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Performance of Cold-Formed Steel Channel Beams with Web Openings under Pure Bending

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ABSTRACT: *The aim of this paper is to investigate numerically the flexural behavior of cold-formed channel beams with web openings. A nonlinear finite element model (FEM) for cold-formed channel beam was verified against experimental test and showed a good agreement with experimental results in term of ultimate load capacity, load-deflection curves and failure mode results. Based on the verified model several configurations of web openings were analyzed. The numerical results clarified that, there is no significant effects in the load capacity of beams when the hole diameter-to-web depth ratio (dh/hw) is up to 0.5. However, the load capacity is obviously decreased when (dh/hw) further increases up to 0.8. Lastly, a parametric study was carried out to emphasize which size of openings gives best performance during loading.*

KEYWORDS: *Cold-formed steel; Finite Element Analysis; Lipped channel-section; Web openings.*

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I. INTRODUCTION

In the recent years the cold formed steel (CFS) beams became widely used in the residential and industrial buildings as purlins, bracing and girts. In order to allow building services such as electric wiring, fire and heating systems access through cold formed steel beams to preserve the floor height of these buildings to a minimum, web openings need to be inserting to the beam during the manufacture process. Consequently, studying the structural behavior of cold formed steel channels with web openings is crucial problem. Appropriate use of web openings can enhance the aesthetic appeal and improve the constructional efficiency of CFS beam systems.

The openings which placed in the webs of cold-formed steel channel beams and columns have clear effects on the failure modes and moment capacities of these structural members. A number of researchers such as Yu and Davis [1], Oritz-Colberg [2], Shanmugam et al. [3,4] and Loov [5] successively conducted numerous experimental and theoretical investigations on the failure modes and moment capacities of stub columns, medium long columns and long columns with web holes in recent decades. Moen and Schafer [6,7] carried out a series of tests and finite element analyses (FEA) on cold-formed steel channel columns with web holes, and the DSM was extended to perforated compression members.

Up to now, there are few reports about the investigations on cold formed steel channel beams with web holes. In 2012, Yu [8] conducted numerous finite element analyses on cold-formed steel C-section beams with edge stiffened circular web holes to study on the stability behaviors of such beams. In 2015 and 2017, Wang et al. [9,10] performed a number of experimental investigations and numerical studies on cold formed steel built-up section beams with circular web holes to investigate the flexural behaviors and the design method of this kind of beams. Therefore, this study focuses on different failure modes of cold formed steel channel beams with mid span circular web opening and the effects of opening height-to-web depth ratio on moment capacities. The tests of cold formed steel lipped channel beams with various circular opening heights were conducted under four-point bending. The finite element model (FEM) validated by tests were utilized to carry out numerous parametric analyses and the analysis results were verified against experimental test and showed the best openings size range to use.

II. NUMERICAL APPROACHES

Finite Element Model (FEM)

The finite element program ABAQUS [11] was used to simulate the behavior and strength of CFS beams under flexural loading and perform nonlinear analysis of Beam C (Figure 1) subjected to two- point load. The finite element models were initially verified by comparing with a representative experimental data on simply-supported CFS single beam four-point bending test from L. Liam et al. [12] and were subsequently used for parametric studies to investigate the influence of the opening size on the flexural behavior of the beams. The CFS beam section used for initial verification was modelled based on the measured cross-section dimensions of tested specimens reported by test from L. Liam et al. [12] is presented in Table 1.

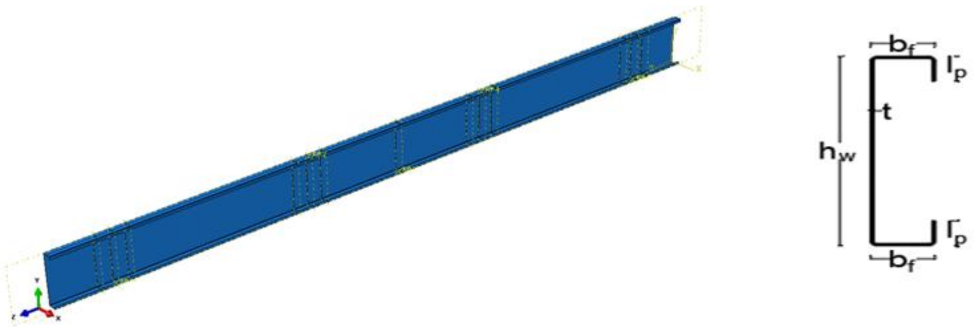


Figure 1. Cross-section of beam C [12].

Table 1. Cross-section dimensions (L. Liam et al. [12]).

Specimen	h_w (mm)	b_f (mm)	l_p (mm)	t (mm)	r (mm)
Beam (B-C)	250	43	15	2.5	2

Element type

All cold-formed steel beams were modelled by using four-noded shell element S4R with six (three translational and three rotational) degrees of freedom for each node with the reduced integration for the profiles. The (S4R) element was chosen because it is a general-purpose shell element from the ABAQUS program library. It also takes transverse shear deformation into account as well as the thick shell elements. However, the S4R element uses a mixed finite element formulation as it can be seen in detail in the ABAQUS Theory Manual [11]. Moreover, many researchers in this area often use this type of element in their numerical analyses.

III. MATERIAL MODEL

Von-misses yield criterion with isotropic strain hardening was used to model the material nonlinearity of the CFS. The material properties used in the analysis were defined based on the stress-strain results of the coupon tests given from L. Liam et al. [12] is presented in Table 1. The behavior was defined as a quadrilinear curve (gradual yielding behavior) as shown in Figure 2. The adopted values for E1, E2 and E3 were respectively 38, 10 and 0.5% of the elastic modulus. It should be mentioned that these material properties were used for both the flat portions and the fillet corners of the sections in this analysis.

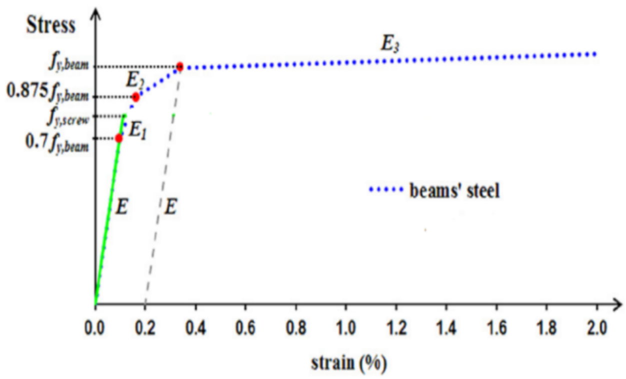


Figure 2. Stress-strain relationship of the beam material [12].

Table 2. Material properties of FEM (L. Liam et al. [12]).

Specimen	E (GPa)	σ_y (MPa)	σ_u (MPa)
Beam (B-C)	208	295	412

Finite element mesh

Firstly, the influence of the finite element size on the behavior of cold-formed steel beams was studied. It was found that by using finite element meshes of 5×5 mm, 10×10 mm or 20×20 mm good simulations results could be obtained as shown in (figure 3), but 5×5 mm finite element meshes size takes a lot of time to complete analysis and 20×20 mm finite element meshes size don't give the accuracy which we get from 10×10 mm finite element meshes size. Considering both the accuracy and time-efficiency of FEM analysis, finite element meshes size of 10×10 mm (length by width) were used in all simulations by the ABAQUS program in flat portions, and it should be mentioned that finer mesh sizes were used at the round corners of the beam section, as shown in fig 3.a.

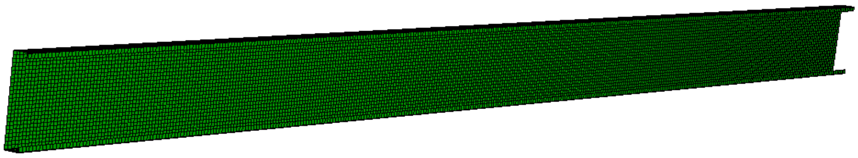


Figure 3. (a) Finite element (FE) mech10×10 mm

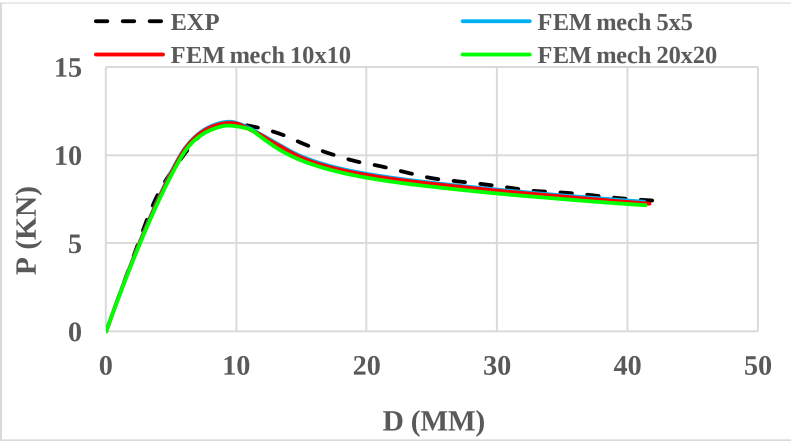


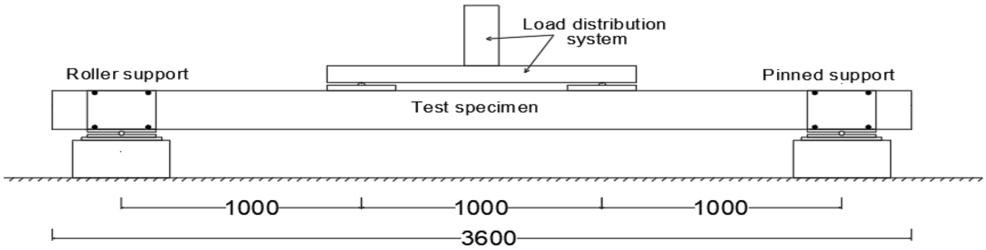
Figure 3. (b) Comparison the FEA load-displacement curves with the experimental results.

Loading and boundary conditions

Coupling constraint was used to simulate the two-point load application in the test set-up, in which the load can be uniformly distributed over the loading area through a single point. The load was applied in a static ricks step to the node sets at two loading points using displacement control with a specified displacement value, and it should be mentioned that this value must be larger than the measured maximum deflection which obtained from the experimental results to ensure that the FEM can reach the ultimate load. The simply supported boundary condition was applied to models by controlling the displacements of nodes at the bottom of end load transfer area by releasing the in-plane rotation at the hinged supported (pin support) and releasing both the in-plane rotation and axial displacement along the beam at roller support.

IV. EXPERMINTAL EVIDANCE

The experimental test on CFS beams had been conducted in Testing Materials and Structures lab of the University of Coimbra (UC), in Portugal [12]. The experimental study consisted of 12 quasi-static bending tests at ambient temperature. This test had been made to study the flexural behavior of different CFS cross-sections. In order to investigate the influence of the thickness, height and length of the beams on its structural behavior several four-point bending test were carried out. Tested beams consisted of one or more CFS profiles. All these profiles had the same nominal thickness (2.5mm), nominal flange width (43mm) and inside bend radius (2mm). The nominal depth was (250mm) and the edge stiffeners of section profiles were (15mm), as shown in Figure 4. The total beam length was 3.6 m, but the supporting span was only 3.00 m. The beams were loaded by two-point loads at the middle third of the supporting span (four-point bending) as shown in Figure 4. The test results of beam C is given 11.72 KN as ultimate load and The load deflection curves is used to verify the numerical model.



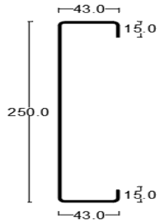


Figure 4. Scheme of the experimental set-up for bending tests. [11] **Beam C**

VERIFICATION OF FINITE ELEMENT MODEL

The results of developed FEM were verified against the published experimental results by L. Liam et al. [12]. The load-displacement predicted by finite element analysis (FEA) was compared with the test result, as shown in Figure 5. The mean value of the experimental-to-FEA load capacity (PEXP /PFEA) ratio was 0.99, it can be seen in table 3. The failure mode of the beam C obtained from FE analysis compared with the test. For local-distortional buckling, a good agreement can be seen between the experimental and FEA results, as shown in Fig. 6. The ultimate load and failure mode comparisons show the FEM closely predicted the behavior of CFS beam C subjected to pure bending.

Table 3. Comparison of Experimental and FEA Ultimate Moment Capacities.

Specimen	P_{EXP} (KN)	P_{FEM} (KN)	P_{EXP}/P_{FEM}
Beam (B-C)	11.72	11.82	0.99

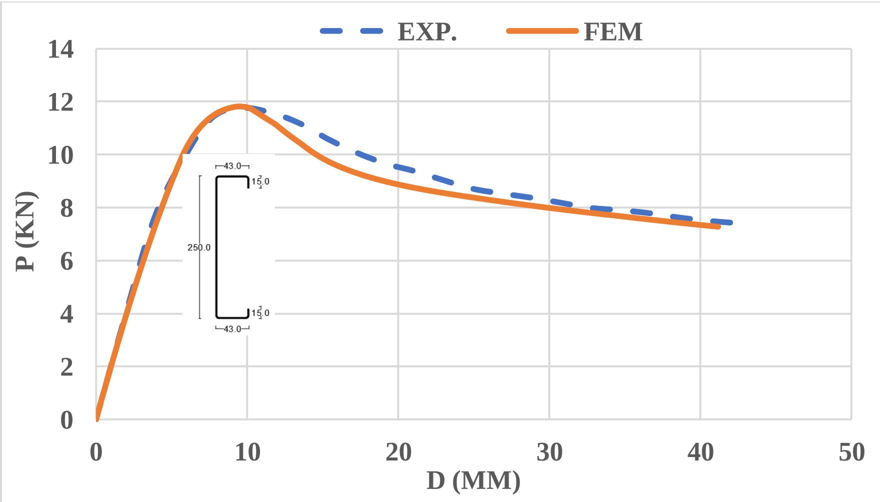
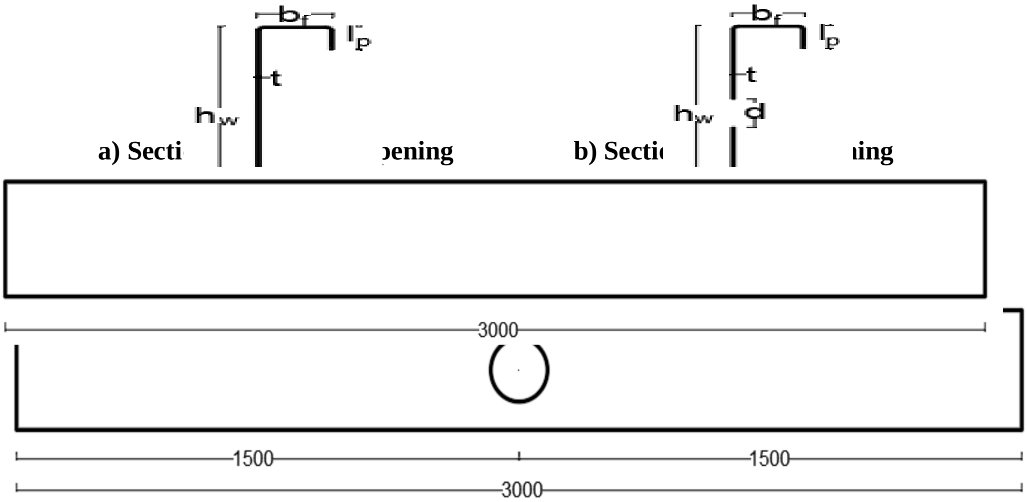


Figure 5. Comparison the FEA load-displacement curve with the experimental results.

Figure 6. Comparison the FEA failure mode with the experimental results [12].

PARAMETRIC STUDY

Based on the validated model, FE parametric analyses on perforated cold-formed steel channel beams with various sizes of web openings. The openings diameter-to-web height ratio varies from 0.2 to 0.8 corresponding to test specimens. Yield strength fy= 295 MPa, Young's modulus E= 2.08 × 105 MPa and Poisson ratioν=0.3 were used in the FE parametric analyses. The FE models cross-sections dimensions are summarized in Table 4, where $h\,w$ is the web height, bf is the flange width and lp is the perpendicular lip length, ($r = d\ h\,w$) is the ratio between (d=diameter) opening size and ($h\,w$) web height. The nominal thickness of all sections is 2.5 mm. The beams were labelled in such a way to identify the ratio between opening size and web height of specimens. For example, a specimen labelled as (B-C) is mean a solid beam C without opening and a specimen which labelled as (B-C 0.3) is mean beam C with opening which ratio between opening size and web height is 0.3. All of FE beam specimens were modelled for a length of 3600 mm with constant moment span of 1000 mm, as shown in Figure 7.



Beam Cr with web opening

Figure 7. Proposed C-sections types to FEM

Table 4 shown cross -sections dimensions of FE beams, and the numerical maximum load for each beam. The last column in the table give load reduction ratio in beams with web opening to the solid beam C which shown in Figure 8, to compare between them.

Table 4: Finite element beams cross-sections dimensions and max. load.

Section	h_w mm	b_f mm	l_p mm	d mm	$r = \frac{d}{h_w}$	Max. load P_{Max} (KN)	Load reduction Δ%
B-C	250	43	15	----	----	11.82	----
B-C 0.1	250	43	15	25	0.1	11.81	0.085%
B-C 0.2	250	43	15	50	0.2	11.80	0.17%
B-C 0.3	250	43	15	75	0.3	11.78	0.33%
B-C 0.4	250	43	15	100	0.4	11.70	1.02%
B-C 0.5	250	43	15	125	0.5	11.47	3.00%
B-C 0.6	250	43	15	150	0.6	11.07	6.35%
B-C 0.7	250	43	15	175	0.7	10.47	11.42%
B-C 0.8	250	43	15	200	0.8	9.56	19.12%

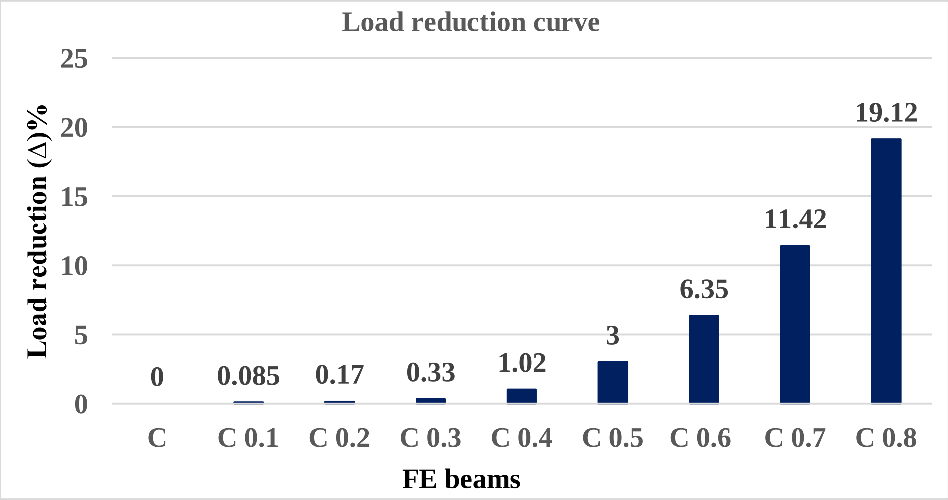


Figure 8. Load reduction curve for FE specimens.

$$- \Delta = \frac{(P_{max_c}) - (P_{max})}{(P_{max_c})} * 100\%$$

- (P_{max_c}) = **Maximume load of beam (B-C)**

V. RESULTS AND DISCUSSION

FE model provided a good correlation of the load-deflection curve all over the loading history for the solid beam C (B-C) as shown before in Figure 5. Moreover, the numerical failure mode was also comparable to the experimental failure mode during the FE parametric analyses, it was found that tested beams failed by local-distortional buckling interaction, as shown in Figure 9. This ensures reliable results obtained for the parametric study. Figure 10, shows a comparison among the beam sections with openings height-to web depth ratio (r) varies from 0.2 to 0.8 corresponding to test specimen. The results show that increasing hole height-to-web depth leads to Precipitate the geometric failure and decrease of the CFS beams load capacity. From Fig.8, there is no significant effects in the load capacity of beams when the hole diameter to-web depth ratio (dh/hw) is up to 0.5. However, the load reduction is obviously increase when ($r = d\ h\ w$) further increases up to 0.8.

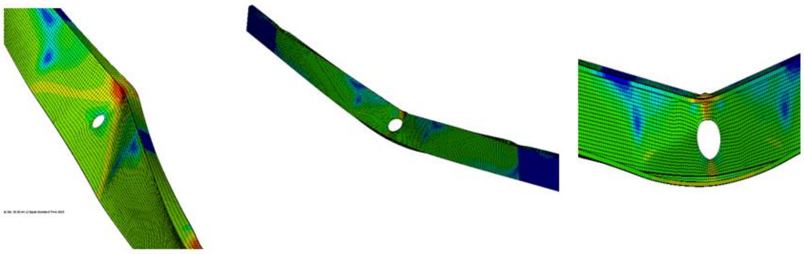


Figure 9. Finite element models failure mode results.

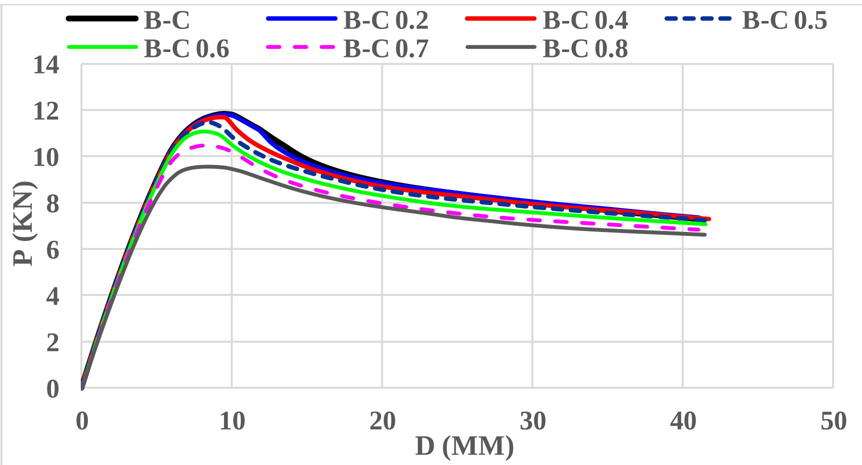


Figure 10. Comparison the FEA load-displacement curve with the experimental results.

VI. CONCLUSIONS

Because of the desire to preserve the clear floor height, web openings need to be inserting to the beam during the manufacture process. So, this study has investigated the effectiveness of web opening size on flexural behavior of CFS beams. A finite element model was developed and verified against the experimental results in terms of failure modes and moment capacities. Then, the validated model was used to carry out extensive parametric analysis of CFS beams with web opening. The following conclusions can be drawn from the present study. The excessive slenderness of CFS members often is the main reason of beam failure. The geometric failure may occur before section yielding. So, applying openings to the web lead to Precipitate the geometric failure modes and decrease beam capacities. From the results we can show that the decrease of beam capacities is closely related to the hole height-to-web depth ratio. The influence of web opening on beam capacities is relatively small with a maximum reduction value about 3.00% when the opening height to-web depth ratio increases from 0 to 0.5, and the dramatic reduction in beam capacities is found with a maximum reduction value of 19.12% when the opening height-to-web depth ratio further increases to 0.8. Therefore, it is preferred to use circular opening with a height of less than 50% of the web depth, and if opening height increases than 50% of the web depth, the beam should be strengthened.

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