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Load carrying capacity of innovative Cold Formed Steel column.

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***ABSTRACT**: Cold Formed Steel is an excellent alternative to the traditional hot-rolled steel section as it is very light in weight and has a high strength to weight ratio. Considerable research has resulted in a simplified method of CFS design known as Direct Strength Method (DSM). This method is now well established in the codes of practices for the design of CFS because of its simplicity. With recent advances in the manufacturing technology of CFS, it is possible to manufacture sections with perforations which are utilised for plumbing, electrical and any other functional purpose. Current DSM method is validated mainly for the sections without perforations. Due to its simplicity in predicting the capacity of the section, this method is employed to calculate load carrying capacity of innovative CFS column sections with perforations by developing Finite Strip Models and using Direct Strength Method. Freely available Finite Strip Program, CUFSM, is used for analysis.*
***Keywords:** Cold Formed Steel, CUFSM, Direct Strength Method, Finite Strip Analysis, and Perforations.*

1. INTRODUCTION

In countries like India, where there is scarcity of shelter, particularly for the economically backward class, there is a need to provide an alternative which will provide an economical solution. 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 material.

Cold formed steel beams and columns are typically manufactured with perforations to enhance their functional use. For example, in low and midrise construction, holes are prepunched in columns to accommodate the passage of utilities in the walls and ceilings of buildings as shown in Fig. 1.1. In case of cold-formed steel storage rack columns, perforations allow for variable shelf configurations as shown in Figure 1.2. Currently, Members with discrete holes, are limited to certain hole sizes, shapes, and configurations. It greatly hampers an engineer's design flexibility and decreases the reliability of cold-formed steel components where holes exceed these prescriptive limits.

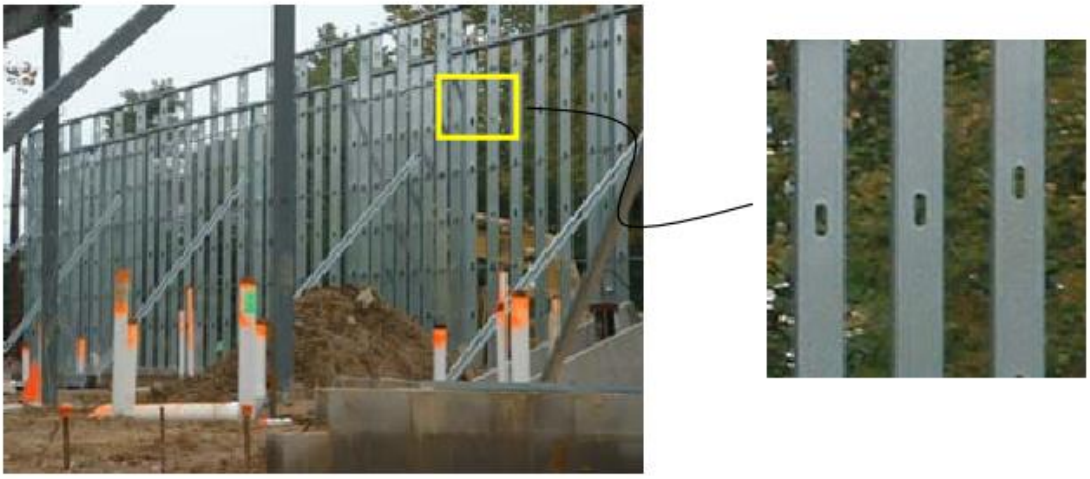

Figure 1.1 Perforations Pattern[1]

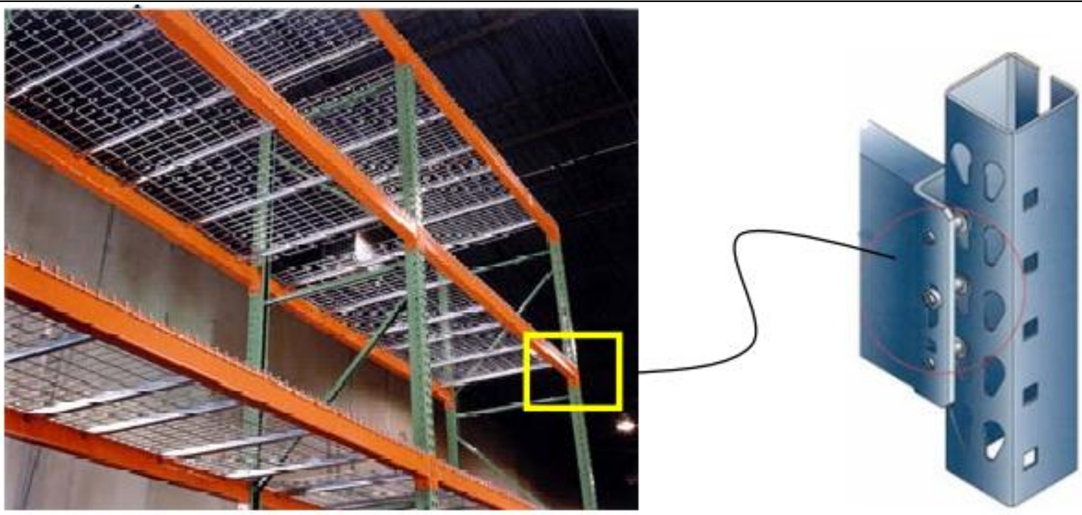

Figure 1.1 Hole patterns in storage rack columns[1]

2. DIRECT STRENGTH METHOD

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 manufactures 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.

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.

2.1 Finite Strip Method

The Finite Strip Method (FSM) is the basis for the DSM. Similar to the Finite Element Method (FEM), the FSM consists of segregating a member into longitudinal strips over the cross-section as shown in Figure 2.1. Once a member is divided into strips, a numerical stability analysis is performed utilizing conventional matrix techniques.

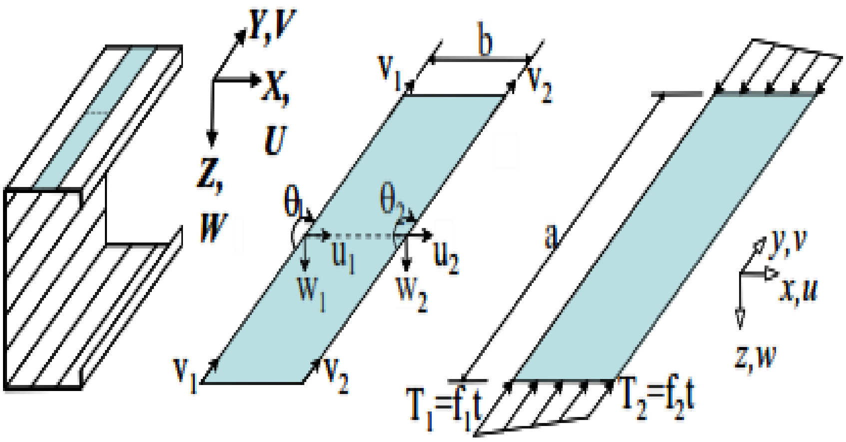

Figure 2.1.1 Coordinates, Degrees of Freedom, and Loads of a Typical Strip[2]

For a given distribution of edge tractions on a member the geometric stiffness scales linearly, this leads to the stability eigenvalue problem of interest, which for a single eigen (buckling) mode, φ, and eigen(buckling) value λ may be expressed as

$$K_e\varphi = \lambda K_g\varphi \quad (2.1)$$

Both Ke and Kg are a function of the strip length, *a*. Therefore, the elastic buckling value and the corresponding buckling modes are also a function of a. The problem can be solved for several lengths, *a*, and thus a complete picture of the elastic buckling value and modes can be determined. The minima of such a curve can generally be considered as the critical buckling loads and modes for a member. CUFSM follows this implementation and an example is provided in Figure 2.2

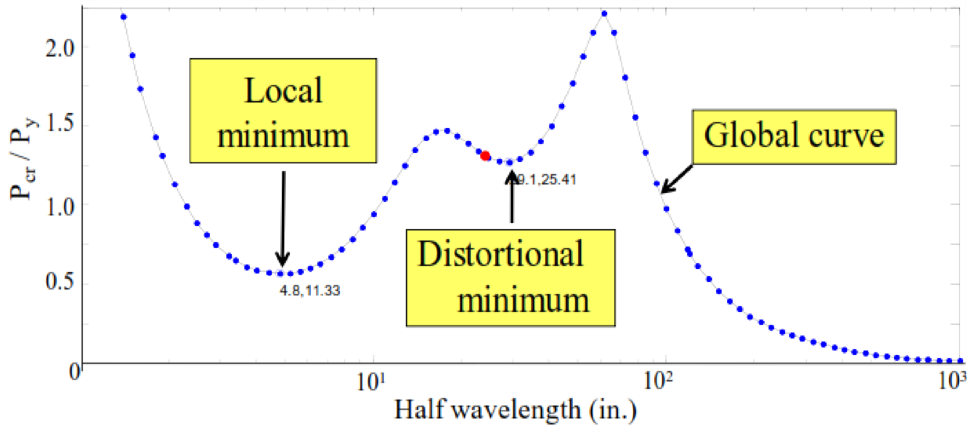

Figure 2.1.2 FSM Output.[2]

2.2 DSM Equations

Capacity of the column is calculated as per DSM based upon three limit states viz. global buckling, local buckling and distortional buckling. The Global, Local, Distortional slenderness ratios are considered correspondingly to calculate the section capacity as per the DSM equations. i.e.

2.2.1: Flexural, Torsional, or Torsional-Flexural Buckling.

The nominal axial strength, Pne for flexural, or torsional- flexural buckling is ,

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

$$\text{For, } \lambda_c > 1.5;\ P_{ne} = \left(\frac{0.877}{\lambda_c^{\,2}}\right) P_y \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2.2.1)$$

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

$$Py = A_g F_y$$

Where, Pcre= Minimum of the critical elastic column buckling load in flexural, torsional, or torsional-flexural buckling.

2.2.2: Local Buckling.

The nominal axial strength, P_{nl}, for local buckling is,

$$\text{For, } \lambda_l \le 0.776;\ P_{nl} = P_{ne}$$

$$\text{For, } \lambda_l > 0.776;\ P_{nl} = \left(1 - 0.15\left(\frac{Pcrl}{Pne}\right)^{0.4}\right)\left(\frac{Pcrl}{Pne}\right)^{0.4} Pne \ldots\ldots\ldots\ldots\ldots\ldots(2.2.2)$$

$$\lambda_l = \sqrt{\frac{Pne}{Pcrl}}$$

Pcrl = Critical elastic local column buckling load.

2.2.3: Distortional Buckling.

The nominal axial strength, P_{nd}, for distortional buckling is

$$\text{For, } \lambda_d \le 0.561;\ P_{nd} = P_y$$

$$\text{For, } \lambda_d > 0.561;\ P_{nd} = \left(1 - 0.25\left(\frac{Pcrd}{Py}\right)^{0.6}\right)\left(\frac{Pcrd}{Py}\right)^{0.6} Py \ \ldots\ldots\ldots\ldots\ldots\ldots(2.2.3)$$

$$\lambda_d = \sqrt{\frac{Py}{Pcrd}}$$

Pcrd= Critical elastic distortional column buckling load.

3. PROPOSED SECTION

The equations of DSM were modified by Moen C.D.[] to accommodate the influence of holes. He proposed six alternatives out of which following equations predicted the column capacity more accurately. Equation (2.2.3) was modified as,

For, $\lambda_d \le \lambda_{d1},\ \ P_{nd} = P_{ynet}$

$$\text{for } \lambda_{d1} \le \lambda_d \le \lambda_{d2}, \quad Pnd = Pynet - \left(\frac{Pynet - P_{d2}}{\lambda_{d2} - \lambda_{d1}}\right)(\lambda_d - \lambda_{d1})$$

$$\text{for } \lambda_d > \lambda_{d2}, \qquad Pnd = \left(1 - 0.25\left(\frac{Pcrd}{Py}\right)^{0.6}\right)\left(\frac{Pcrd}{Py}\right)^{0.6} Py \text{ ....(3.1)}$$

$$\text{When, } \lambda_{d1} = 0.561\left(\frac{Pynet}{Py}\right); \quad \lambda_{d2} = 0.561\left[\left[14\left(\frac{Py}{Pynet}\right)^{0.4}\right] - 13\right];$$

$$P_{d2} = \left(1 - 0.25\left(\frac{1}{\lambda_{d2}}\right)^{1.2}\right)\left(\frac{1}{\lambda_{d2}}\right)^{1.2} Py$$

Other equations remain same provided that the the critical elastic buckling loads Pcrℓ, Pcrd, and Pcre are calculated including the influence of holes.

Following member cross-section is proposed for the study. The thickness of the section is 3 mm and overall length is 3m. The section has holes longitudinally at 200mm c/c.

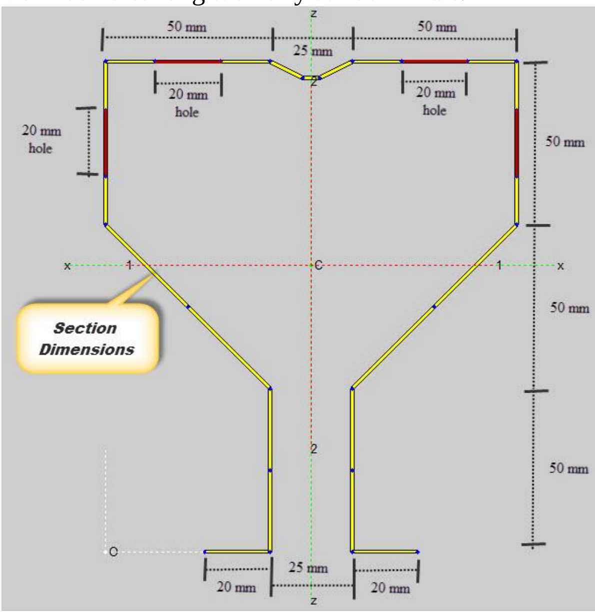

Figure 3.1 Proposed Cross- section

3.1 Local Buckling

Local buckling in perforated column is assumed to occur either buckling in gross cross-section between perforations (Pcrlnh) or buckling of the unstiffened strips of web adjacent to a perforation, (Pcrlh). The buckled mode shape with the lowest critical buckling load is Pcrl. To get the value of Pcrnh , the gross cross section is analysed in CUFSM. The procedure followed in this case is similar to the DSM design guide for unperforated section.

The Pcrlh i.e. net section elastic buckling curve is generated in CUFSM by deleting all nodes and elements in perforated region. Here to isolate the local buckling from distortional buckling, corners are to be restrained in z-direction.

A reference stress of 6.894 N/mm^2 is applied to the cross-section to generated the buckling loads.

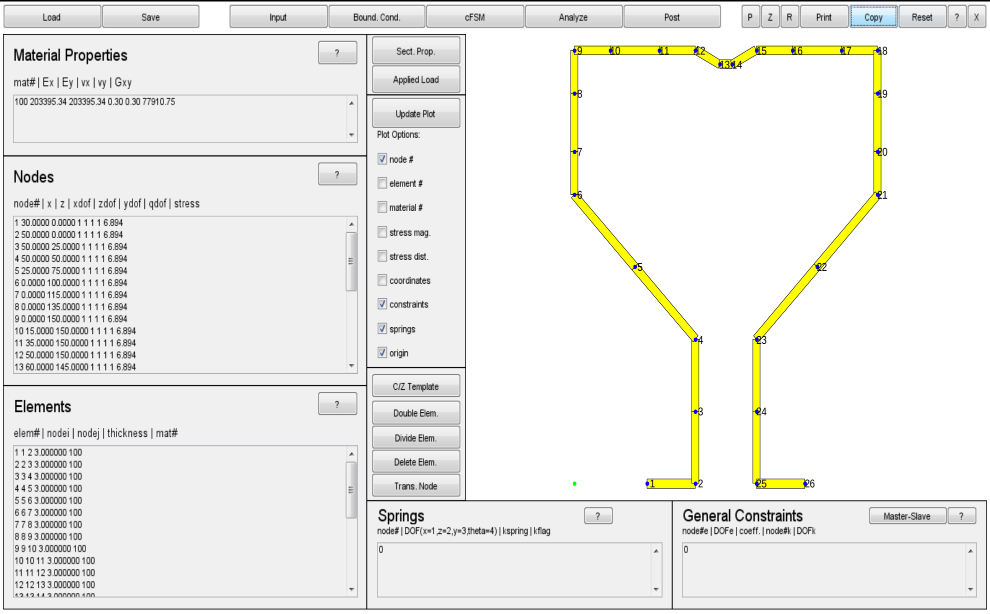

Figure 3.2 Geometry of proposed section in CUFSM.

For gross cross section,
Analysis input, for 1 ksi, i.e. 6.894 N/mm2 stress,
Py=10522.63 N , Output gives load factor = 156.51 and half wave length = 200 mm

$$\therefore \frac{P_{crlnh}}{P_y} = 156.51$$

$$P_{crlnh} = 156.51 \times 10522.63$$

$$P_{crlnh} = 1646.79 \text{ kN}$$

For net cross section.
To isolate local buckling from distortional buckling, corners of the section are restained in z-direction.

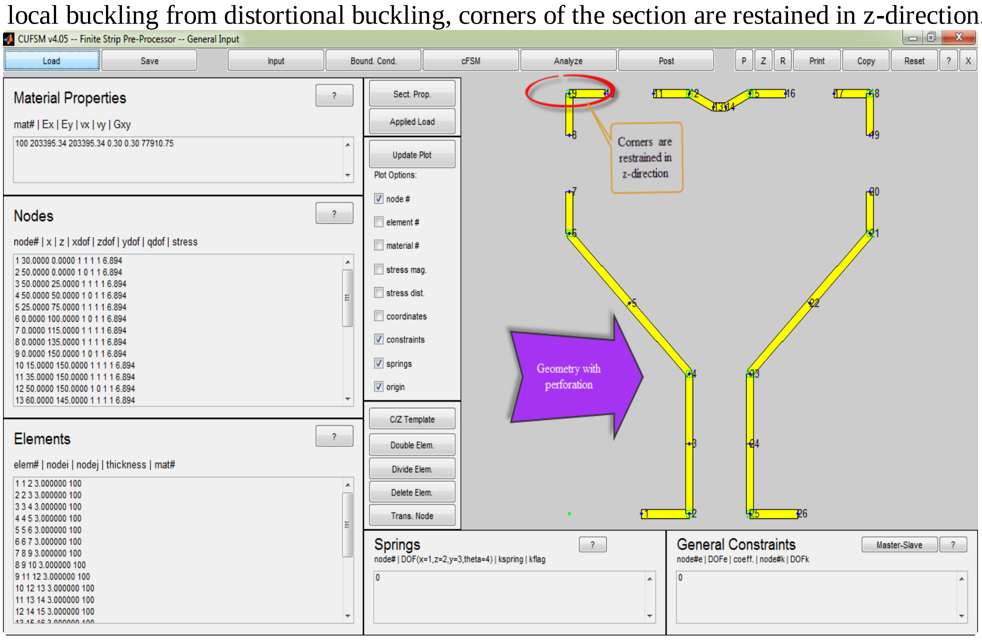

Figure. 3.3 Net cross section in CUFSM

Analysis input, stress =6.894 N/mm2
Py=8868.07 N, output gives load factor =234.53 and half wave length = 60 mm,

$$\therefore \frac{P_{crlh}}{P_y} = 234.53$$

$$P_{crlh} = 234.53 \times 8868.07$$

$$P_{crlh} = 2079.81 \text{ kN}$$

Pcrl is minimum of Pcrlnh and Pcrlh.

∴ Pcrl =1646.79 kN.

3.2 Distortional Buckling.

The section does not have a distinct local minimum corresponding to distortional buckling (Figure 3.3), and therefore a constrained finite strip analysis (Schafer and Ádàny 2006) is performed in CUFSM to identify *Lcrd* (Figure 3.6). The constrained finite strip analysis is performed with a straight corner model to obtain *Lcrd* (Schafer and Ádàny 2006). Analysis input, Stress = 6.894 N/mm2, Py=10522.63 N,

Output gives, Load factor =170.89 and half wave length = 200mm

$$\therefore \frac{P_{crd}}{P_y} = 170.89$$

$$P_{crd} = 170.89 \times 10552.63$$

$$P_{crd} = 1798.10 \text{ kN}$$

Reduced web thickness is then found out and implemented in second finite strip analysis to get correct value of Pcrd

The reduced web thickness is calculated with (Moen and Schafer 2009a)

$$t_r = \left(1 - \frac{L_h}{L_{crd}}\right)^{1/3} t$$

$$t_r = \left(1 - \frac{20}{200}\right)^{1/3} 3$$

$$t_r = 2.896 \ mm$$

Where, Lh= length of hole.

Second finite strip analysis is performed with the reduced web thickness i.e.2.896 mm

Analysis input, Stress=6.984 N/mm2, Py= 10379.234 N.

Analysis output gives, Load factor = 150.46, half wave length =200 mm.

$$\therefore \frac{P_{crd}}{P_y} = 150.46$$

$$P_{crd} = 150.46 \times 10379.234$$

$$P_{crd} = 1561.62 \text{ kN}$$

It is found that perforations result in 13% reduction in section capacity in distortion.

3.3 Global Buckling.

To restrain global translation in x-direction and tensional rotation about z- axis, Mid-height bracing is provided. It results in following unbraced lengths. For unbraced column, K=1

Lx=1500 mm	Kx=1.0
Ly=3000 mm	Ky=1.0
Lt=1500 mm	Kt= 1.0

Holes are provided along length at 200 mm c/c. It results 13 nos of holes in 3000mm length. Therefore,

Lyg=3000-(13x 20)=2740 mm.

Lynet=(13x20)=260 mm.

Lxg=1370mm

Lxnet=130mm

Ltg=1370 mm

Ltnet=130 mm

As the holes are symmetrically placed, the geometric factor *T* is zero.

To calculate flexural and flexural – torsional buckling, weighted average of section properties are calculated as follows.

Table.3.1 Gross and Net section properties

(A) Gross Section Properties			**(B) Net Section Properties**		
A_g	$mm.^2$	**1526.34**	A_{net}	$mm.^2$	**1286.34**
I_x	$mm.^4$	**4255210.31**	I_{xnet}	$mm.^4$	**3507985.55**
I_y	$mm.^4$	**2457248.32**	I_{ynet}	$mm.^4$	**1815748.32**
r_x	mm.	**52.80**	r_{xnet}	mm.	**52.22**
r_y	mm.	**40.12**	r_{ynet}	mm.	**37.57**
J	$mm.^4$	**4579.03**	J_{net}	$mm.^4$	**3859.03**
C_w	$mm.^6$	**37228958356.51**	C_{wnet}	$mm.^6$	**34951849828.87**
X_0	mm.	**0**	X_{0net}	mm.	**0**
Y_0	mm.	**129.22**	Y_{0net}	mm.	**156.21**
I_{x0}	$mm.^4$	**4255210.31**	I_{x0net}	$mm.^4$	**3507985.55**
I_{y0}	$mm.^4$	**27944175.66**	I_{y0net}	$mm.^4$	**33204456.28**
r_{x0}	mm.	**52.80**	r_{x0net}	mm.	**52.22**
r_{y0}	mm.	**135.30**	r_{y0net}	mm.	**160.66**
r_o	mm.	**145.23**	r_{onet}	mm.	**168.93**

$$I_{xavg} = \frac{Ix.Lxg + Ixnet.Lxnet + Tx(Ix - Ixnet)}{Lx}$$

$$I_{xavg} = \frac{4255210.31 \times 1500 + 3507985.55 \times 130 + 0}{1500} = I_{xavg} = 4190450.83 \text{ mm}^4$$

$$I_{yavg} = \frac{Iy.Lyg + Iynet.Lynet + Ty(Iy - Iynet)}{Ly}$$

$$I_{yavg} = \frac{2457248.32 \times 2740 + 1815748.32 \times 260 + 0}{300} = I_{yavg} = 2401651.65 \text{ mm}^4$$

$$r_{yavg} = \left(\frac{r_y Lyg + r_{ynet} Lynet + Ty(r_y - r_{ynet})}{Ly} \right)$$

$$r_{yavg} = \left(\frac{40.12 \times 2740 + 37.570 \times 260 + 0}{3000} \right) = r_{yavg} = 39.899 \text{ mm}$$

$$r_{xavg} = \left(\frac{r_x Lxg + r_{xnet} Lxnet + Tx(r_x - r_{xnet})}{Lx} \right)$$

$$r_{xavg} = \left(\frac{52.80 \times 1370 + 52.22 \times 130 + 0}{1500} \right) = r_{xavg} = 52.749 \text{ mm}$$

$$\mathrm{J}_{avg} = \left(\frac{J.L_{tg} + J_{net}.L_{tnet} + Tt(J - J_{net})}{L_t} \right)$$

$$\mathrm{J}_{avg} = \left(\frac{4579.038 \times 130 + 3859.03 \times 130 + 0}{1500} \right) = J_{avg} = 4516.63 \text{ mm}^4$$

$$r_{oavg} = \left(\frac{r_o.L_{tg} + r_{onet}.L_{tnet} + T_t(r_o - r_{onet})}{L_t} \right)$$

$$r_{oavg} = \left(\frac{145.237 \times 1370 + 168.93 \times 130 + 0}{1500} \right) = r_{oavg} = 147.29 \text{ mm}$$

$$y_{oavg} = \left(\frac{y_o.L_{tg} + y_{onet}.L_{tnet} + T_t(y_o - y_{onet})}{L_t} \right)$$

$$y_{oavg} = \left(\frac{129.221 \times 1370 + 156.21 \times 130 + 0}{1500} \right) = y_{oavg} = 131.56 \text{ mm}$$

$$x_{oavg} = 0$$

The warping constant, Cw, does not follow weighted average approximation. It has to be calculated based upon distributed hole region in CUFSM or CUTWP. Distributed hole region, dh* , is calculated as given by Moen and Schafer 2009a.

In this case, there are two patterns of holes, due to symmetry, dh* is calculated as follows,

h= 50-3=47 mm

h_0=h , out to out depth of element containing hole.

$$d_h^* = d_h + \frac{1}{2}(h_o - d_h)\left(\frac{d_h}{h_o}\right)^{0.2}$$

$$d_h^* = 20 + \frac{1}{2}(47 - 20)\left(\frac{20}{47}\right)^{0.2}$$

$$d_h^* = 31.379 \text{ mm}$$

$$C_{wavg} = 0.641 \text{ in}^6$$

3.3.1 Global Buckling Loads. (AISI-S100-07, section C4)

$$\sigma_{ex} = \frac{\pi^2 EI_{xavg}}{A.(K_x.L_x)^2}$$

$$\sigma_{ex} = \frac{\pi^2 203395.34 \times 4190450.83}{1526.34 \times (1 \times 1500)^2} = 2449.44 \text{N/mm}^2$$

$$\sigma_{ey} = \frac{\pi^2 EI_{yavg}}{A.(K_y.L_y)^2}$$

$$\sigma_{ey} = \frac{\pi^2 203395.34 \times 2401651.65}{1526.34 \times (1 \times 3000)^2} = 350.95 \text{N/mm}^2$$

$$\sigma_t = \frac{1}{A.r_{oavg}^2}\left[G.J_{avg} + \frac{\pi^2 EC_{wavg}}{(K_t.L_t)^2}\right]$$

$$\sigma_t = \frac{1}{1526.34 \times 147.29^2}\left[77910.75 \times 4516.63 + \frac{\pi^2 \times 203395.34 \times 32489574138.784}{(1 \times 1500)^2}\right] = 883.114 \text{ N/mm}^2$$

$$\beta = 1 - \left(\frac{y_{oavg}}{r_{oavg}}\right)^2 \quad \because \quad \text{(AISI Eq C 4.1.2-3)}$$

$$\beta = 1 - \left(\frac{131.56}{147.29}\right)^2 = 0.202$$

$$\sigma_{eyxt} = \frac{1}{2\beta}[\sigma_{ex} + \sigma_t] - \sqrt{(\sigma_{ex} + \sigma_t)^2 - 4.\beta\sigma_{ex}.\sigma_t} \quad \because \quad \text{(AISI Eq C 4.1.2-1)}$$

$$\sigma_{eyxt} = \frac{1}{2 \times 0.202}[350.95 + 883.114] - \sqrt{(350.95 + 883.114)^2 - 4 \times 0.202 \times 350.95 \times 883.114}$$

$$\sigma_{eyxt} = 319.65 \text{ N/mm}^2$$

$$P_{cre} = A \times \text{Min } (\sigma_{ex}, \sigma_{ey}, \sigma_{eyxt})$$

$$P_{cre} = 1526.34 \times \ (319.65)$$

$$P_{cre} = 487.903 \text{ kN}$$

3.4 Ultimate strength calculations.

Inputs are, Pynet=8.868 kN, Py=10.522 kN, Pcrl=1646.79 kN, Pcrd=1561.62 kN, Pcre=487.903 kN.

From DSM Equations.(refer section 2.2)

3.4.1 DSM Global buckling Strength.

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

$$\lambda_c = \sqrt{\frac{10522}{487903}} = 0.1468$$

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

$$P_{ne} = \left(0.658^{0.1468^2}\right) 10522$$

$\therefore P_{ne} = 10.47$ kN

3.4.2 DSM local buckling Strength.

$$\lambda_l = \sqrt{\frac{Pne}{Pcrl}}$$

$$\lambda_l = \sqrt{\frac{10.47}{1646.79}} = 0.079$$

For, $\lambda_l \le 0.776;\ P_{nl} = \text{Min}\ (P_{ne}, P_{ynet})$

$\therefore P_{nl} = \text{Min}\ (10.47, 8.868)$

$P_{nl} = 8.868$ kN

3.4.3 DSM Distorsional buckling Strength.

$$\lambda_d = \sqrt{\frac{Py}{Pcrd}}\ .$$

$$\lambda_d = \sqrt{\frac{10.522}{1561.62}} = 0.082$$

$$\lambda_{d1} = 0.561\left(\frac{Pynet}{Py}\right)$$

$$\lambda_{d1} = 0.561\left(\frac{8.868}{10.522}\right) = 0.472$$

$$\lambda_{d2} = 0.561\left[\left[14\left(\frac{Py}{Pynet}\right)^{0.4}\right] - 13\right]$$

$$\lambda_{d2} = 0.561\left[\left[14\left(\frac{10.522}{8.868}\right)^{0.4}\right] - 13\right] = 1.117$$

$$P_{d2} = \left(1 - 0.25\left(\frac{1}{\lambda_{d2}}\right)^{1.2}\right)\left(\frac{1}{\lambda_{d2}}\right)^{1.2} Py$$

$$P_{d2} = \left(1 - 0.25\left(\frac{1}{1.117}\right)^{1.2}\right)\left(\frac{1}{1.117}\right)^{1.2} 10.522 = 7.19 \text{ kN}$$

For, $\lambda_d \le \lambda_{d1},\ \ P_{nd} = P_{ynet}$

$\therefore$

$P_{nd} = 8.868$ kN

Predicted column capacity,

Pn= Min (Pne, PnL, Pnd)

Pn=8.868 kN.

4. CONCLUSION

Direct Strength Method is simple and has wide applicability. It does not depend upon effective width calculations and iterations. Most importantly it encourages engineers to optimise the section for the most effective use. Perforations providing functional advantage generate complexities in the analysis and design at the same time. Conventional method based upon effective width concept become tedious to apply for innovative sections. In this paper DSM is applied to calculate load carrying capacity of the innovative cold formed steel column. It is found that there is considerable decrease in the distortional buckling and overall column capacity due to perforations.

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