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Extension of Direct Strength Method for Slender Cold Formed Steel Column Sections with Perforations

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ABSTRACT

Revolutionary development has taken place in the design methodology of thin walled structures since the introduction of direct strength method (DSM) (Dr. B Schafer 2004). DSM gives direct approach for analyzing and designing the cold formed steel sections. The effort has also been put to extend DSM for the cold formed steel sections with perforations by Dr. C D Moen(2008). Though this method gives fairly accurate results for columns with medium height, but the method is not suitable for very short and slender columns. In this paper effort has been put to suggest modification in DSM formulae for slender columns. Particular column section was modelled with finite element method with different height and thickness combinations. The same section was then analyzed by DSM in CUFSM 4.06 software. Sufficient database was created through this, and the variation in the results with DSM was incorporated in modified formula in terms of thickness and length.

Keywords-cold formed steel, DSM, slender columns, perforation.

I. Introduction

In India mass housing is the need of the hour, for which cold formed steel can be proved as very economical and efficient alternative. Cold Formed Steel has the potential to be that solution as it has Attractive appearance, Fast construction, Low maintenance, Easy extension, Lower long-term cost, Non-shrinking and non-creeping at ambient temperatures, No requirement of formwork, Termite-proof and rot proof, Uniform quality, Non combustibility. Also it is a recyclable. Effective width method is widely accepted around the world and in India for the design of cold formed steel structures, but the new method which gives direct approach known as Direct Strength Method (DSM) has also evolved significantly. DSM is the future of thin walled structures and as if today it is only accepted in few countries. Also DSM is to be extended to sections with perforations,so that its applicability can broaden. This paper deals with the extension of DSM to the sections with perforations for slender columns and intends to give modification in the formulae given by Moen C. D. et al. (2011).

Lots of research is going on to simplify the design of Cold Formed Steel sections to make it more reliable and practically acceptable. Addition of perforations serves lot of advantages for the practical purpose but at the same time it generates complications in design. Considerable efforts are required to study the impact of hole on the strength of the member. The aim of the current research is to study and compare the capacity of perforated columns with the DSM equations and Finite Element Method and study the applicability of the modified DSM equations to the slender column sections with perforation, which gives an opportunity to optimise the design.

II. State Of Art of Analytical Methods Used For Thin Walled Structures

2.1 Effective Width Method

The basis for the Effective Width Method is well explained in textbooks and Specifications, the essential idea is that local plate buckling leads to reductions in the effectiveness of the plates that comprise a cross-section (more formally this can be understood as an idealized version of equilibrium in an effective plate under a simplified stress distribution vs. the actual plate with a nonlinear stress distribution due to buckling).This reduction from the gross cross-section to the effective cross-section as illustrated in Fig. 1 is fundamental to the application of the Effective Width Method.

2.2 Direct Strength Method

The direct strength method (DSM) recognizes that the available models for local and distortional buckling design are far from simple and have significant limitations. It also recognizes that the current trend is to increase the complexity of section shapes and also increase the complexity of the required mathematical models. It therefore proposes a formal design procedure based on elastic buckling solutions for the complete cross section. The particular characteristic of this procedure is that italso recognizes that, for economic design, it is

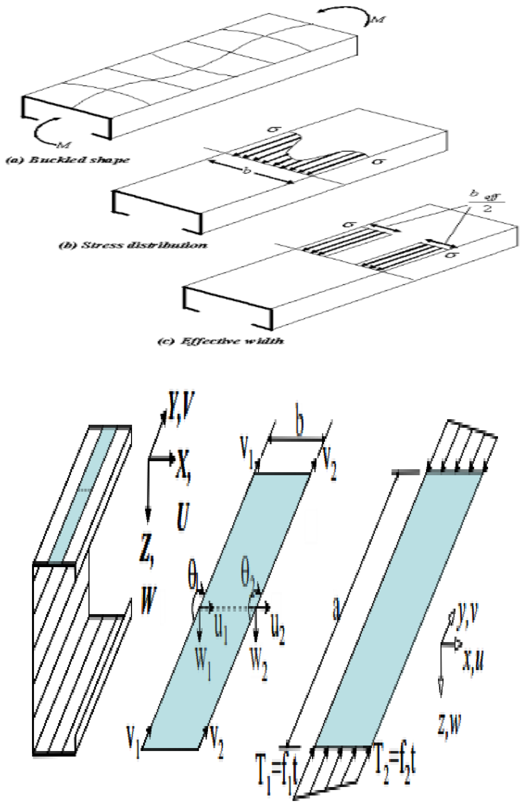


Figure 1: Effective Width Method and DSM

necessary to take advantage of post buckling strength. It is therefore takes the conventional effective width method and applies these to the complete cross section.

DSM is relatively new and represents a major advancement in Cold Formed Steel design because it provides engineers and cold formed steel manufactures with a tool to predict the strength of a member with any general cross section. Cold-formed steel members are manufactured from thin sheet steel, and therefore member resistance is influenced by cross-section instabilities (e.g. plate buckling and distortion of open cross section) in addition to the global buckling influence considered in thicker hot rolled steel sections. DSM explicitly defines the relationship between elastic buckling and load deformation response with empirical equations to predict ultimate strength.

2.2.1Basic Working of DSM

DSM shows that member strength (Mn) is the minimum of the nominal strengths due to local buckling (Mnl), distortional buckling (Mnd) and global buckling (Me). With the buckling loads determined by the elastic buckling analysis, the nominal strengths of Mnl, Mnd and Mne can be determined using the design equations as provided in the Appendix 1 of the AISI Specification. Since the DSM can virtually be used for any cold-formed steel members, safety and resistance factors have been developed both for pre-qualified members and for non-qualified members. Pre-qualified members represent the range of sections used in the development of the DSM design equations and Tables are provided summarizing these dimensions in Appendix 1 of the AISI Specification. For non-qualified members, the safety and resistance factors provided in AISI Specification Chapter 1.1(b)

To calculate the capacity of cold formed steel member with DSM, the elastic buckling properties of a general cold formed steel cross-section are obtained from an elastic buckling curve. This curve is generated by employing the finite strip method.

2.3 Finite Element Method

Finite element model of the above section was done using ABAQUS 6.12.0 finite element software package. Abaqus is a general purpose finite element modelling software for numerically solving a wide variety of mechanical problems. As far as structural analysis is concerned, the following types of analyses are possible: Static analysis, Modal analysis, Harmonic analysis, Transient dynamic analysis, Spectrum analysis and buckling analysis. The primary unknowns are the nodal degrees of freedom. For structural analysis problems, these degrees of freedoms are displacements. Other quantities such as stresses, strains and reaction forces are derived from the nodal displacements. In general, a finite element solution may be broken into the following three stages.

- ✓ Pre-processing: defining the problem.
- ✓ Solution: assigning loads, constraints and solving.
- ✓ Post processing: further processing and viewing of the results.

III. Strategy for Extending DSM to Columns with Holes

Direct Strength Method can be extended to the columns with perforations by maintaining the assumption that elastic buckling properties of a cold-formed steel column can be used to predict strength. For a column with holes the elastic buckling loads Pcrl, Pcrd, Pcre are calculated including the influence of holes. In 2011, Moen C. D. has proposed equations by keeping the same assumption and using the finite strip analysis as a part of AISI research program to extend DSM to columns with holes. These are developed from classical buckling solutions for columns and plates with holes (Moen and Schafer 2009b; Moen and Schafer 2009a) Elastic buckling loads including the influence of holes are viable parameters for predicting capacity in a Direct Strength approach (Moen 2008).

However, when yielding controls strength, modifications to the existing DSM design expressions for columns without holes were needed. Engineering intuition tells us that column strength should be limited to the squash load of the column at the net section, Pynet =Anet x Fy, where A is the cross-sectional area at a hole. The net section strength limit has been confirmed in experiments (Ortiz-Colberg 1981; Sivakumaran 1987; Miller and Peköz 1994; Abdel-Rahman and Sivakumaran 1998) and is implemented in the DSM design expressions for columns with holes.

DSM gives formula for flexural buckling as;

$$\text{For, } \lambda_c \leq 1.5;\ P_{ne} = \left(0.658^{\lambda_c^2}\right) P_y \quad (1)$$

$$\text{For, } \lambda_c 1.5;\ P_{ne} = \left(\frac{0.877}{\lambda_c^{\,2}}\right) P_y \quad (2)$$

$$\lambda_c = \sqrt{\frac{Py}{Pcre}}$$

$$Py = A_g F_y$$

IV. Analytical Study

The section is selected from S. Narayanan et al. (2003), and analytical study is carried out on it. It is observed that DSM gives very crude results for slender and short columns with perforations. The section is dimensioned in such a way that it will fail in global buckling only, so that global buckling can be studied thoroughly for slender columns. Analytical study was carried out by two methods viz. direct strength method and finite element method. Analysis is done through available software packages, CUFSM 4.05 for DSM which is freely available at http://www.ce.jhu.edu/bschafer/cufsm and ABAQUS 6.12.1 for finite element method.

4.1 Finite Element Modelling

Finite element model of the above section was done using ABAQUS 6.12.1 finite element software package. Abaqus is a general purpose finite element modelling software for numerically solving a wide variety of mechanical problems. For the given model details are:

Element type:

Three ABAQUS finite elements commonly employed in the elastic buckling analysis ofthin walled structures are the S9R5, S4 andS4R elements as shown in fig. 2 the S4 and S4R finite elements are fournode general purpose shell elements valid for both thick andthin shell problems. Both elements employlinearshape functions to interpolate deformationbetween nodes. S4R element has been used formeshingthe model.

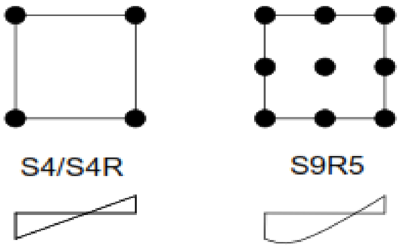


Figure 2: ABAQUS S4\S4R shell element and ABAQUS S9R5 shell element

Boundaryconditionsandloading:

Boundary condition for the modelled column is pinned-pinned, free to wrap. End cross section nodes are restrained in X and Z direction and nodes at the centre are restrained in Y direction to prevent Rigid Body motion.A reference load of 1 kN is applied as a shell edge load over the perimeter of the column. Column has perforations at 140 cm c/c. Modulus of Elasticity is 212000 MPa and Poission's Ratio as 0.3.

Analysis:

Liner Eigen buckling analysis was performed with Abaqus 6.12.1. Eigen value obtained from the analysis is used to calculate the buckling capacity of section. It was observed that the convergence was non-monotonic, hence to find accurate eigenvalue, the models were meshed with 30mm and 10mm mesh and then average of eigen values obtained through this was taken.

4.2 Direct Strength Method

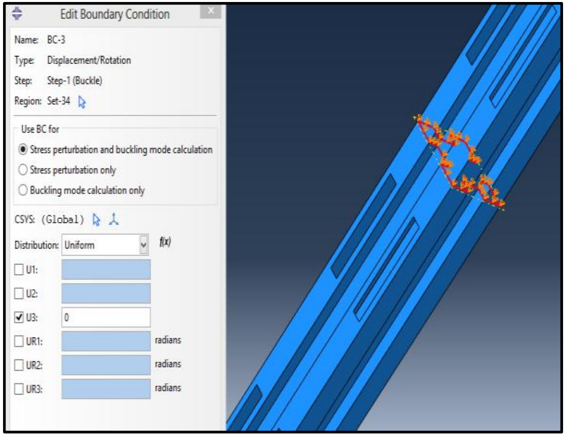
Finite Strip Modelling:

For finite strip analysis CUFSM 4.06, a freely available program for elastic buckling analysis of thin walled sections is used. The geometry of the section is modelled by giving input as the coordinates of the nodes. Thickness is assigned tonodes.

Material Properties:

The following material properties are assigned to the section.

Young's modulus = E = 212000 MPa

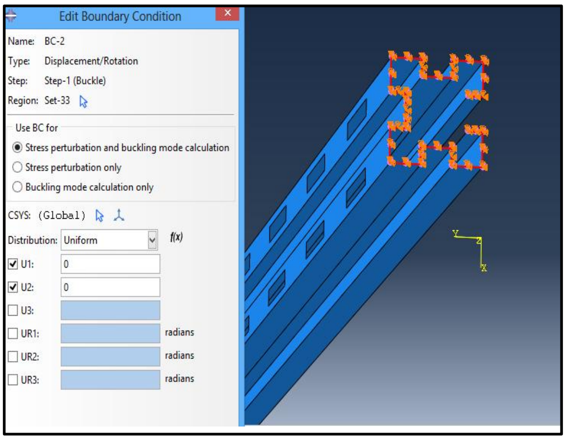


Name: BC-3
Type: Displacement/Rotation
Step: Step-1 (Buckle)
Region: Set-34

Use BC for
● Stress perturbation and buckling mode calculation
○ Stress perturbation only
○ Buckling mode calculation only

CSYS: (Global)
Distribution: Uniform f(x)
☐ U1:
☐ U2:
☑ U3: 0
☐ UR1: radians
☐ UR2: radians
☐ UR3: radians

Figure 3: Boundary condition at mid height **node**



Edit Boundary Condition

Name: BC-2
Type: Displacement/Rotation
Step: Step-1 (Buckle)
Region: Set-33

Use BC for
● Stress perturbation and buckling mode calculation
○ Stress perturbation only
○ Buckling mode calculation only

CSYS: (Global)
Distribution: Uniform
☑ U1: 0
☑ U2: 0
☐ U3:
☐ UR1: radians
☐ UR2: radians
☐ UR3: radians

Figure 4: Boundary condition at end nodes

Shear Modulus = G= 8000 MPa
Poison’s ratio = v = 0.3
Gross and net section properties:

The gross section and net section properties are calculated with the section property calculator in CUFSM. To determine the net section properties in CUFSM, assign a thickness of zero to the elements at the location of the perforations, but do not delete them.

To consider the effect of **perforation** the method suggested by C D Moen and B W Schafer (2011) was adopted and buckling capacity of section was found out.

V. Parametric Study

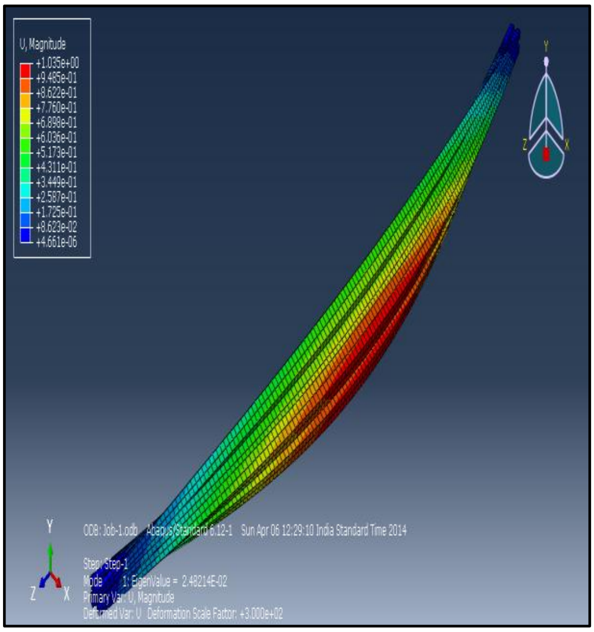
A series of parametric study was carried for the given section. The thickness was varied from 0.8mm to 2 mm. seven different lengths (1, 1.5, 2, 2.5, 3, 3.1, 4.6, 6.1, 7.6 m) were considered for all the thicknesses. Every combination of length and thickness was modelled with Abaqus 6.12.1 and CUFSM 4.06.

VI. Results and Discussion

From the results it is observed that for the results for short and slender columns are not accurate. There is necessity for modifying the formulae in terms of variable parameters such as length, thickness, λ etc.

It is observed that as the thickness increases the difference increases, i.e the accuracy of DSM decreases with increase in the thickness. The existing formula for the P is;

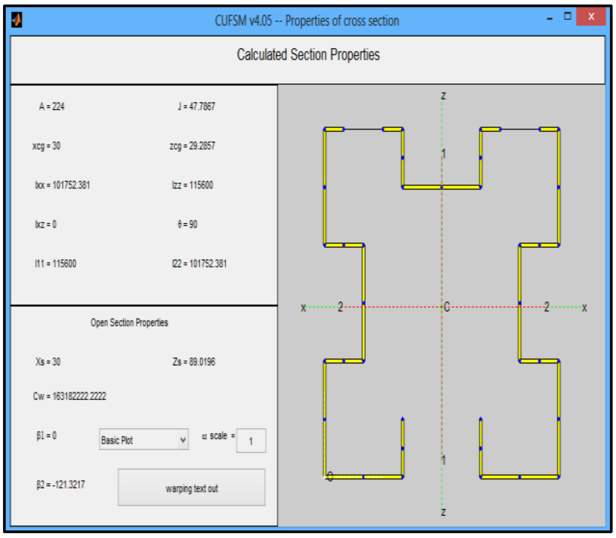
$$\text{For, } \lambda_c > 1.5;\ P_{ne} = \left(\frac{0.877}{\lambda_c^{\,2}}\right) \quad \text{….(3)}$$



ODB: Job-1.odb Abaqus/Standard 6.12-1 Sun Apr 06 12:29:10 India Standard Time 2014

Step: Step-1
Mode 1: EigenValue = 2.48214E-02
Primary Var: U, Magnitude
Deformed Var: U Deformation Scale Factor: +3.000e+02

Figure 5: First mode shape of the model



CUFSM v4.05 -- Properties of cross section

Calculated Section Properties

A = 224
J = 47.7867
xcg = 30
zcg = 29.2857
Ixx = 101752.381
Izz = 115600
Ixz = 0
θ = 90
I11 = 115600
I22 = 101752.381

Open Section Properties

Xs = 30
Zs = 89.0196
Cw = 163182222.2222
β1 = 0
β2 = -121.3217

Figure 6: Section geometry of a proposed section

Table 1. Comparison of DSM and FEM

Length (M)	DSM (KN)	FEM (KN)	% DIFF	Capacity With Modified Formula(KN)
1	128.74	264.51	51.33	-
1.5	100.06	130.44	23.29	-
2	70.426	79.206	11.09	-
2.5	46.031	56.597	18.67	-
3	32.1	41.583	22.81	-
3.1	30.107	39.495	23.77	-
4.6	13.875	22.67901	38.82	21.23939017
6.1	8.049	15.649	48.57	14.13234558
7.6	5.319	11.645	54.32	10.41877331

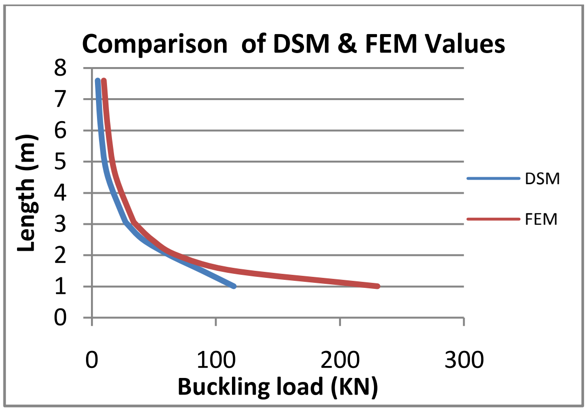


Figure 7: Comparison between DSM and FEM for 1.8 mm thick section

In the existing formula the dependency of P on length, thickness and λ is not considered. But we have observed that it plays important role in deciding the P for global buckling. We need to incorporate the dependency of P on length, thickness, λ.
This can be incorporated as follows;

For$t < 1.5$

$$P = \frac{(t+0.4)}{(\lambda)^{\frac{(t+2)}{1.2}}} \times \frac{l}{(4+t)} \times P_y..(4)$$

For$1.5 \le t \le 2.5$

$$P = \frac{(t+0.7)}{(\lambda)^{\frac{(t+2)}{1.5}}} \times \frac{l}{(4+t)} \times P_y..(5)$$

This formula gives satisfactory results for slender column sections with perforations with 5 to 15 % variation.

VII. Conclusion

Lots of research is going on to simplify the design of Cold Formed Steel sections to make it more reliable and practically acceptable. Addition of perforations serves lot of advantages for the practical purpose but at the same time it generates complications in design. Considerable efforts are required to study the impact of hole on the strength of the member, especially slender members.

The above suggested modification in the formula for slender column with perforation is just a small step towards this and more rigorous study for different sections with different boundary conditions, perforations is needed to carry out to sharpen the available formulae and achieve more accuracy in predicting the buckling load carrying capacity of thin walled sections.

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