DESIGN OF PERFORATED COLD-FORMED STEEL TUBULAR STUB COLUMNS – DSM APPROACH

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This paper presents a preliminary attempt on the design of cold-formed steel tubular stub columns, having two opposite central circular perforations at column mid-height. The work is an extension to a previous experimental study on the structural performance of perforated cold-formed steel stub columns reported by the authors. Initially, finite element (FE) models were developed and validated against the previous test results. Upon validation, FE models were then developed to generate ultimate column capacities of a wide range of cross-sections and perforation size to flat wide ratio up to 0.5. A total of 134 stub column capacities comprising of 15 test and 119 FE analyses results were employed to assess the suitability of the existing Direct Strength Method (DSM) design prediction detailed in American Standard. Based on the analysis, it was found that the current DSM design equation provides overly conservative and scattered predictions. Hence, a new set of modified DSM equation was proposed, considering the effect of perforation size and cross-section slenderness. The newly proposed modified DSM approach is found to provide accurate and conservative predictions.

Keywords: Cold-formed steel, Tubular sections, Stub columns, Circular perforations, Direct Strength Method.

1 Introduction

Structural tubular/hollow steel sections are popular and widely used in many architecturally exposed steel structures, due to their inherent structural advantages such as high compression, bending and torsional resistances as well as aesthetically pleasing appearance, over open and hot-rolled sections (see Gardner *et al.* 2010, Wardenier *et al.* 2010, Imran *et al.* 2018). In tubular steel construction, perforation(s) (cut-outs, holes, openings) are provided for various purposes such as services (e.g., electrical wirings, air and water circulations, maintenance works etc.), optimisation of construction material, reducing member weight, aesthetic needs, etc., (e.g. Shanmugam 1997, Moen and Schafer 2009b, Pellegrino *et al.* 2009, Moen and Schafer 2011, Ghazijahani *et al.* 2014 etc.). However, the introduction perforation(s) on the structural member/ element(s) may alter the stability or stress distribution, thereby reducing the ultimate capacity of the member. Therefore, it is imperative to study the effect of perforation(s) and develop a conservative and reliable design equation for perforated cold-formed steel tubular members.

Researches on the effect of perforation on various structural elements such as plates (e.g. Kumai 1951, Schlack 1964, Vann 1971, Ritchie and Rhodes 1975, Shanmugam *et al.* 1999, Saad-Eldeen *et al.* 2016, Saad-Eldeen *et al.* 2019 etc.), beams (such as Yu and Davis 1973, Narayanan and Rockey 1981, Sivakumaran and Zielonka 1989, Shan *et al.* 1994, Zhao *et al.*

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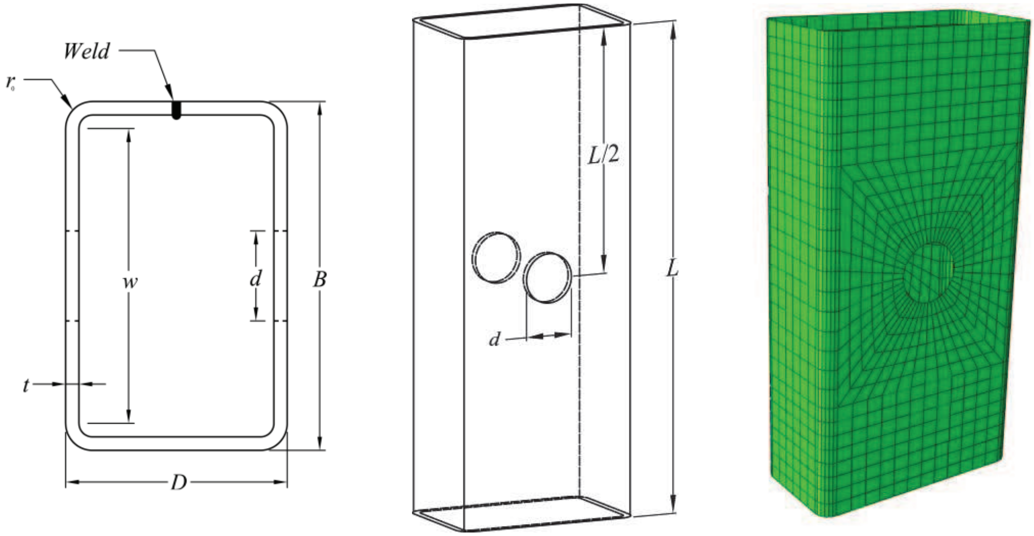
2019) and columns (e.g. Marshall and Nurick 1970, Pu *et al.* 1999, Dhanalakshmi and Shanmugam 2001, Moen and Schafer 2011, Feng and Young 2015, Yao *et al.* 2016 etc.) have been studied from the early 1950's. Based on the studies, it has been reported that the introduction of perforation(s) on a structural member can greatly affect the overall stability and load distribution of the member, thereby reducing the ultimate member capacity. Moreover, it is also observed that most of the earlier studies, both experimental and numerical investigations, are found to primarily focus on platted and opened section. Additionally, as reported previously, the presently available design equations are unsuitable for perforated tubular columns since they are developed based on ultimate capacities of perforated open sections and applicable to limited diameter to flat width ratios up to 0.7, see Singh and Singh (2018).



(a) (b) (c)

Figure 1. Typical representation of the perforated stub column and definitions of symbols showing: (a) plan view, (b) three dimensional view and (c) three dimensional FE model

2 Experimental investigation

In this section, earlier experimental investigation on the ultimate capacity of perforated cold-formed steel tubular stub columns conducted by the authors (Singh and Singh 2018) is briefly presented. The study comprises of evaluating the effect of perforation diameter on the ultimate capacity of stub columns and the ultimate capacities were then utilised to assess the compatibility of existing international design codes (AISI S100-16 2016) as well as proposed design equations (e.g. Shanmugam and Dhanalakshmi 2001, Shanmugam *et al.* 1999, Miller and Peköz 1994 etc.) for perforated cold-formed steel columns. The stub columns were prepared from commercially available cold-formed steel hollow sections, manufactured by Tata Steel India under the brand name – Tata Structure YSt 310 (see in Tata Steel 2013). The steel material has nominal yield stress and tensile strength of 310 MPa and 450 MPa respectively, and elongation at fracture of 10%. The cross-sectional dimensions and material properties are conformed to Indian Standard, IS 4923 (1997). A total of 31 concentrically loaded stub column tests were performed, considering five different cross-sections, and perforation sizes (perforation diameter, d to flat width, w ratios ranging from 0.1 to 0.9). Figures 1(a) and (b) present a typical representation of the perforated stub column. Based on the stub column test results, it was observed that the reduction in ultimate column capacities were ~ 9.57%, 18.24%, 31.15% and 44.00%, for perforation size ratio, d/w of 30%, 50%, 70% and 90% respectively. In addition, the comparison of test results with design predictions have shown that most of the currently available international design equations provide conservative and reliable but scattered predictions for the design of perforated cold–formed steel SHS/RHS structural stub columns having central circular perforation size ratio, d/w up to 0.9.

In this study, an attempt has been made to develop a design equation for perforated cold-formed steel stub columns considering the Direct Strength Method (DSM) approach detailed in American standard, AISI S100-16 (2016). Firstly, FE models were developed and validated against the experimental results conducted by the authors (Singh and Singh 2018). The validated FE procedure was further utilised for parametric study, to cover a wide range of cross-section slenderness as well as perforation sizes, which have not been covered in the test programme. The columns capacities generated from the FE models as well as test results (reported by the authors in Singh and Singh 2018) have been used to assess the applicability of the present Direct Strength Method (DSM) for design of perforated cold-formed steel stub columns. Further, a modified DSM has also proposed.

3 Finite element modelling and validation

The commercial FE software Abaqus (2010) version 6.9 have been used for the parametric study. Initially, FE models have been developed using the measured cross-sectional dimensions, stress-strain material properties, local geometric imperfection reported by the authors previously (Singh and Singh 2017, 2018). Because of the thin-walled nature, a 4-noded doubly curve shell element with reduced integration designated as S4R, which has six degrees of freedom (three translational and three rotational) at each node, has been employed to develop the stub columns. As reported by previous researchers such as Theofanous *et al.* (2009); Patton and Singh (2012) etc., the S4R shell element has been known to generate accurate results for thin-walled tubular structures. Two opposite central circular perforations have been made at column mid-height. After a careful mesh convergence study, an element size of ~2 times the thickness of the cross-section considering an aspect ratio of ~ 1.0 has been used in the flat region. However, a finer mesh has been employed to simulate curve geometry in the corner regions as well as periphery of the perforations. A three dimensional FE model is shown in Figure 1(c). The engineering stress-strain material properties reported by Singh and Singh (2017) for both flat and corner regions are converted to their corresponding true values and assigned to the flat and corner regions of the stub columns. A Poisson's ratio value of 0.3 has been incorporated in the FE models. Residual stresses are ignored in the present FE modelling as their effect on the load-deformation has been found to be insignificant based on the earlier study (see Ellobody and Young 2005, Ma *et al.* 2016 etc.). The bottom and top edges of the FE models have been tied (using Kinematic Coupling Method available in Abaqus 2010 library) through two reference points: RP1 and RP2 respectively. The end conditions of the stub columns have been simulated by restraining all degrees of freedom except the translational degree of freedom in the loading direction, i.e., RP2 through which concentrated point load has been applied. The validation of the FE model involves two-step process.es Firstly, linear eigenvalue buckling analysis has been performed using the Lanczos Eigensolver available in the Abaqus (2010) to extract the lowest buckling mode shape. The extracted mode shape is then employed to serve as a geometrically and materially non-linear imperfect geometry of the perforated stub column. Local geometric imperfection amplitude value derived from the predictive model proposed by authors for perforated cold-formed steel stub columns, presented in Eq. (1) has been considered.

$$\omega_0 = 0.0303\left(\frac{\sigma_{0.2}}{\sigma_{cr}}\right)t \tag{1}$$

in which, $\sigma_{0.2}$ and σ_{cr} are the 0.2% proof stress and critical buckling stress respectively.

The accurateness of the numerical modelling procedure followed in the present study has been assessed by comparing the results of numerical simulations and the tests. Figure 2 presents the comparison of the complete load versus end-shortening curve generated from the FE models against the perforated stub column results (reported by Singh and Singh 2017) for 50 × 50 × 2.9 perforated stub columns. Additionally, Table 1 presents the ratio of the test to the FE ultimate column capacities and also the corresponding end-shortenings (ultimate displacements). Based on the comparison, it can be evident the present FE procedure is able to generate accurate full load deformation response which are very close to the test results. Hence, the FE modelling procedure is employed for parametric study in the following section.

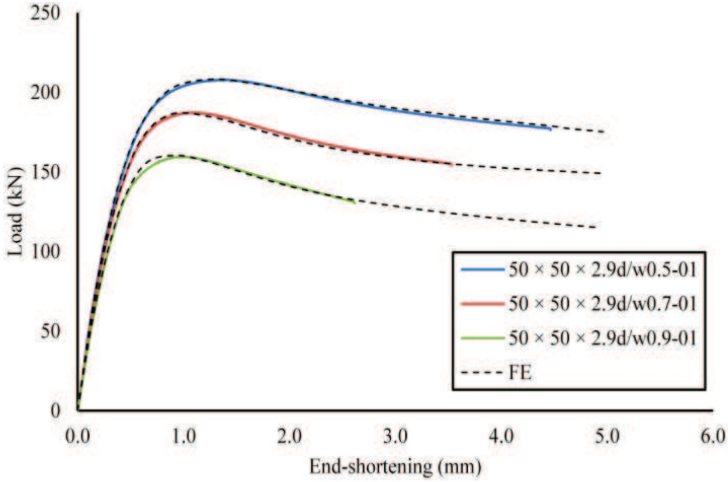


Figure 2. Experimental and numerical load-end shortening curves for 50 × 50 × 2.9 stub columns

Table 1. Comparison of FE simulation results against the test results

Cross-sections	Test		FE		Test/FE	
	P_{Test} (kN)	δ_{Test} (mm)	P_{FE} (kN)	δ_{FE} (mm)	P_{FE} / P_{Test}	δ_{FE} / δ_{Test}
50 × 50 × 2.9*d*/*w*0.5-1	207.99	1.42	208.23	1.26	1.00	1.13
50 × 50 × 2.9*d*/*w*0.7-1	187.16	1.09	186.40	0.89	1.00	1.22
50 × 50 × 2.9*d*/*w*0.9-1	159.44	1.01	160.38	0.93	0.99	1.09
60 × 60 × 2.6*d*/*w*0.1-1	295.65	1.30	292.60	1.24	1.01	1.05
60 × 60 × 2.6*d*/*w*0.3-1	271.65	1.13	272.57	1.19	1.00	0.95
60 × 60 × 2.6*d*/*w*0.3-2	274.38	1.13	272.44	1.19	1.01	0.95
60 × 60 × 2.6*d*/*w*0.5-1	254.21	1.16	243.04	1.05	1.05	1.10
60 × 60 × 2.6*d*/*w*0.7-1	216.72	0.85	212.41	0.78	1.02	1.09
60 × 60 × 2.6*d*/*w*0.7-2	214.89	0.81	212.73	0.77	1.01	1.05
60 × 60 × 2.6*d*/*w*0.9-1	181.20	0.71	181.62	0.82	1.00	0.87
60 × 60 × 2.6*d*/*w*0.9-2	183.95	0.73	184.75	0.82	1.00	0.89
66 × 33 × 2.6*d*/*w*0.7-1	151.82	1.39	151.23	1.18	1.00	1.18
66 × 33 × 2.6*d*/*w*0.9-1	119.72	1.05	120.10	1.00	1.00	1.05
Mean/average					1.01	1.05
Coefficient of variance (COV)					0.01	0.10

4 Parametric studies

Following the validated numerical procedure for perforated stub columns (detailed in the previous section), parametric studies have been performed. FE models have been developed considering nominal cross-sectional dimensions for both square (SHS) and rectangular hollow sections (RHS) detailed in Tata Steel (2013), to cover a wide range of cross-sections slenderness and perforation diameter to flat width ratio, d/w up to 0.5 (design equations for d/w up to 0.9 is underway). the material properties adopted in the FE models for parametric study are based on the experimentally recorded stress-strain curves (both flat and corner) of 60 × 60 × 2.6 cross-section, as the average yield stress and ultimate strength of the experimental results are approximately close to that of 60 × 60 × 2.6 cross-section. The FE stub column length has been set four times the minimum of the cross-sectional width. A total of 119 stub column capacities have been generated from the FE models.

5 Direct strength method

In Section E of North American Specification AISI S100-16 (2016), design equations are provided to estimate the nominal axial capacity member in compression. Based on this Section E, the nominal axial strength of a member in compression shall be the minimum of axial capacity of a member for yielding and global buckling (P_{ne}), local buckling interacting with yielding and global buckling (P_{nl}) and distortional buckling (P_{nd}). The distortional buckling (P_{nd}) is ignored as closed sections are considered in the current study. The nominal strengths for yielding and global buckling are calculated in accordance with Section E2 of AISI S100-16 (2016). The effect of holes/perforations in the estimation of elastic flexural buckling stress is considered based on the guidelines presented in Appendix 2 of AISI S100-16 (2016). Moreover, for member with perforations, the nominal axial strength for local buckling can be estimated either Effective Width Method (EWM) or Direct Strength Method (DSM) detailed in Section E3 of AISI S100-16 (2016). In this paper, the applicability of the DSM approach for design of perforated cold-formed steel tubular stub columns having two opposite central circular perforation at column mid-height is assessed. The critical elastic local column buckling considering the influence of perforation is incorporated, as detailed in Appendix 2 of AISI S100-16 (2016). The plate buckling coefficient value of 0.43 has been employed for elements with holes.

6 Analysis and proposed equation

In this section, the applicability of DSM design prediction for perforated stub column is assessed. The unfactored stub column capacities generated from the test and FE models for perforation size to flat width ratio up to 0.5 is considered. The comparison of the test and FE column capacities against the DSM prediction is shown in Table 2. Based on the analysis, it is observed that the current design prediction for perforated column presents overly conservative design (~ 80% based on the current column capacities considered) and scattered (COV of 0.18) prediction. Therefore, an attempt has been made to develop an accurate and effective design equation for perforated stub columns in this paper, based on the current test and FE ultimate column capacities. The design equation is developed in accordance with the DSM design equation detailed in AISI S100-16 (2016), for perforation size to flat width ratio up to 0.5. It is worth mentioning that the critical elastic buckling stress recommended by Moen and Schafer (2009a) was incorporated in developing the design equation. The proposed design equation is provided in Eq. (2). The values of coefficient depend on the perforation size to flat width ratio, as provided in Table 3. The column capacities from the test and FE are compared with the proposed design prediction as shown in Figure 3 and the statistical comparison is also presented in Table 3. It can be seen that proposed design equations provides conservative and less scattered prediction.

$$\text{For } \lambda_l \le 0.776 \qquad P^*_{DSM} = P_{ne}\left\{\frac{K_1}{\lambda_l^{K_2}}\right\}$$

$$\text{For } \lambda_l > 0.776 \qquad P^*_{DSM} = P_{ne}\left\{\frac{K_3}{\lambda_l^{0.8}} + \frac{K_4}{\lambda_l^{1.6}}\right\} \tag{2}$$

in which P^*_{DSM}, P_{ne} and λ_l are the proposed modified DSM prediction, nominal axial strength for yielding and global buckling and cross-sectional slenderness; and K_1, K_2, K_3 and K_4 are the set of coefficients, generated based on the best fit regression analysis.

Table 2. Statistical comparison of DSM (AISI S100-16, 2016) and proposed design prediction

Statistical parameters	P_u / P_{DSM}	P_u / P^*_{DSM}
Average/Mean	1.81	1.00
Standard deviation (SD)	0.33	0.06
Coefficient of variance (COV)	0.18	0.06

Table 3. Coefficient for design of perforated cold-formed steel hollow sections with circular perforation

Perforation size ratio, (d/w)	Coefficients			
	K_1	K_2	K_3	K_4
$0.0 < d/w \le 0.2$	0.9516	0.2016	0.7760	0.0300
$0.2 < d/w \le 0.3$	0.8506	0.2587	0.8116	– 0.0629
$0.3 < d/w \le 0.5$	0.7643	0.2780	0.8614	– 0.1566

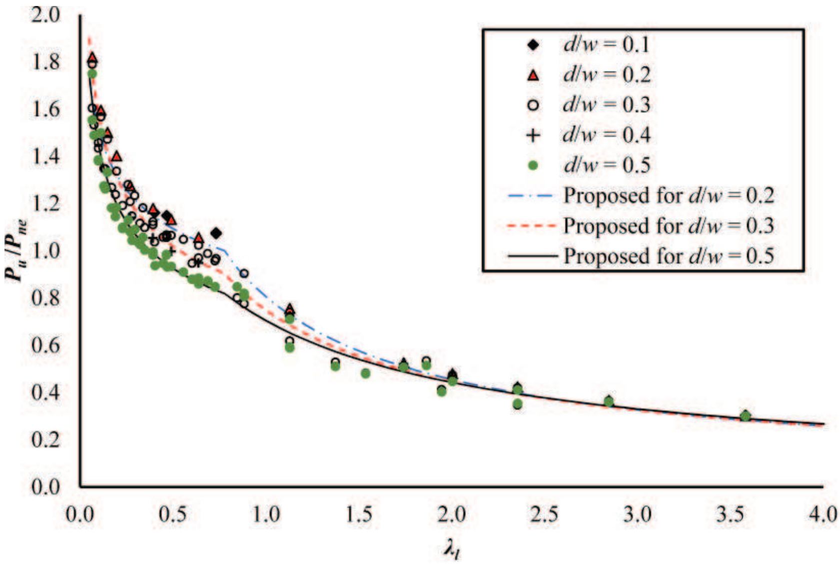


Figure 3: Comparison of Test and FE column capacities against the proposed modified DSM curves

7 Conclusions

In the present study, an attempt has been made to develop modified design equation for perforated stub columns considering direct strength method (DSM) approach. Finite element models were developed and validated against the previous experimental studies performed by authors. Using the validated FE models, parametric studies have been performed to generate columns capacities for wide range of cross-sections and perforation size to flat width ratio up to 0.5. Considering the test and FE column capacities, presently available DSM design equation for perforated stub columns have been assessed and found to provide overly conservative and scattered prediction. Therefore, a modified DSM design equations have then been developed. The proposed modified DSM approach is found to generate accurate and conservative design prediction.

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