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Scopus Compendex and Geobase Elsevier,
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Journals, Poland, Directory of Research Journals

International Journal of Earth Sciences and Engineering

www.cafetinnova.org

ISSN 0974-5904, Volume 09, No. 03

June 2016, P.P.258-263

Flexural Behaviour of Cold Formed Steel Hat Shaped Beams

ASHOK M, JAYABALAN P AND JAYA PRABHAKAR K
Department of Civil Engineering, National Institute of Technology, Tiruchirappalli, Tamilnadu, India
Email: *ashok_citizen@yahoo.com*

Abstract: The hat shaped cold formed steel sections are commonly used in light-weight steel constructions, such as residential, industrial and commercial buildings. Hat sections are torsionally rigid than other sections and have a greater resistance to lateral-torsional buckling. This paper presents the flexural behaviour of cold formed steel hat shaped beams with different d/b based on codal provisions. The finite element model is developed to compare with the theoretical results. The finite element model is used to investigate the effect of factors such as d/b ratio and lip size which affects the ultimate strength behaviour of the hat shaped section. The parametric study has been done for various lip sizes ranging from 10 mm to 20 mm with increment of 5 mm and d/b ratio varying from 0.5 to 1 at 0.25 increments. The ultimate strengths obtained from the theoretical analysis and the finite element analyses are compared. The results show that with the increase in the lip size of the hat shaped sections, the load carrying capacity of the beam increases.

Keywords: *Cold formed steel, Hat sections, Finite elements, Direct strength method*

1. Introduction

Metallic materials are widely used in many ways such as buildings, automobiles, railway coaches, utility poles, aircrafts, ships, agricultural machinery, and electrical equipment and so on. There are two main types of metallic materials for construction, namely hot rolled and cold formed steel. Hot rolled sections are quite familiar. Cold formed steel sections are typically thin-walled members. The thickness of steel sheet in cold formed constructions is usually 1 to 3 mm, generally not thicker than 12.5 mm. The method of forming the cold formed steel sections by cold rolling or press brake operation or bending brake operation. The most common section of cold formed steel flexural members are C and Z sections. Now a days hat and sigma sections are mostly used for a secondary member such as purlins and grits.

The complex stability behavior of hat shaped section such as local, distortional and lateral-torsional buckling affects the ultimate strength. Relatively short-wavelength buckling of individual elements of the section lead to local buckling. Lateral-distortional buckling occurs at cross section whereas translation and rotation at the compression flange of the member leads to distortional buckling. Asim Karim has investigated the global optimization of cold-formed steel hat-shape beams based on the AISI Specifications using the computational neural network model. The steel yield strengths varied from 250 N/mm^2 to 345 N/mm^2. The loading on the beam is assumed to be a uniformly-distributed load of intensity q. In the parametric studies, span length is varied from 2 m to 8 m. The intensity is varied from 2.5 kN/m to 20 kN/m. The global optimum values of the thickness (t), the web flat depth to thickness ratio (d/t), and the flange flat width to thickness ratio (b/t) for the hat sections were obtained [1]. The flexural behaviour of cold formed steel beams subjected to non-uniform bending caused by transverse loading was investigated by means of buckling, post buckling, and collapse and DSM design. The critical load factors evaluated by GBT (Generalized Beam Theory) analysis, plastic collapse load factors obtained from first order elastic-plastic Shell Finite Element Analysis(SFEA) and ultimate load factors calculated by nonlinear elastic-plastic SFEA were also performed in ANSYS [2]. The post buckling behaviour and the ultimate strength of thin-walled structural members were investigated by the finite element method considering both geometrical nonlinearity and material nonlinearity. Hat section and channel sections were used for this research study [3]. Erik Stefan Bernard developed profiled steel decks with flat-hat stiffeners. The experimentally determined buckling stresses were compared with computer analysis based on the finite-strip method. The existing design procedure for local buckling in Australian Standard AS1538-1988 and various methods involving distortional buckling were compared with the test results [4]. Shan-shan Cheng has investigated the analytical study of the flexural buckling and lateral–torsional buckling of cold-formed steel channel section beams subject to combined compression and bending about their major and minor axes. The worst case for the buckling of a cold-formed channel section beam is when it is subjected to pure compression, which yields the lowest critical compressive stress [7]. M. Bock has investigated the parametric study and proposed a new equation to predict the ultimate strength of stainless steel cold-formed members subjected to web crippling. The results have also been compared with the European design rules and all available experimental results found in the literature to assess their applicability. The study was focused on square hollow sections (SHS), rectangular hollow sections (RHS) and hat sections undergoing concentrated loads in one flange. A new unified web crippling resistance expression based on numerical simulations and thereafter validated with experimental results was proposed [5]. A. Uzzaman has investigated the use of cold-formed steel top-hat sections for purlins as an alternative to conventional zed-sections. Effect of different thicknesses and steel grades were studied. The results were compared against Eurocode 3 design calculations and finite element analysis. The Z-sections were shown to be more efficient for all cases, while the comparison showed that top-hat sections performed similarly for frame spacing's of 3 m and 4 m. For frame spacing's of 5 m and 6 m, use of top-hat sections would not be efficient [17]. Nirosha Dolamune Kankanamge has investigated the lateral–torsional buckling behavior of simply supported cold-formed steel lipped channel beams subjected to uniform bending. They show that both vertical and lateral deflections at failure increases with increase in span and that the beam failure occurred suddenly in the case of shorter spans [6].

Only a limited number of researches had reported on the cold formed steel hat shaped sections. This paper presents the behavior of hat shaped section modeled using finite element software and evaluated numerically with the Direct Strength Method (DSM).

2. Material Properties

In the present study, the stress-strain curve was considered as bilinear. The following material properties were taken for a thickness of 2mm.

Young's modulus, E=205 GPa, Poisson's ratio, μ=0.3, Yield stress, f_y=250MPa[2].

3. Design of Cold-Formed Steel Sections

The two important theoretical predictions by using codal methods, namely, the effective width method (EWM) and the direct strength method (DSM).

3.1 Direct Strength Method (DSM)

Direct Strength, has been formed to decrease the current complexity, ease of calculation, provide a better and flexible design procedure, and integrates with established numerical methods. Advantages of the Direct Strength Method of design include

- no effective properties for strength,
- no element calculations,
- no iteration for beams,
- gross properties of the section used for strength calculations,
- interaction of elements in local buckling (e.g., web/flange interaction),
- reduction in systematic error in portions of the main Specification,

Use of the Direct Strength Method requires determination of the elastic buckling behavior of the member and using that data in a series of ultimate strength curves to predict the strength. Ultimate strength is a function of elastic buckling stress and the yield stress of the material. The method has been widely examined for beams and columns only.

The nominal flexural strength M_n is the minimum of M_{ne}, M_{nl} and M_{nd} as given below.

3.1.1 Lateral-torsional buckling

The nominal flexural strength M_{ne}, for lateral-torsional buckling, is shown as follows:

For $M_{cre} < 0.56M_y$

$$M_{ne} = M_{cre}$$

For $2.78M_y \geq M_{cre} \geq 0.56M_y$

$$M_{ne} = \frac{10}{9}M_y\left(1 - \frac{10M_y}{36M_{cre}}\right)$$

For $M_{cre} > 2.78M_y$

$$M_{ne} = M_y$$

Where $M_y = S_f F_y$

M_{cre} = Critical elastic lateral-torsional buckling moment

S_f = Gross section modulus

3.1.2 Local buckling

The nominal flexural strength M_{nl}, for local buckling, is shown as follows:

For $\lambda_l \leq 0.776$

$$M_{nl} = M_{ne}$$

For $\lambda_l > 0.776$

$$M_{nl} = \left(1 - 0.15\left(\frac{M_{crl}}{M_{ne}}\right)^{0.4}\right)\left(\frac{M_{crl}}{M_{ne}}\right)^{0.4} M_{ne}$$

Where $\lambda_l = \sqrt{\frac{M_{ne}}{M_{crl}}}$

M_{crl} = Critical elastic local buckling moment

3.1.3 Distortional buckling

The nominal flexural strength M_{nd}, for distortional buckling, is shown as follows:

For $\lambda_d \leq 0.673$

$$M_{nd} = M_y$$

For $\lambda_d > 0.673$

$$M_{nd} = \left(1 - 0.22\left(\frac{M_{crd}}{M_y}\right)^{0.5}\right)\left(\frac{M_{crd}}{M_y}\right)^{0.5} M_y$$

$$\text{Where } \lambda_d = \sqrt{\frac{M_y}{M_{crd}}}$$

M_{crd} =Critical elastic distortional buckling moment

3.2 Effective Width Method (EWM)

In the American Iron and Steel Institute publication introduced to the concept of ``effective width" of stiffened elements of a cold-formed section. The cold-formed members have very high width-to-thickness ratios; they are likely to buckle elastically under low compressive stress. A certain width of the plate close to the corners is still effective in resisting further compressive load while the stiffened edges of the plate remain stable. The original width of the plate which is still effective is called ``effective width". This method delivers a clear model for the locations in the cross-section where material is ineffective in carrying load and incorporate local–global interaction where reduced cross-section properties influence global buckling.

4. Finite Element Modelling

The model cross section of the hat section beam is shown in Figure 1.

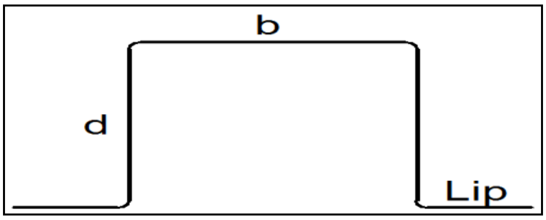

***Figure 1** Cross section of hat shaped beam*

The flexural behavior of hat shaped section was studied by modeling using ABAQUS versions 6.11 part module. It includes geometry modelling, property and section assigning, assembling, meshing, defining boundary conditions and analysis. Models created and explained about linear and non-linear static analysis. Each component of the beam was modelled as a three dimensional (3D) deformable planer shell element and simple hat section model as shown in Figure 2. The geometric parameters considered for the present study are given in Table 1.

***Table 1:** Cross section dimensions for hat shaped beams*

Parameter	Details
Span of the beam	2000mm,2500mm and 3000mm
Thickness	2mm
d/b ratio	0.5, 0.75 and 1
Lip size	10mm, 15mm and 20mm

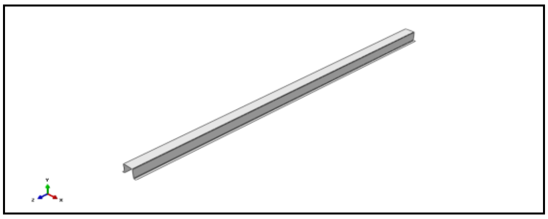

***Figure 2** Hat shaped section model*

4.1 Element type and Meshing

The hat shaped beams are modelled using shell element. S4R element type was chosen. S4R is a 4-noded doubly curved thin shell element, reduced integration, hourglass control. A mesh convergence study was made as tabulated in Table 2. Based on the mesh convergence study a mesh size of 35x35 mm was chosen. Assembled and meshed model as shown in Figure 3.

***Table 2:** Mesh convergence*

Mesh size, mm.	No. of Elements	Ultimate Load, kN.
60	333	6.14
50	497	9.16
45	557	9.24
40	636	8.9
38	656	8.89
35	716	8.91
32	955	8.92
30	1003	8.91
20	2008	8.4

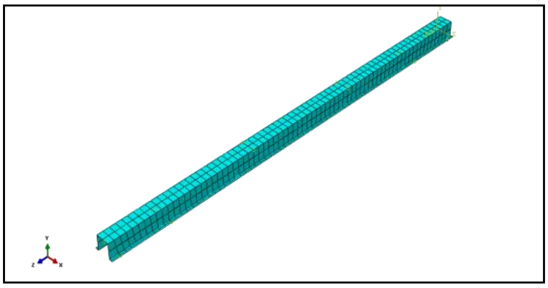

***Figure 3** Assembled and meshed model*

4.2 Boundary Condition and Loading

All the beams were modelled for simply supported conditions only. A total span of 2100mm was adopted. In the model, a span of 2500mm was chosen such that an outer projection of 200mm was allowed on either side of the beam. To simulate the pinned support, all degrees of freedom of the nodes except the rotation in X direction were constrained, whereas for the roller support only the translations in the X and Y were constrained. The translations in the direction X of all nodes located at each end of both supports were constrained in order to prevent their lateral deformation. Two point loading applied at one third of the span, was considered for linear and non-linear analysis in ABAQUS. The corresponding ABAQUS model is shown in Figure 4.

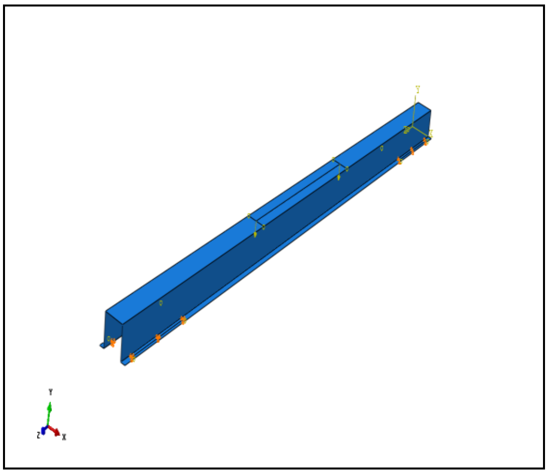

Figure 4 *Boundary condition and loading*

4.3 Non-Linear Analysis

Initially buckling modes were established by doing linear perturbation analysis. Under the loading; the Eigen values were obtained from which the elastic buckling load was calculated. In the next step, the RIKS analysis was performed to establish non-linear behaviour wherein geometrical non linearity was incorporated. Material non linearity was also incorporated as a function of depth of web. An imperfection of 1/300 of depth of web was adopted in appropriate mode shape [8].

4.4 Validation of the Model

The validation of modelling was done using the input from Basaliga, camotim and coda[2].

A mesh size of 20mmX20mm was adopted and S4R element type was used. An imperfection scale factor of L/1000 was used where 'L' is the effective length of the beam. The section details and the ultimate loads are given in the Table 3.

Table 3: *Section dimensions and ultimate loads*

Beam	L (mm)	B (mm)	d (mm)	t (mm)	Ultimate Load (kN) Journal	Ultimate Load (kN) FEM	% Error
1	1000	60	120	1	10.4	10.1	2.9
2	2000	60	120	2	48.7	47.8	1.8
3	4000	60	120	2	22.9	22.5	1.7

5. Results and Discussions

5.1 Eigen Value Buckling Analysis

The linear perturbation step available in ABAQUS, which can be used for elastic buckling analysis. The Eigen buckling modes are shown in Figure 5.

5.2 Comparison of Ultimate Load

Linear and non-linear analyses are carried out for hat shaped cold formed beams and the results are compared with direct strength method as shown in Table 4. The deformed shape of the hat shaped section is shown in Figure 6.

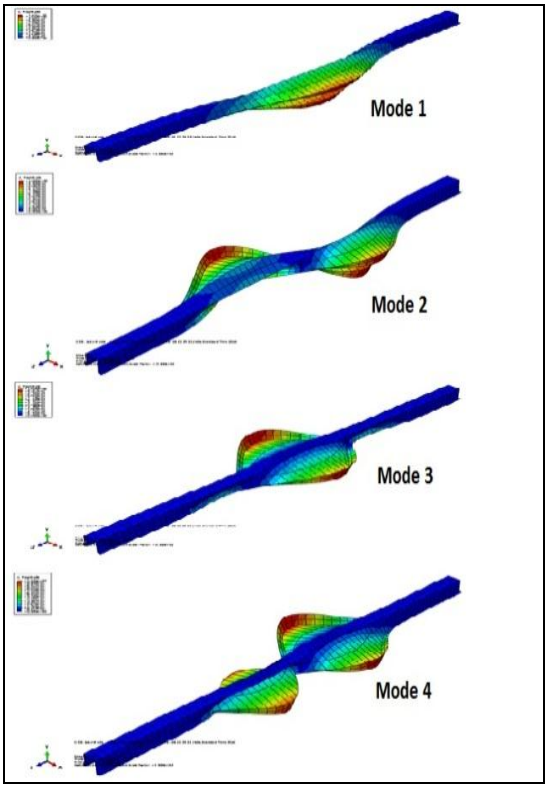

Figure 5 *Elastic buckling modes from ABAQUS*

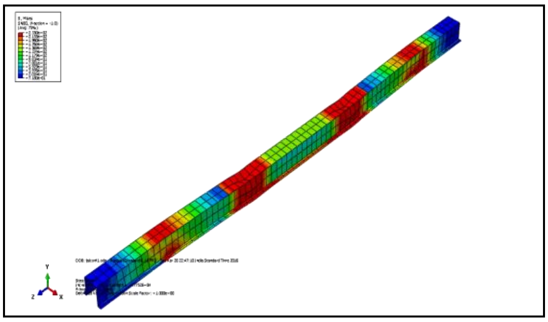

Figure 6 *Local buckling*

Table 4: *Ultimate load calculated using DSM and FEM*

L (mm)	Hat (mm) (d x b x Lip)	d/b	Ultimate load in kN DSM	Ultimate load in kN FEM	FEM/ DSM
2000	80x160x10	0.5	8.22	8.75	1.06
	80x160x15		9.93	9.58	0.96
	80x160x20		8.88	10.00	1.13
	80x107x10	0.75	8.75	9.12	1.04
	80x107x15		9.35	9.99	1.07
	80x107x20		11.02	10.53	0.96
	80x80x 10	1	9.34	8.97	0.96
	80x80x 15		9.53	9.95	1.04
	80x80x 20		9.75	10.12	1.04
2500	80x160x10	0.5	7.52	6.98	0.93
	80x160x15		7.65	7.05	0.92
	80x160x20		7.93	7.79	0.98
	80x107x10	0.75	9.51	10.23	1.08
	80x107x15		9.94	10.98	1.10

	80x107x20		11.88	11.45	0.96
	80x80x 10	1	9.52	10.15	1.07
	80x80x 15		10.09	10.95	1.09
	80x80x 20		10.62	11.24	1.06
3000	80x160x10	0.5	6.95	6.15	0.88
	80x160x15		7.26	6.85	0.94
	80x160x20		7.73	7.05	0.91
	80x107x10	0.75	8.93	9.28	1.04
	80x107x15		9.33	9.89	1.06
	80x107x20		11.32	10.62	0.94
	80x80x 10	1	7.53	8.73	1.16
	80x80x 15		9.33	9.02	0.97
	80x80x 20		9.29	9.98	1.07

5.3 Effect of d/b ratio

As per AISI S100-2007 d/b ratio between 0.14 to 0.87. In this present study d/b ratio selected are 0.5, 0.75 and 1. With an increase in the d/b ratio, the member is subject to local buckling very earlier and has less load carrying capacity compared to the lower d/b ratio members. Load carrying capacity was increased up to the AISI S100-2007 limit and then decreased over the limit. This is due to the earlier local buckling of the member. The comparison chart drawn for three different d/b ratios is shown in Figure 7, Figure 8 and Figure 9.

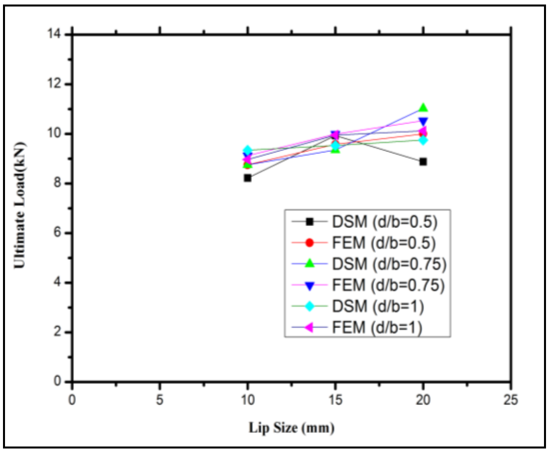

Figure 7 *Ultimate load vs lip size for L=2000mm*

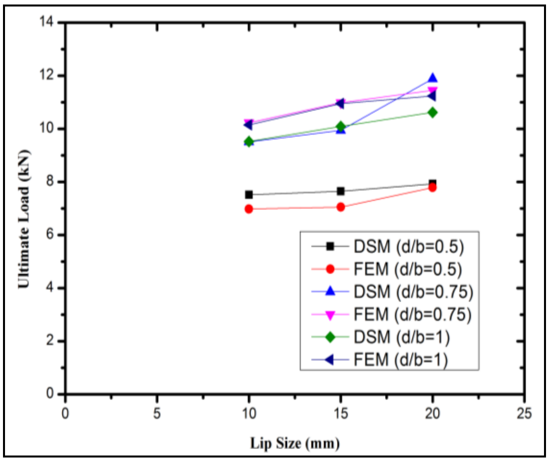

Figure 8 *Ultimate load vs lip size for L=2500mm*

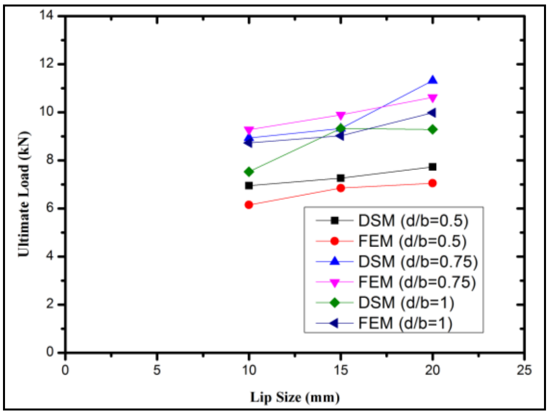

Figure 9 *Ultimate load vs lip size for L=3000mm*

5.4 Effect of Lip Size

With an increasing the lip size, load carrying capacity also increases. This is because webs are getting more stiffened with increase in lip size. Lip sizes of 10, 15 and 20 are used. Lip size of 20 takes more load than the lower one within the AISI S100-2007 limit. Hence further study needs to conclude the effect of lip size.

6. Conclusions

A total of 27 hat shaped beams were modeled in this study. Numerical investigation was carried out using direct strength method and compared with the FEM analysis. Based on the results obtained the following conclusions are drawn for the hat shaped sections. The hat shaped cold formed steel beams are predominantly affected by the local buckling failure mode. Load carrying capacity of the hat shaped sections increases with an increase in d/b ratio and also the lip sizes. Ultimate load obtained from FEM analysis has shown good comparison with the results of direst strength method. This hat shaped beams could be used as a flexural member in structures subjected to light and moderate loads.

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