The Performance of Cold-Formed Steel Members with Stiffened Perforations

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Abstract- CFS sections are usually supplied with openings to adapt construction services. Nevertheless, the area lowering in the web influences their strengths. If stiffeners are provided near the web openings, the reduction in flexural capacity could be recovered. Therefore, this paper introduces a study on the CFS section with stiffened perforations. A finite element (FE) analysis was accomplished. The numerical model was verified versus experimental and numerical tests from prior research and then utilized in performing parametric studies. The influence of circular openings with various sizes and various stiffener lengths on the flexural capacity was examined in the nonlinear analysis. Depending on the findings of the study, it has been determined that the introduction of stiffened openings into the CFS members will result in the restoration of the original flexural capacity.

Keywords: **stiffened openings; cold formed steel; numerical model**

I. INTRODUCTION

Cold-formed steel (CFS) material is becoming growingly widespread in structural engineering due to its increased ratio of strength-to-weight [1], [2]. It is common in engineering applications to use CFS beams as primary structural members [1]. Several types of stability loss are covered in the design of CFS members: lateral-torsional, local, and distortional buckling [3]. The presence of openings in CFS beams eases the passage of cables and other services. The major disadvantage of the existence of openings in CFS beams is that they reduce the beam's structural strength because they have less ability to resist external loads [4]. It is common practice now to add edge stiffeners to openings to minimize the openings' impact on the members' capacity [5].

Limited investigations were performed on CFS beams/purlins with stiffened openings in the literature. Chen et al. [6] examined the bending strength of channel sections with stiffened openings. The authors observed that the existence of stiffened holes improved the bending capacity by up to 14.5%. Moreover, Yu [5] developed a new method based on DSM for indicating the local moment of C-sections with stiffened perforations. However, Perampalam et al. [7] examined the distortional moment of channel sections with stiffened perforations. Based on the results of the study, the edge stiffeners greatly increased the moment capacity exceeding the original capacity of the solid beams. Web-crippling strength can be significantly increased by adding stiffened perforations to CFS beams, according to Uzzaman et al. [8].

In the literature, there is a substantial amount of research available on CFS beams with un-stiffened openings. Regarding of bending tests, Wang and Young studied the behavior of built-up members using perforations [9]. The authors stated that increasing the hole depth/web height ratio resulted in a decrease in the maximum moment. Moreover, Zhao et al. [10] discovered that the openings made the failure of members to be combined local - distortional failure. However, Ling et al. [11] examined the behavior of sections with perforations under lateral-torsional moment. From the results, it was figured out that, compared with other opening shapes, C-hexagon openings showed the least reduction in lateral torsional buckling capacity. Regarding of shear tests, De'nan et al. [12] studied the behavior of Z-sections with holes under shear strength. It was found that diamond-shaped holes performed better under shear strength than circle-shaped holes. Regarding of web crippling examinations, Uzzaman et al. [13] observed that the LTB behavior of web-crippling of the CFS beams is mainly affected by the location and size of openings.

Regarding of CFS beams without web openings, comprehensive studies are known in the literature. Nguyen et al. [14] studied the Z-beam behavior with different stiffener arrangements. The authors observed that thick sections reached the ultimate moment at a slower rate than thinner sections. In addition, the behavior of built-up C-sections exposed to the flexural moment was addressed by Manikandan and Thulasi [15]. They found that members using edge and intermediate stiffeners improved their strength. However, Haidarali and Nethercot studied the behavior of CFS Z-sections with intermediate stiffeners [16]. They stated that the ultimate change in flexural capacity was between 1% and 5% as a result of differences in the location of the intermediate stiffener. Ghannam [17] addressed the performance of CFS built-up sections under flexural capacity. The authors found that an increase in yield strength and steel thickness is associated with an increase in bending capacity.

No numerical examination is known in the last research reviewing the bending behavior of Z-sections using stiffened perforations. Therefore, the primary consideration of such paper is to examine the performance of Z-sections using web openings under the effect of flexural strength.

To perform the research goal, the following procedure needs to be followed: Firstly, create a numerical model to emulate the flexural performance of Z-members with perforations. Secondly, the suggested numerical model must be validated and compared to the previous studies. Finally, achieving a parametric analysis to examine the impact of edge stiffener size and opening size on the behavior of investigated beams.

II. MODEL DESCRIPTION

A. *General*

The FE software ABAQUS [18] was utilized to emulate the performance of CFS beams with stiffened openings under bending analysis. All models in this paper were taken to be circular with edge-stiffened holes that were positioned in the pure flexure area of the model. The buckling analysis needs a two-stage analysis. The buckling modes of CFS sections are first evaluated using the eigenvalue analysis. Then, the non-linear model is implemented using the "Static General" procedure. Material non-linearity and initial imperfection are incorporated in this stage of the analysis. This analysis determines failure modes and moment-deflection responses.

B. The mesh type and size

All parts of the FE model are meshed utilizing a 4-node shell element (S4R) according to earlier researches [7], [19]. The member length is 2.6 m as presented in Figure 1. The element size was 10 mm. The mesh type is presented in Figure 2.

C. Load implantation and boundary conditions

The models have been provided with simply supported boundary conditions at the center of lateral plates, that are connected to the member via 'tie' restraints. A displacement control approach was utilized to apply the load at two middle side plates. It was assumed that the straps would act as boundary conditions just on the top and bottom flanges at the loading and support positions, similar to the numerical model presented in [7] (see Figure 3 for more details).

D. Material modelling

The material of CFS beams was assumed as elastic-perfectly plastic model as shown in Figure 4. The FE models were generated with a modulus of elasticity of 210000 MPa, a yield strength of 450 MPa. To assure that no collapse will appear within the lateral plates, they were created as rigid bodies. The Poisson's ratio was 0.3. The models were generated without the consideration of residual stresses [19].

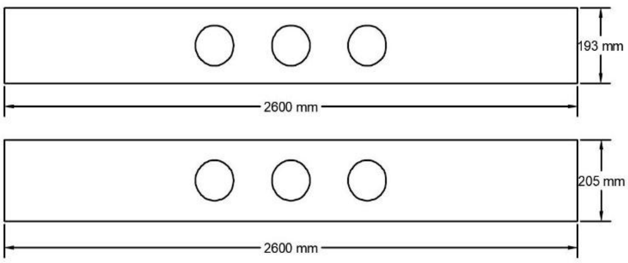


Figure 1. The member dimensions

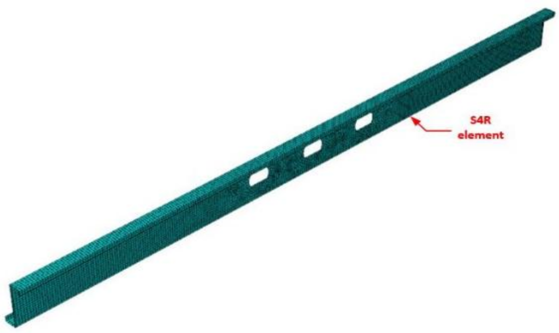


Figure 2. The mesh type of a typical beam

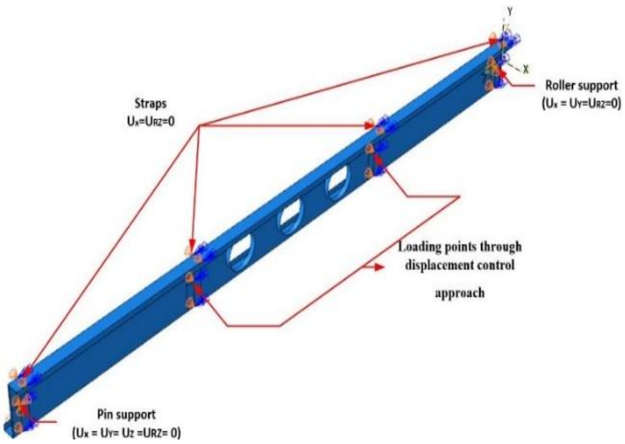


Figure 3. Boundary conditions of an investigated beam

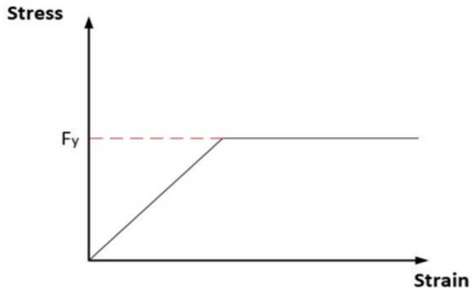


Figure 4. Stress-strain curve for studied beams

E. Initial imperfection

An initial imperfection with a value of 0.64*t*, where *t* is the thickness of the CFS sections, was presented in the non-linear analysis [7].

III. VALIDATION STAGE

The generated FE model was verified against a series of existing tests in literature. An evaluation of the precision of the model to simulate Z-section beams subjected to bending moment was conducted by comparing it to the numerical model of Haidarali and Nethercot [20]. Subsequently, the capability of the FE model to simulate the CFS members with stiffened circular openings was verified with the experimental investigation of Chen et al. [6]. It should be noted that all models in the verification study were subjected to two concentrated loads at two points of beam length. A description of the properties of the models that have been verified is given in Table 1. The flexural capacity of CFS samples reported in the previous studies (M_{ps}) and that presented by the proposed FE model (M_{FE}) are presented in Table 1.

A. Validation of results

As depicted in Table 1, FE model results were compared successfully with those from previous studies. A comparison of failure modes attained from experimental investigation of Chen et al. [6] with that acquired from FE model for 240-L4000-EH3 are shown in Figure 5. Figure 6 demonstrates a comparison of load-deflection curve determined from the generated FE model with that in [20].

Table 1. Validation of the FE model

Specimens	Beam length	Section depth	Section width	Lip length	Thickness	Lip inclination (degree)	Hole depth	Stiffener length	F_y (MPa)	M_{ps} (kN.m)	M_{FE} (kN.m)	M_{ps}/M_{FE}
Numerical analyses of Haidarali and Nethercot [20]												
D8.5Z120-4 (25% CDF)	4878	214	67	24	3.0	54.2	-	-	422.70	28.47	29.20	0.98
Experimental results of Chen et al. [6]												
240-L4000-UH3 (with unstiffened holes)	4000	240	45	15	1.8	90.0	140	-	333.00	10.60	11.30	0.94
240-L4000-EH3 (with stiffened holes)								13		13.30	13.00	1.02

Remark: all geometries are in mm, F_y: yield stress

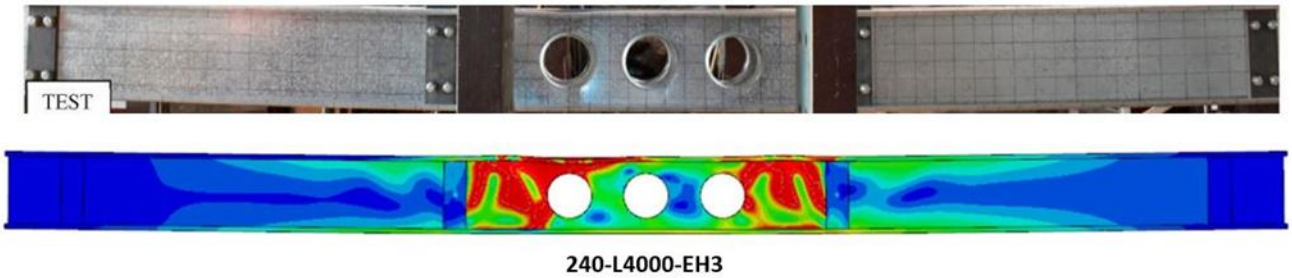


Figure 5. The collapse shape of [6] compared to the FE of 240-L4000-EH3

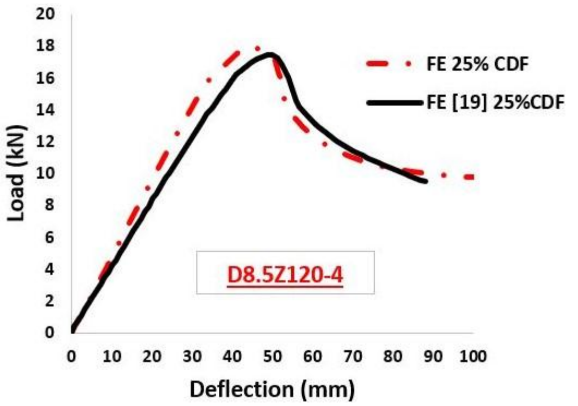
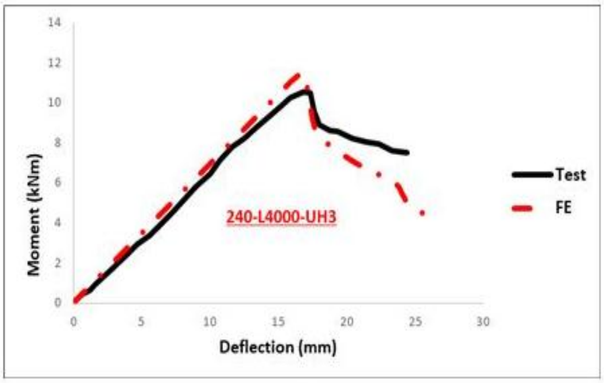
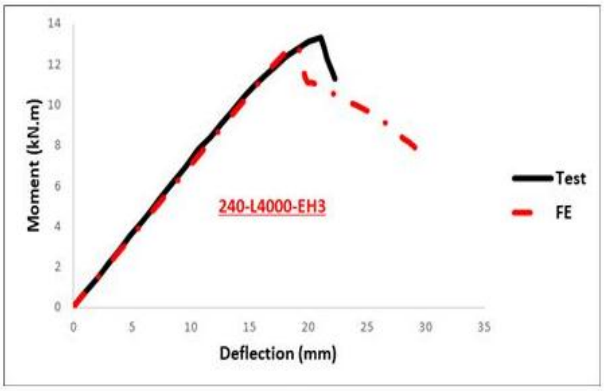


Figure 6. The load-deflection curve between FE and [20]



a



b

Figure 7. The moment -deflection curve between FE and [6] for: a: unstiffened holes, b: with stiffened holes

Moreover, a comparison of moment-deflection curves determined from the generated FE model and those in [6] are presented in Figure 7. It can be indicated that the curves predicted by the FE model and those stated in the previous studies are compatible and agree well. Hence, the trust of the model is improved when compared to earlier results.

IV. PARAMETRIC STUDY

After verifying the FE models, the strength of CFS members with stiffened openings was determined using parametric analyses. The parameters used in the parametric analyses are the steel thickness (t), opening size (d/h), and stiffener length (S) as indicated in Figure 8 and Table 2.

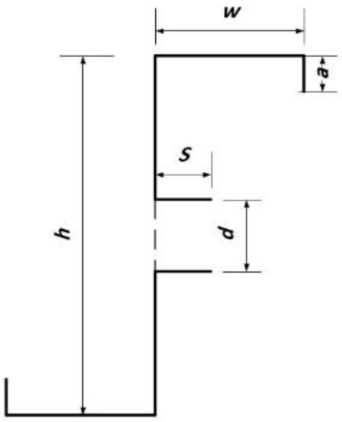


Figure 8. The variables of the sections

Table 2. Beams parameters

Specimens	*h*	*w*	*a*	*t*	*d/h*	*S*	F_y (MPa)
section 1	205	50	16	1	0, 0.5, 0.7	0, 5, 10, 15, 20	450
section 2	193	50	22	2			

Remark: all geometries are in mm

A. *Influence of steel thickness (t)*

An analysis of the impact of steel thickness on flexural strength was conducted on the examined beams. The thicknesses considered in this study were 1 and 2 mm. Figure 9 presents the influence of the steel thickness on strength of beams with a stiffened length of 20 mm, where M_s and M_u are moment of section without openings (solid section) and moment of stiffened openings section respectively. As seen in Figure 9, large openings reduced the bending strength by up to 20%, so the stiffeners were not able to recover the solid beam strength for sections that were 2.0 mm thick and had large openings.

B. *Influence of the ratio of perforation depth to web height (d/h)*

To examine the influence of perforation depth on bending capacity, the perforation depth to web height ratio (*d/h*) varied to be 0.0, 0.50, and 0.70. Figure 10, presents the moment-deflection curves of section 1 and section 2 with S = 0. From Fig. 10, it can be observed that increasing opening depth to web height causes a decrease in the flexural capacity of the CFS Z-members.

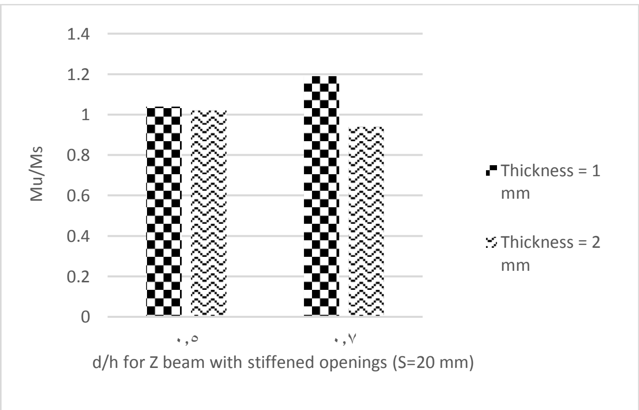


Figure 9. The impact of steel thickness on flexural strength of examined members with *S* = 20 mm

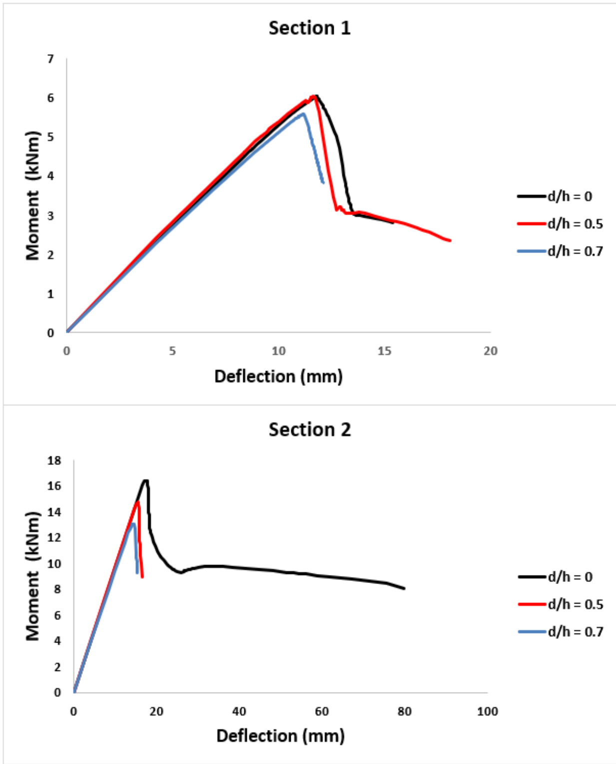


Figure 10. The moment-deflection curves of section 1 and section 2 with *S* = 0

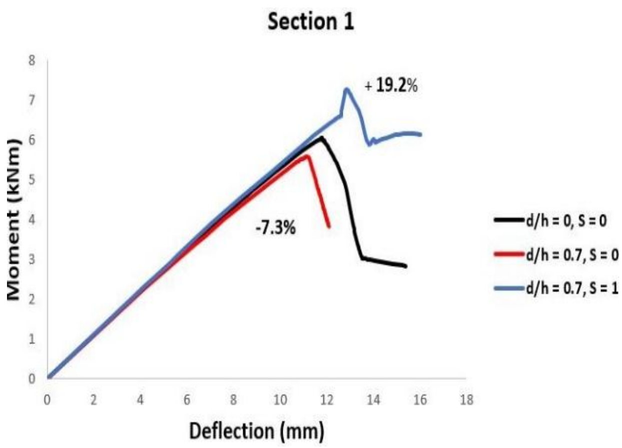


Figure 11. The impact of *S* on the strength

C. *Influence of stiffener length (S)*

The impact of S on the bending strength of investigated beams with openings was analyzed. The S considered in this study were varied from 0 to 5, 10, 15, and 20 mm. For instance, Figure 11 presents the impact of S on the bending moment of examined members. It was observed that for section 1, the bending capacity decreased (up to 7.3%) because of the presence of the circular openings. Stiffened openings could raise the bending moment equal to 19.2% compared with a solid member.

V. CONCLUSIONS

The purpose of such an examination is to study the performance of CFS members with stiffened web perforations under the bending moment. Furthermore, the impact of different parameters on flexural performance is examined. In this study, the following results were obtained:

1. Comparisons between literature findings and those developed by the present FE model indicate that the present model can suggest the performance of examined members using stiffened perforations with good precision. The comparisons contained the moment-deflection curves and the failure modes.
2. Large openings reduced the bending strength by up to 20%, so the stiffeners were not able to recover the solid beam strength for sections that were 2.0 mm thick and had large openings.
3. Increasing the *d/h* ratio generates a decrease in the strength of the CFS sections.
4. As a result of stiffened openings being introduced into the CFS, the original flexural capacity could be recovered.

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Conflicts of Interest: The authors declare that there is no conflict of interest.

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