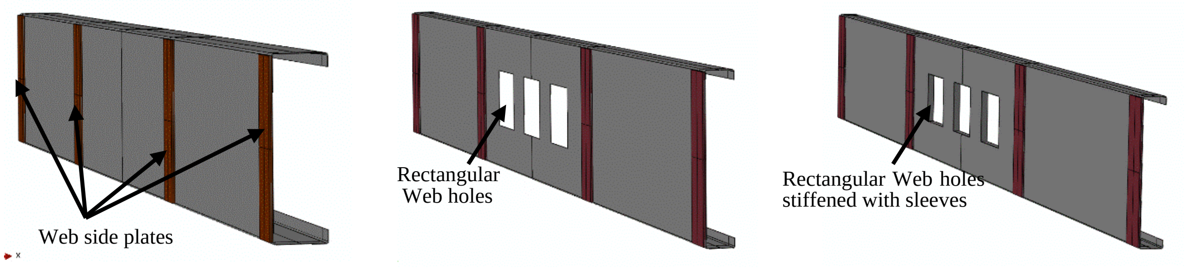
Table 1: Available CFS sections and optimised dimensions for bending

Available Sections		**Optimised dimensions**			
L = 337 mm (t = 1, 2 mm)	L = 415 mm (t = 1, 2 mm)	L = 337 mm		L = 415 mm	
		t = 1 mm	t = 2 mm	t = 1 mm	t = 2 mm
					
$M_{bd(1mm)}$ = 4.87 kNm $M_{bd(2mm)}$=15.58kNm	$M_{bd(1mm)}$=6.93kNm $M_{bd(2mm)}$=22.09kNm	M_{bd} = 6.04 kNm (24 %)	M_{bd} = 16.74 kNm (8 %)	M_{bd} = 8.77 kNm (27 %)	M_{bd} = 26.76 kNm (21 %)

3. Non-linear FE analysis of LCBs with web openings

3.1 General

This section presents brief information on the FE model development process. A commercially available, advanced FE modelling software ABAQUS version 2017 was used for the analysis. FE models of LCB sections were developed as a four-point bending set-up with simply supported boundary conditions. This arrangement ensures the pure bending failure at the mid span with the absence of the shear stress. The four-point loading set-up has total span of 2600 mm and the mid-span is 1000 mm. The load and support conditions were provided through attaching 70 mm wide and 5mm thick web side plates. The rectangular openings were located in the pure bending region of the model to ensure the effect on the bending capacity. Figure 2 shows the schematic diagram of the considered LCB sections with and without web openings, and with sleeve stiffened web openings.



(a) Solid web (b) Web openings (c) Stiffened web openings

Figure 2: Schematic diagram of the FE models

3.2 Material Model

The CFS material was considered as perfect plasticity model due to the negligible strain hardening behaviour. The FE models were developed with yield strength of 450 MPa, modulus of elasticity of 210 GPa and Poisson's ratio of 0.3. To ensure no failure to occur in web side plates the yield strength of the web side plates (see Figure 2) was taken as three times of the yield strength of the LCB channels. The residual stresses and corner strength enhancements were not incorporated into the FE models as both counteract each other (Schafer et al., 2010).

3.3 Element selection and mesh control

S4R shell element, an isoperimetric quadrilateral shell with four nodes and five degrees of freedom per node and has reduced integration, was used in FE models. Paying attention towards the accuracy and the computational time, 5 mm × 5 mm mesh size was selected for the flat regions of the FE models

(Keerthan and Mahendran, 2011) while finer mesh size of 1 mm × 5 mm was used at the round corners. However, the web side plates were refined with 10 mm × 10 mm mesh size. Figure 3 illustrates the provided mesh refinements of the FE models.

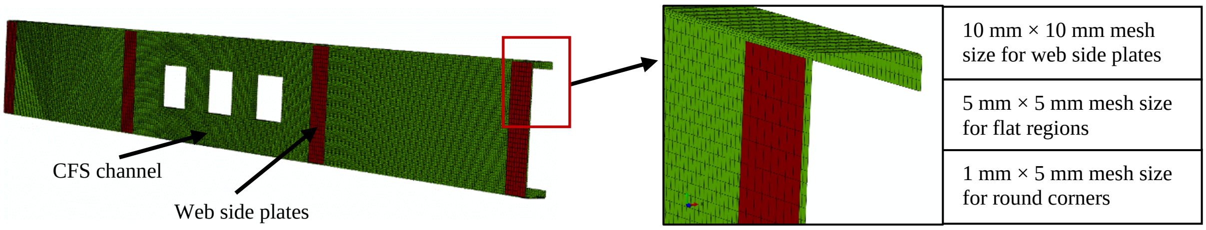


Figure 3: Mesh refinements of FE models

3.4 Load and boundary conditions

Simply supported boundary conditions were provided to the models at the centre of the web side plates which are attached to the LCB model with 'tie' constraints. The load was applied through displacement control approach at two middle web side plates (see Figure 4). Straps were simulated as boundary conditions only at the loading and support points at the top and bottom flanges. No straps were provided in the middle span as the scope of this study is to calculate the bending capacity subject to distortional buckling. Similar straps arrangement also employed in past studies (Pham and Hancock, 2013) for distortional buckling tests.

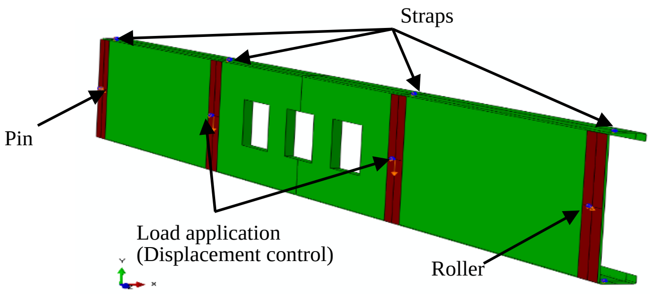


Figure 4: Boundary conditions for the FE models

3.5 Analysis procedure

Both linear and non-linear buckling analysis were performed. The buckling analysis was performed to incorporate the initial geometrical imperfection shape and magnitude in the non-linear analysis. The lowest buckling mode was considered as the initial imperfection shape and imperfection magnitude was taken as 0.64t (t = thickness of the CFS channel) (Schafer and Pekoz, 1998). The non-linear analysis was used to obtain the accurate ultimate bending capacity of the LCBs subject to distortional buckling due to the ability to account for the material yielding and large deformations. The parameters used in the non-linear static analysis were selected according to (Keerthan et al., 2014b).

3.6 Validation of the FE models

The aforementioned FE model characteristics were verified against the experimental results (Pham and Hancock, 2013) of six distortional buckling tests on LCB channels. The comparison of the ultimate bending capacities obtained from the test and FE models are presented in Table 2. The validation process for the six specimens resulted mean and Coefficient of Variation (COV) values of 1.04 and 0.09, respectively. These values demonstrate a satisfactory agreement. Figure 5 depicts the load-displacement behaviour and failure mode comparison obtained from test and FE analysis. It can be seen that the load-displacement between test and FE is consistent and predicts the ultimate bending capacity with good agreement. Figure 5 also shows a different post-failure behaviour between test and FE model. However, this variation likely to be not taken into consideration as design of the CFS beams is based on ultimate bending capacity. Also, the failure modes between FE analysis and experiments are very similar. Therefore, the elaborated FE models are suitable to predict and assess the flexural behaviour of LCBs with web openings.

Table 2: Verification of the FE models against the test results (Pham and Hancock, 2013)

Specimen	**Web/ (mm)**	**Flange / (mm)**	**Lip /(mm)**	**Thickness / (mm)**	**Yield strength/(MPa)**	**Test / (kN)**	**FE / (kN)**	**Test/ FE**
Mw_C15015	152.70	64.77	16.57	1.50	541.1	9.47	9.28	1.02
Mw_C15019	153.38	64.47	16.00	1.90	534.5	12.90	14.55	0.89
Mw_C15024	152.60	62.70	19.70	2.40	485.3	17.96	16.71	1.07
Mw_C20015	203.70	76.08	16.42	1.50	513.4	12.20	12.60	0.97
Mw_C20019	202.60	77.92	17.28	1.90	510.5	18.85	21.77	0.87
Mw_C20024	202.35	76.61	20.38	2.40	483.5	27.88	26.72	1.04
Mean								1.04
COV								0.09

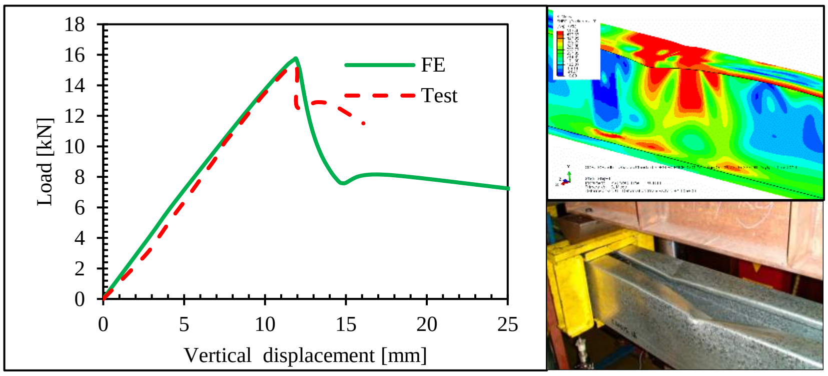


Figure 5: Load-vertical displacement behaviour and failure mode comparison of Mw_C20015 (Pham and Hancock, 2013)

4. Parametric studies

The coil lengths, thickness, opening height-to-web depth ration, and length of the sleeve stiffener were varied in this parametric study. The varying parameters are presented in Table 3. In total 80 FE models were developed. The parametric study models are labelled as Coil length ("337" or "415" mm); Optimised or Standard section ("O/S"); Thickness ("1/2" mm); Opening height to web depth ratio ("0.2/0.4/0.6/0.8"); Sleeve length ("0/5/10/15/20").

Table 3: Details of the parametric study plan

Coil length/ (mm)	**Thickness/ (mm)**	**Hole height/ Web depth**	**Sleeve length / (mm)**	**Number of Models**
337	1, 2	0.2, 0.4, 0.6, 0.8	0, 5, 10, 15, 20	40
415	1, 2	0.2, 0.4, 0.6, 0.8	0, 5, 10, 15, 20	40
Total				**80**

5. Results

The effectiveness of providing rectangular stiffened and unstiffened web openings to the optimised channels was investigated through 80 FE models. The bending capacity of the 80 FE models was compared with the corresponding standard LCB sections. The parametric study results for the optimised LCB with 415 mm coil length and 1 mm thickness are presented in Table 4. Figure 6 shows the bending failure mode obtained for the 337 mm coil length LCBs on various occasions. Overall, it can be noticed that providing rectangular web openings, the optimised channel is capable of regaining the bending capacity loss with less amount of material usage compared to the standard LCB sections. In addition, the sleeve stiffening arrangement raises the bending capacity substantially beyond the original capacity of the standards sections. For example, 415-O-1-0.2-20 specimen resulted a 44% of the enhanced bending capacity compare to its corresponding standard section with approximately same amount of material

(3% less). However, for larger web openings and for the 2 mm thickness sections the sleeve stiffeners were unable to regain the original capacity as these large web openings have caused up to 30% of bending capacity reduction (see Figure 7a). From the parametric study, it has been concluded that 15 mm would be the optimum sleeve stiffening length as excessive sleeve length subjects to buckling and results in reduction of bending capacity (see Figure 7b).

Table 4: Parametric study results for the optimised LCB (coil length=415 mm and thickness=1 mm)

FE Model	M (kNm)	M/M_s	M/M_o	A%	FE Model	M (kNm)	M/M_s	M/M_o	A%
415-O-1-0.2-0	8.66	1.25	0.99	100	415-O-1-0.6-0	8.41	1.21	0.96	100
415-O-1-0.2-5	8.8	1.27	1.00	76	415-O-1-0.6-5	8.8	1.27	1.00	87
415-O-1-0.2-10	9.85	1.42	1.12	51	415-O-1-0.6-10	8.8	1.27	1.00	75
415-O-1-0.2-15	9.73	1.40	1.11	27	415-O-1-0.6-15	8.85	1.28	1.01	62
415-O-1-0.2-20	9.96	1.44	1.14	3	415-O-1-0.6-20	8.96	1.29	1.02	50
415-O-1-0.4-0	8.65	1.25	0.99	100	415-O-1-0.8-0	7.34	1.06	0.84	100
415-O-1-0.4-5	8.86	1.28	1.01	84	415-O-1-0.8-5	8.28	1.19	0.94	89
415-O-1-0.4-10	8.91	1.29	1.02	69	415-O-1-0.8-10	8.69	1.25	0.99	78
415-O-1-0.4-15	8.95	1.29	1.02	53	415-O-1-0.8-15	8.81	1.27	1.00	67
415-O-1-0.4-20	8.96	1.29	1.02	38	415-O-1-0.8-20	8.84	1.28	1.01	56

Note: M = Bending capacity with unstiffened and stiffened openings; M_s=Bending capacity of the corresponding standard sections; M_o=Bending capacity of the optimised sections; A% = Reduction in web area reference to the opening size.

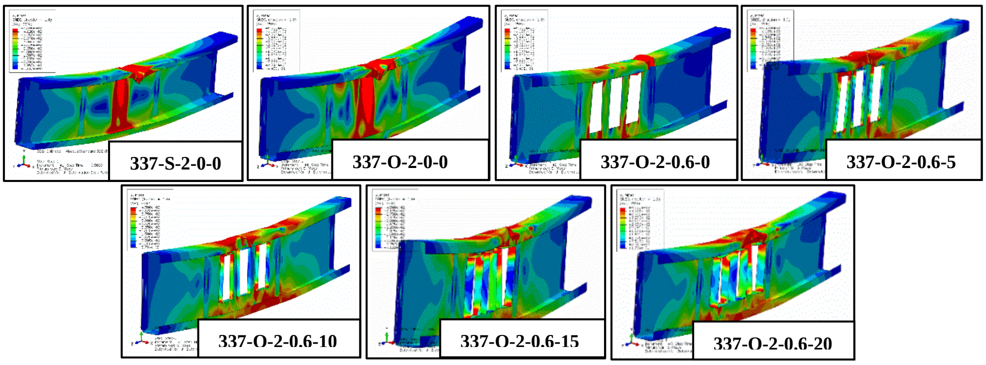
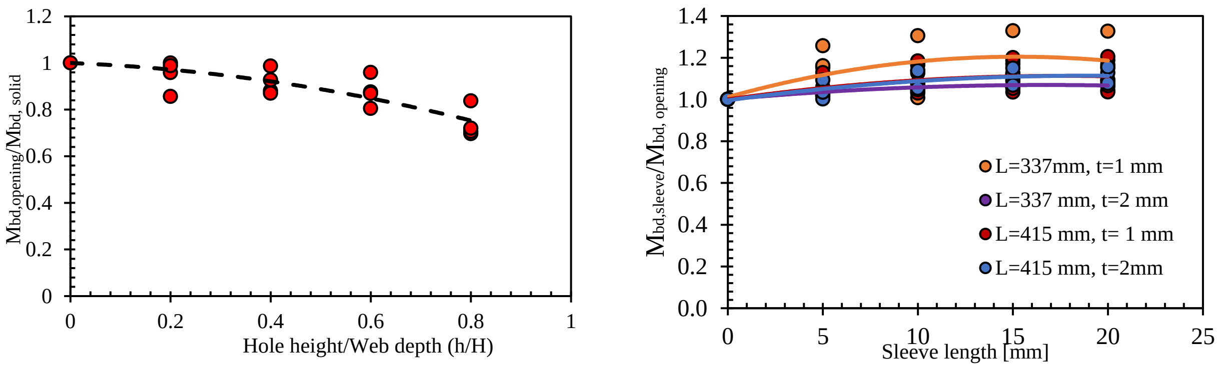


Figure 6: Distortional buckling failure modes of LCBs with 2 mm thickness and 337 mm coil length



(a) Rectangular opening size (b) Sleeve length

Figure 7: Effect of sleeve length and web opening size on the bending capacity

6. Proposed design equations

With the generated wide range of bending capacity results database, the available DSM based design equations are extended to cover the different sleeve stiffening lengths. DSM equations for the distortional buckling of CFS beams provided in AS/NZ 4600 and AISI S100 are given in Eq. (1) to (2).

For $\lambda_d \leq 0.673,$ $$M_{bd} = M_y + \left[1 - \frac{1}{C_{yd}^2}\right](M_p - M_y) \quad (1)$$

$$\text{For } \lambda_d > 0.673, \qquad M_{bd} = \left[1 - 0.22\left(\frac{M_{od}}{M_y}\right)^{0.5}\right]\left(\frac{M_{od}}{M_y}\right)^{0.5} M_y \tag{2}$$

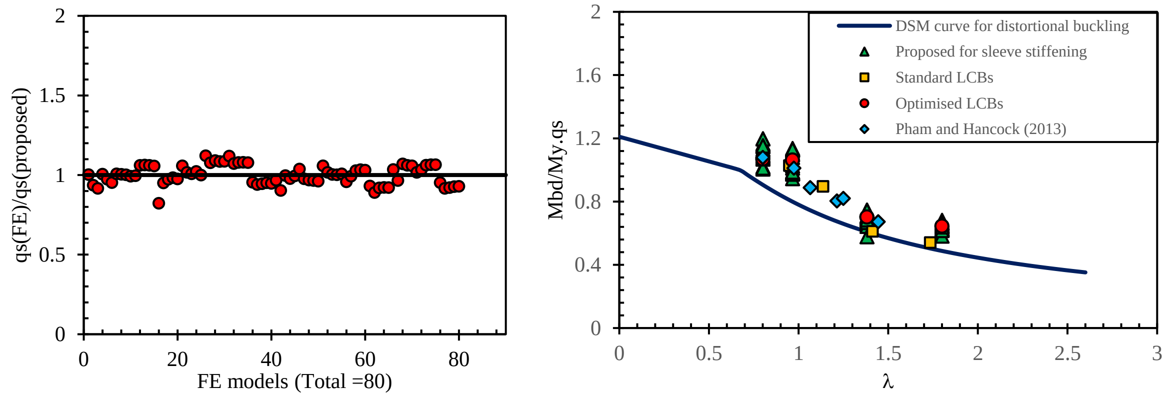
Where M_{bd} = ultimate bending capacity for distortional buckling, $\lambda_d = \sqrt{M_y/M_{od}}$ = non-dimensional slenderness, M_y = yielding moment, M_{od} = elastic distortional buckling moment, M_p = plastic moment and $c_{yd} = \sqrt{0.673/\lambda_d} \leq 3$. These equations are only applicable for the solid web LCBs. AISI S100 and AS/NZ 4600 provide DSM based design guidelines to predict the ultimate bending capacity of the CFS beams with rectangular web holes. However, there are no design provisions provided for sleeve stiffened rectangular web openings. Therefore, a simple approach is developing a reduction factor (q_s) as a function of influencing parameters such that the ultimate bending capacity of LCBs with sleeve stiffened rectangular web openings ($M_{bd,\,sleeve}$) can calculate from its corresponding solid web LCB's capacity (M_{bd}) as given in Eq. (3)

$$M_{bd,sleeve} = M_{bd} \times q_s \tag{3}$$

Where M_{bd} can be calculated from Eq. (1)-(2) and q_s can be calculated from Eq. (4). Eq. (4) was developed based on the parametric study results of 80 FE models with different influencing parameters (H=web height, h=opening height, H_l=lip length, H_f=flange width, s= sleeve length, t=thickness). The equation for q_s was developed and optimised through the classic genetic algorithm and using generalised reduced gradient solving method. The optimisation resulted in mean and COV values of 1.00 and 0.06, respectively.

$$q_s = \left\{1 - \frac{\left[\frac{h}{H}\right]^{0.112}\left[\frac{H_l}{H_f}\right]^{0.103}}{\left[\frac{H}{t}\right]^{0.084}}\right\} \times \left\{1 + \left[0.049 + \left(\frac{s}{t}\right)\right]^{0.037}\right\} \tag{4}$$

Figure 8a shows the comparison of the reduction factor obtained from the FE analysis and proposed equation and Figure 8b shows the bending capacity prediction of the LCBs sleeve stiffened rectangular web openings subject to distortional buckling using modified DSM equations. In this study, the width of the opening was maintained to 150 mm and yield strength was considered as 450 MPa. Further extensive studies are required to enlarge the application of the proposed DSM equations.



(a) Accuracy of the proposed q_s (b) 80 FE models in DSM plot

Figure 8: Proposed new design equations

7. Concluding remarks

This research highlights the effectiveness of providing web openings to the optimised CFS LCBs. First, the standard LCBs were optimised and up to 25% of bending capacity enhancement was achieved with the same amount of steel material. Four sizes of the rectangular web openings along with four different sleeve stiffener lengths were introduced to the optimised LCBs and capacity reduction and regaining ability was investigated through developing 80 FE models. From the FE analysis, it was found that proving the web openings to the optimised section is a good option as the capacity is enhanced already with the optimisation and thus compensates the bending capacity loss due to the opening. However, despite using large web opening sizes, the full capacity is gained back with the sleeve stiffeners. In addition, stiffening length of 15 mm was identified as the optimum sleeve and updated DSM based design equations were proposed to predict the bending capacity of the LCBs with sleeve stiffened rectangular web opening subject to distortional buckling.

Acknowledgements

The authors of this paper would like to acknowledge Northumbria University and MMC Engineer Ltd for their technical and financial support.

References

American Iron and Steel Institute (AISI), 2016. Specifications for the cold-formed steel structural members, cold-formed steel design manual, AISI S100, Washington DC, USA.

Standards Australia, AS/NZS 4600, 2018. Cold-formed steel structures. Sydney, Australia.

Degtyareva, N., Gatheeshgar, P., Poologanathan, K., Gunalan, S., Lawson, M. & Sunday, P. 2019. Combined bending and shear behaviour of slotted perforated steel channels: Numerical studies. *Journal of Constructional Steel Research,* 161**,** 369-384.

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

Keerthan, P. & Mahendran, M. 2011. Numerical Modeling of LiteSteel Beams Subject to Shear. *Journal of Structural Engineering,* 137**,** 1428-1439.

Keerthan, P. & Mahendran, M. 2012. Shear behaviour and strength of litesteel beams with web openings. *Advances in Structural Engineering,* 15**,** 171-184.

Keerthan, P. & Mahendran, M. 2013a. Experimental studies of the shear behaviour and strength of lipped channel beams with web openings. *Thin-Walled Structures,* 73**,** 131-144.

Keerthan, P. & Mahendran, M. 2013b. 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., Mahendran, M. & HUGHES, D. 2014b. Numerical studies and design of hollow flange channel beams subject to combined bending and shear actions. *Engineering Structures,* 75**,** 197-212.

Mahendran, M. & Keerthan, P. 2013. Experimental studies of the shear behavior and strength of LiteSteel beams with stiffened web openings. *Engineering Structures,* 49**,** 840-854.

Moen, C. D., Schudlich, A. & Von Der Heyden, A. 2013. Experiments on Cold-Formed Steel C-Section Joists with Unstiffened Web Holes. *Journal of Structural Engineering,* 139**,** 695-704.

Perampalam, G., Poologanathan, K., Gunalan, S., Ye, J. & Nagaratnam, B. 2019. Optimum Design of Cold-formed Steel Beams: Particle Swarm Optimisation and Numerical Analysis. *ce/papers,* 3**,** 205-210.

Pham, C. H. & Hancock, G. J. 2013. Experimental Investigation and Direct Strength Design of High-Strength, Complex C-Sections in Pure Bending. *Journal of Structural Engineering,* 139**,** 1842-1852.

Schafer, B. W., Li, Z. & Moen, C. D. 2010. Computational modeling of cold-formed steel. *Thin-Walled Structures,* 48**,** 752-762.

Schafer, B. W. & Pekoz, T. 1998. Computational modeling of cold-formed steel: characterizing geometric imperfections and residual stresses. *Journal of Constructional Steel Research,* 47**,** 193-210.

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

Tsavdaridis, K. D. & D'Mello, C. 2011. Web buckling study of the behaviour and strength of perforated steel beams with different novel web opening shapes. *Journal of Constructional Steel Research,* 67**,** 1605-1620.

Tsavdaridis, K. D. & D’Mello, C. 2012. Vierendeel Bending Study of Perforated Steel Beams with Various Novel Web Opening Shapes through Nonlinear Finite-Element Analyses. *Journal of Structural Engineering,* 138**,** 1214-1230.

Tsavdaridis, K. D. & Galiatsatos, G. 2015. Assessment of cellular beams with transverse stiffeners and closely spaced web openings. *Thin-Walled Structures,* 94**,** 636-650.

Ye, J., Hajirasouliha, I., Becque, J. & Pilakoutas, K. 2016. Development of more efficient cold-formed steel channel sections in bending. *Thin-Walled Structures,* 101**,** 1-13.

Zhao, J., Sun, K., Yu, C. & Wang, J. 2019. Tests and direct strength design on cold-formed steel channel beams with web holes. *Engineering Structures,* 184**,** 434-446.