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# EFFECT OF CONNECTORS INTERACTION IN BEHAVIOUR AND ULTIMATE STRENGTH OF INTERMEDIATE LENGTH COLD FORMED STEEL OPEN COLUMNS

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## ABSTRACT

This work aims to study the effect of connector interaction in behaviour and ultimate strength of intermediate length CFS open sections under axial compression. A stiffened channel section is considered for the study it included a total of 6 structural tests. Finite element models were developed using ANSYS including geometric and material non linearities. The numerical results were validated on the basis of the test results and both has good agreement with each other. An extensive parametric study on the influence of depth and spacing of connectors was carried out using this finite element procedure. The strength predicted by the finite element model and tested specimens of open sections were compared with the design strength calculated using the DSM–AISI 100:2007, AS/NZS: 4600-2005 and IS: 801-1975. Recommendations concerning the design of the section with connectors are given based on the results.

**Keywords:** Cold-Formed Steel; columns; connectors; thin walled members; distortional buckling

## 1. INTRODUCTION

Cold formed steel members have been widely used in building applications for over six decades in the world. But in India it is developing now. Cold formed steel members has different applications such as purlins, beams and columns etc. in industrial and housing systems. The reasons behind the growing popularity of these products include their ease of fabrication, high strength/weight ratio and suitability for a wide range of applications. Though they have many advantages, being thin elements they are prone to buckling. In

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compression, open cross sections have three instability modes, namely local, distortional and flexural / flexural torsional buckling. The behaviour of short compression member is well defined in the literature. The global buckling (flexural/flexural torsional) behaviour of cold-formed steel sections have been extensively studied in the past. The present Indian code of practice for design of cold formed steel members, is under revision. Local and global buckling occurs at relatively short and long half wave lengths respectively. But distortional buckling occurs at intermediate half wave length.

A brief review of literature on the ultimate strength and buckling modes of cold-formed steel columns are presented here.

Takahashi [1] was the first to publish a paper describing distortion of thin walled open section. Hancock [2] presented a detailed study of a range of buckling modes (Local, distortional, and flexural-torsional) in a lipped channel sections. Lau and Hancock [3] provided simple analytical expressions to allow the distortional buckling stress to be calculated explicitly for any geometry of cross-section of thin-walled lipped-channel section columns. Kwon and Hancock [4] studied simple lipped channels and lipped channels with intermediate stiffener under fixed boundary conditions. They chose section geometry and yield strength of steel to ensure that a substantial post-buckling strength reserve occurs in a distortional mode for the test section. Lau and Hancock [5] provided design curves for sections where the distortional buckling stress and yield stress were approximately equal. Davies and Jiang [6] used the Generalized Beam Theory to analyse the individual buckling modes either separately or in selected combinations.

Distortional buckling strength of few innovative and complex geometrical sections has been studied by S. Narayanan and M. Mahendran [8]. For intermediate length pallet rack columns, the distortional strength was studied by providing spacers to connect the flanges of upright sections by R.S. Talikoti, K.M. Bajoria [9]. The partly closed thin walled steel columns were studied by Milan Veljkovic, Bernt Johanson [10]. Kwon et. Al [11] studied the buckling interaction of the channel columns. M.V. Anil Kumar and V. Kalyanaraman [12] studied the evaluation of direct strength method for CFS Compression members without stiffeners.

Though many research works have been performed on buckling of thin-walled columns, only limited works have been made on interaction of connectors on the behavior and strength of intermediate length cold formed steel open columns.

The present study affiliates a new trend that could be applicable in light industrial steel building. In that regard, the possibility of using series of connectors in intermediate length CFS open columns to interconnect the lips is introduced. The ultimate capacity of axially loaded intermediate length CFS channels may adversely be affected by distortional buckling. Either to eliminate or delay distortional buckling mode the connectors are introduced. The primary objective of the research is to gain an improved understanding of the behaviour and strength of intermediate column with connectors under axial compression by using experimental and numerical methods. The main task is to examine the behaviour and strength of intermediate length pin-ended column with connectors for which there are no design rules currently available. Connectors are the transverse elements of CFS sheet used to connect the lips of the open sections using self-driving screw. For this work, stiffened channel section was considered. A finite element model simulating the behaviour of this of section was developed. The results obtained from the finite element analysis were verified against the tests conducted on this section. Totally six columns were tested (One full open, one full closed and others are with connectors of 1 to 4). Parametric study was performed to investigate the effect of connectors on the behaviour and strength of this section by varying the depth and interval of connectors. The results obtained from the numerical analysis and experimental study for the full open sections are compared with design strength calculated using the DSM – AISI 100:2007, AS/NZS : 4600- 2005 and IS: 801-1975 for cold-formed steel structures.

## 2. EXPERIMENTAL RESEARCH

*2.1 General and selection of section*

A stiffened lipped channel section has chosen for the study. The cross-sectional dimensions are fixed based upon the limitations given in the draft IS 801 code. The ends of the columns are considered to be pinned and the length is taken as 1600mm. The length of the column is chosen in the range where distortional buckling occurs by performing elastic buckling analysis using CUFSM software.

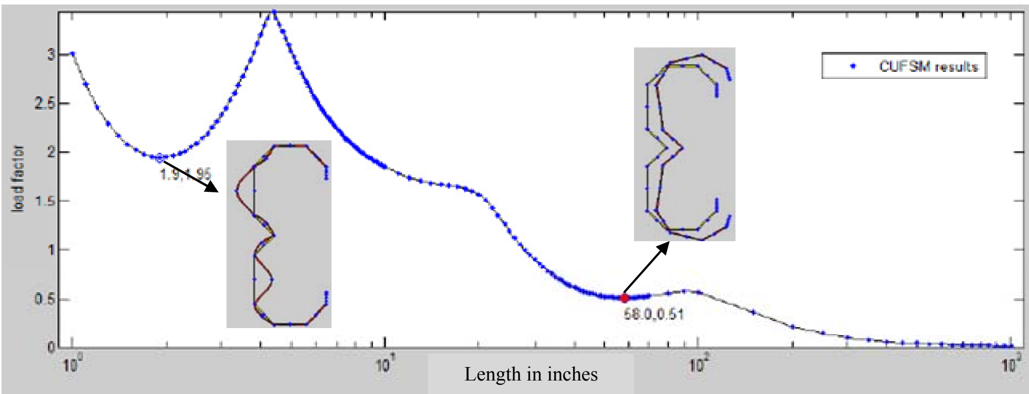


Figure 1. Buckling plot for channel section

The load factor of buckling stress for each buckling mode is plotted against the buckle half wave length (in inches) is shown in Figure 1 for SS-C0 section. From the figure it can be observed that distortional buckling occurred at intermediate half wave length of approximately 1473 mm and also the rotation of the sides about the uppermost flange web junction. The chosen dimensions and cross-section profile is shown in Figure 2. The following are the naming convention for the test specimens

1st Term : Test specimen type: SS – Stiffened section

2nd Term: Number of connectors: C0 – No connector, C1 – One Connector, CC–Closed connector

3rd Term: Depth of connector: d50 – connector depth is 50mm, d75 – connector depth is 75mm

The fully closed specimen is achieved by closing the entire open area of the cross section with 12 nos of equally spaced screws on each side of the lip leaving a gap of 5 mm at the top and bottom to allow axial deformation. Figure 4 shows the fully closed section.

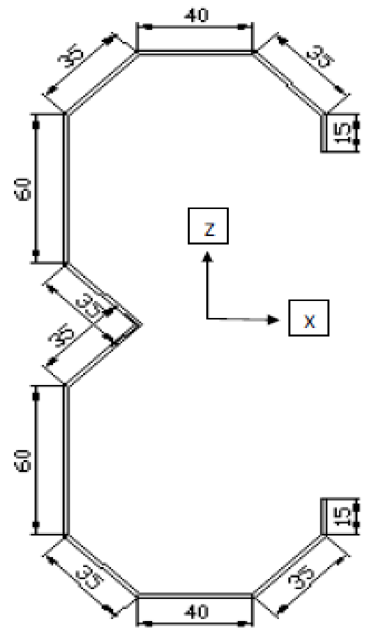


Figure 2. Cross section of channel column

*2.2 Material properties*

The coupons are prepared by using the same material which is used to prepare the test specimens. The material properties were determined by carrying out standardized tensile tests according to IS 1608-2005 (Part-1).

The material properties are shown below

Yield Stress ($f_y$) = 350 Mpa
Ultimate Stress ($f_y$) = 450Mpa
Young's Modulus (E) = 201GPa
Tangent Modulus ($E_t$) = 20.12 Gpa
Poisson's Ratio (m) = 0.3
% of elongation = 27%

*2.3 Test procedure*

The specimens are mounted between the platens and its verticality is checked. At either ends between the platens and the end plates of the specimen rubber gaskets were placed to facilitate the hinge condition at either supports.

Dial gauges were placed at mid height on web and flange to measure lateral displacement and one at the lower end to measure the axial deformation. The details of test arrangement are shown in Figure 3. The lateral and axial displacements of the column were recorded after every increment of 2000 N load. The ultimate load at which the deflection increased without increase of load is also recorded.

*2.4 Test results*

The deformed shape of SS-C0 section is shown in Figure 6. On observation it clearly indicates that the predominant mode of failure of the fully opened section is combined overall flexural buckling about minor axis and distortional buckling.

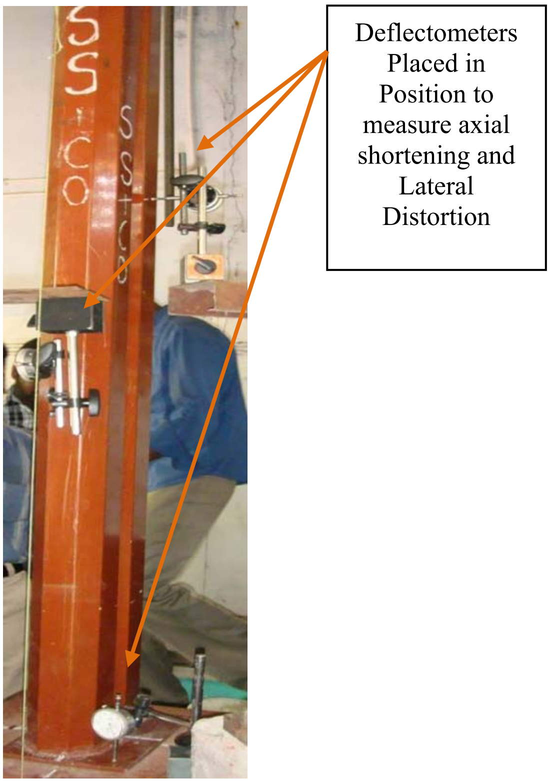


Figure 3. Test set up

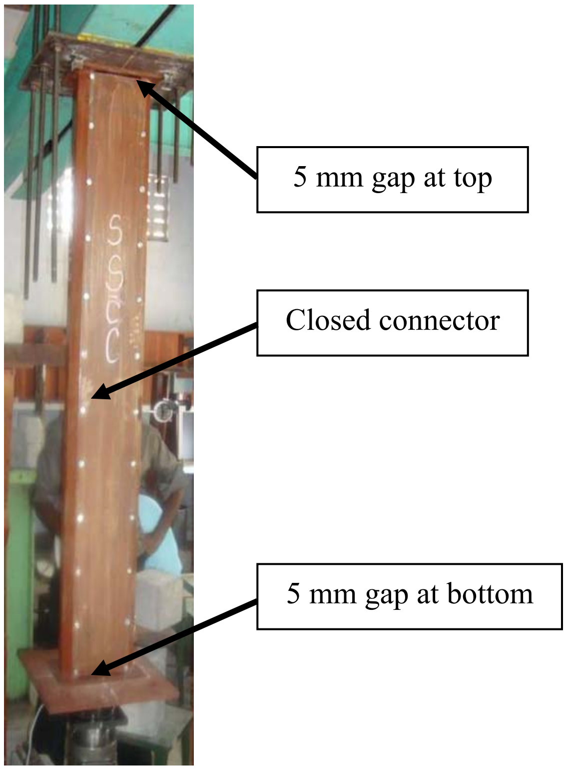


Figure 4. Fully closed section

Also the failure mode changes from combined overall flexural buckling about minor axis and distortional mode to interference of combined local, minor axis overall flexural buckling and distortional buckling mode due to the provision of connectors.

## 2. NUMERICAL ANALYSES

Numerical models were created using the general purpose finite element software ANSYS are validated on the basis of a selection of test results. The models were based on the centre line dimensions of the cross-sections. The residual stresses and the rounded corners of the sections were not included in the model. The effect of residual stresses on the ultimate load is considered to be negligible as recommended by Schafer and Pekoz [7]. Four noded finite linear strain element Shell 181 was used for discretisation of model. The element has six degrees of freedom per each node; three translations (Ux, Uy and Uz) and three rotations (Rx, Ry and Rz). This element is well suitable for analyzing the linear, large rotation, and/

large strain non linear applications. From the series of convergence studies, appropriate mesh size was chosen for this study. A linear buckling analysis was performed first to obtain the buckling loads, local and distortional buckling modes. The elastic modulus (E) was taken as 201000 N/mm$^2$.

The strain hardening of the corners due to cold forming is neglected. The pin-end conditions of the columns were modeled with the loaded end prevented from both rotation about the y-axis, and translations in both x and z directions. On the other hand, the unloaded end is prevented from translation in the three directions x, y, and z and from rotation along the y-axis. A rigid surface was modeled in the loaded end. The load was applied in increment through the master node which is modeled at the centroid of the section. Two types of analysis were carried out. The first is eigen value analysis to determine the buckling modes and load, where the second is non-linear analysis. Convergence study is performed to obtain an optimal element size used for the study. The yield stress of the material (fy) considered 350 N/mm$^2$. In order to account for the Elasto-plastic behaviour, a bilinear stress-strain curve is adopted, having a tangent modulus (Et) of 20120 N/mm$^2$.

The material and geometric nonlinearity is included in the finite element model. In the nonlinear analysis, initial geometric imperfections are modeled by providing initial out-of-plane deflections to the model. The local and distortional buckling modes are extracted from linear buckling analysis. The mode shapes are scaled to percentage of thickness and it is used to create the geometric imperfections for the non-linear analysis. The maximum value of distortional imperfection was taken equal to the plate thickness as recommended by Schafer and Pekoz [7]. Local buckling imperfection was taken as 0.25 times the thickness. Since kwon and Hancock [4] found that the overall imperfections had little effect on the buckling of the columns of intermediate length since these columns generally buckled in a local, distortional, or mixed mode of local and distortional buckling. Therefore this study does not include any overall imperfections in finite element modelling.

## 3. VALIDATION

The FE analysis results are validated by comparing it with the experimental results of these six specimens. The comparisons of ultimate loads ($P_{EXP}$ and $P_{FEA}$) are shown in Table 1. It can be seen that good agreement has been achieved between the experimental and numerical results of all the columns. The mean and standard deviation of the Experimental to FEA ultimate loads are 0.974 and 0.0053 respectively. As an example, the load deflection curve obtained in FEA is compared with the test results for SS-C0 section in Figure 5 and it closely matches with the experimental results.

The shape of the failure mechanism obtained in FEA was very close to the experimentally obtained shape. Figure 6 shows the deformed shape of the SS-C0 column obtained experimentally and confirmed by the FE analysis. As can be seen, very good agreement was achieved. Similar results were obtained for other specimens also.

Table 1: Comparison of results

| Specimen ID | $P_{EXP}$ in kN | $P_{FEA}$ in kN | $\frac{P_{EXP}}{P_{FEA}}$ |
|---|---|---|---|
| SS-C0 | 122 | 126.27 | 0.966 |
| SS-C1-d50 | 138 | 141.88 | 0.973 |
| SS-C2-d50 | 144 | 147.06 | 0.979 |
| SS-C3-d50 | 146 | 149.19 | 0.979 |
| SS-C4-d50 | 148 | 153.48 | 0.964 |
| SS-CC | 162 | 164.58 | 0.984 |
| | | Mean = | 0.974 |
| | | Standard deviation = | 0.0079 |

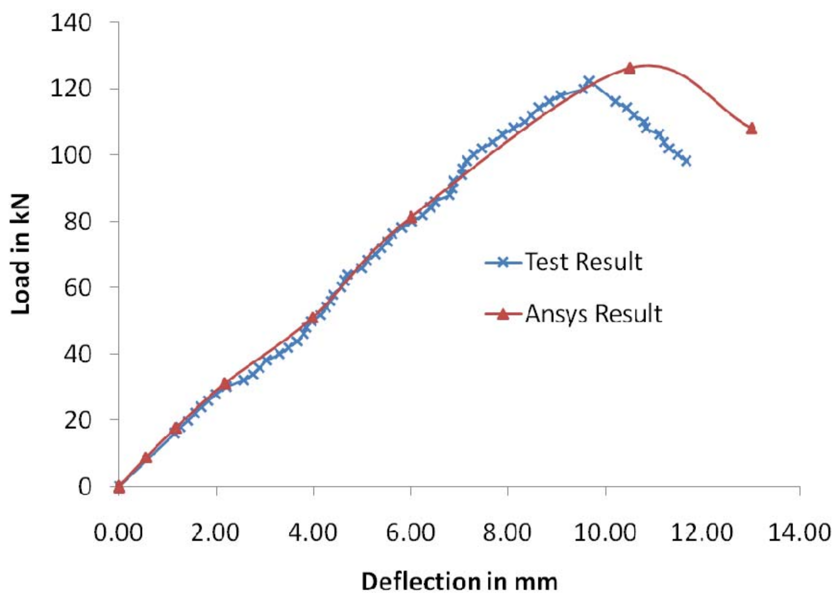


Figure 5. Comparison of results

## 4. PARAMETRIC STUDY

After validating the FEA model, the numerical analysis were continued by conducting a parametric study on the influence of the depth and spacing of connectors on the ultimate load of the column.

Figure 6. Deformed shape of SS-C0

There are several parameters that have direct influence on the response/behaviour of the column. The parameters are illustrated in Figure 7.

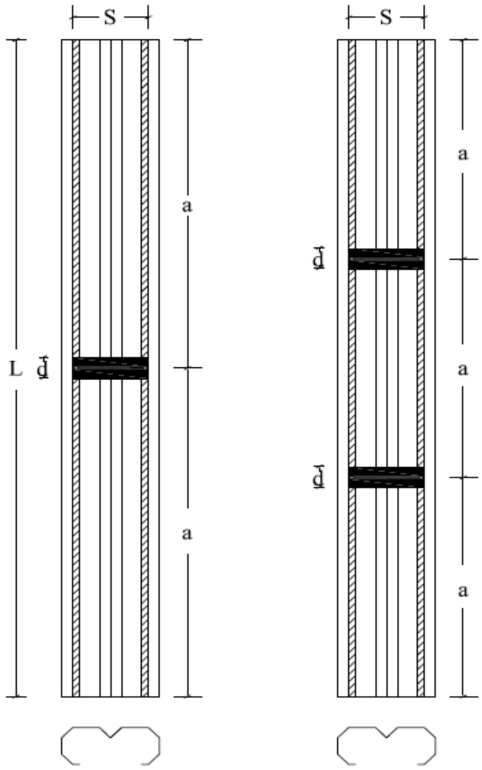


Figure 7. Geometry of the columns

- The term '$\lambda_s$' which is defined as the connector plate slenderness ratio and is given by,

$$\lambda_s = \frac{d}{t} - \sqrt{\frac{\sigma_y}{E}}$$

Where, d = depth of connector plate & t = thickness of connector plate

- The term 'a/L' which is defined as the ratio of the center to center distance (a) between connectors-to-the overall length (L) of the Column
- The term 'd/S' which is defined as the ratio of the depth of the connector plate-to-the breadth of the connector plate

The present study by vary the depth of the connector (d) as 50 mm, 75 mm & 100 mm and for each 'd' four specimens are considered by varying the number of connectors from 1 to 4. The width of the connector is 169.5 mm. Hence three group of sections are formulated based on the 'd/S' ratio. They are 0.295, 0.442, & 0.590. Since the number of connectors varies from 1 to 4, the 'a/L' ratio varies from 0.50, 0.33, 0.25 & 0.20. The Slenderness ratio of the column is 50.03. The combination of the number of connectors and the depth of connectors are shown schematically in Figure 8.

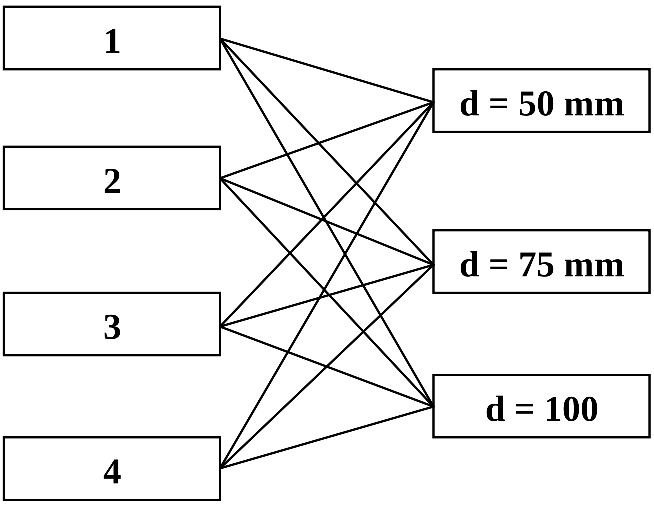


Figure 8. Schematic representation of parametric study

## 5. NUMERICAL RESULTS

The normalized ratios of the ultimate-to-the yield stress of the column were influenced by various parameters and are graphically represented in the following sub sections.

Figure 9 demonstrates the relationship between the normalized ratio of the centre to centre length between connectors to the overall length of the Column (a/L), and the normalized ratio of the ultimate stress to the yield stress of the column ($\sigma_u/\sigma_y$) for different values of (d/S). Obviously, the centre to centre length between connectors has a significant effect on the strength of columns. Enhanced column strength values were obtained upon decreasing the connectors spacing (a). Increasing the number of connectors from 1 to 4 improved the ultimate strength of the columns.

Figure 10 demonstrate the influence of changing the depth of the connector plate on the column strength for a slenderness ratio of 50.03. Apparently, as shown in Figure 10 the column strength increases with the increase in depth of the connector plate.

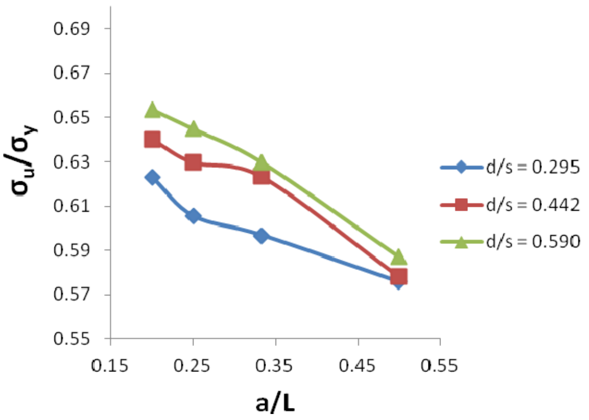


Figure 9. $\sigma_u/\sigma_y$ Vs a/L

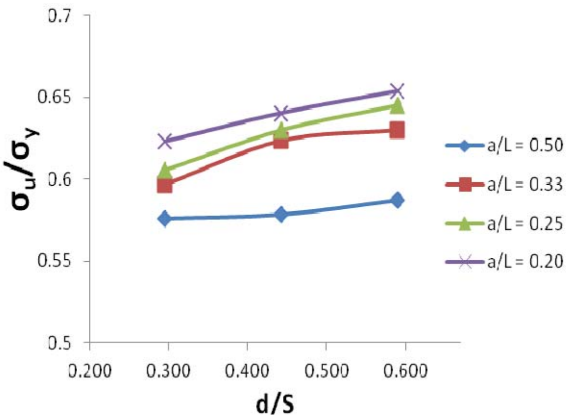


Figure 10. $\sigma_u/\sigma_y$ Vs d/S

Figure 11 demonstrate the influence of connector plate slenderness ratio on the column strength for a slenderness ratio of 50.03. Apparently, as shown in Figure 11 the column strength increases with the increase in plate slenderness ratio. The percentage increase in ultimate load of the column while varying the depth and number of connectors are shown in Table 2.

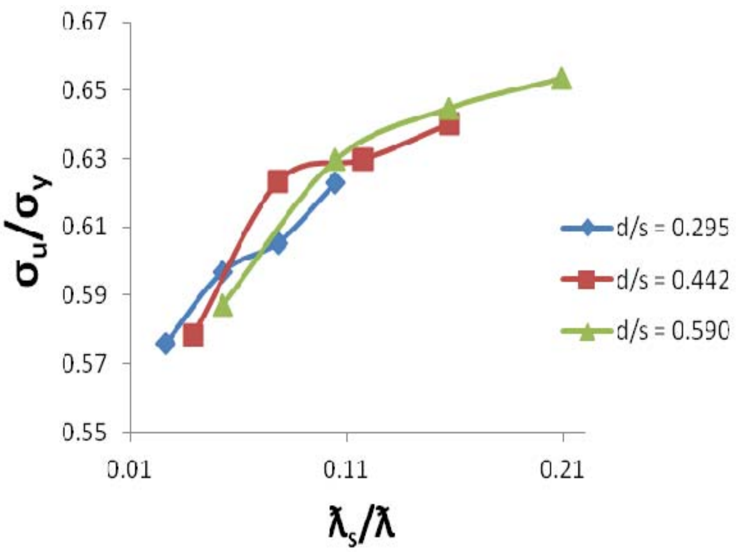


Figure 11. $\sigma_u/\sigma_y$ Vs $\lambda_s/\lambda$

Table 2: Increase in Load Carrying capacity of the column

| Specimen ID | Load in kN | % increase |
|---|---|---|
| SS – C0 | 126.27 | --- |
| SS – C0 – d50 | 141.88 | 12.36 |
| SS – C0 – d50 | 147.06 | 16.46 |
| SS – C0 – d50 | 149.19 | 18.15 |
| SS – C0 – d50 | 153.48 | 21.55 |
| SS – C0 – d75 | 142.5 | 12.85 |
| SS – C0 – d75 | 153.61 | 21.65 |
| SS – C0 – d75 | 155.19 | 22.90 |
| SS – C0 – d75 | 157.77 | 24.95 |
| SS – C0 – d100 | 144.71 | 14.60 |
| SS – C0 – d100 | 155.19 | 22.90 |
| SS – C0 – d100 | 158.9 | 25.84 |
| SS – C0 – d100 | 161.06 | 27.55 |
| SS – CC | 164.58 | 30.34 |

## 6. THEORETICAL ANALYSIS

The unfactored design column strengths were calculated for fully opened section using the Australian/ New Zealand Standards (AS/NZS 4600:2005)[15], Direct Strength Method by North American Specifications (AISI S100-2007)[14] and Indian standards (IS: 801-1975) [13].

The comparison of the unfactored design strengths predicted using the Australian/ New Zealand Standards (AS/NZS 4600:2005), Direct Strength Method by North American Specifications (AISI S100-2007) and Indian standards (IS: 801-1975) are shown in Table 4.

Table 4: Theoretical analysis results

| Specimen | Ultimate Load in kN | | | |
|---|---|---|---|---|
| | $P_{Exp}$ | $P_{DSM}$ | $P_{AS/NZ}$ | $P_{IS}$ |
| T1-C-C0 | 122 | 136.85 | 137.82 | 158.82 |

The design strength predicted by the AS/NZ 4600-2005, DSM and IS standards are unconservative. Since the predominant mode of failure of intermediate length columns is distortional, the mode of failure inferred from AS/NZ specifications, DSM of was distortional buckling. Whereas in IS method, the mode of failure inferred was flexural-torsional as there is no check for distortional buckling. Hence the IS method shows an elevated result than the other two specifications. So, it is mandatory that the IS code has to be revised incorporating the distortional buckling check.

## 7. DISCUSSIONS

From the parametric study, it is ascertained that interaction between parameters like connector plate slenderness ratio ($\lambda_s$), ratio of length (a/L) and ratio of depth to width of connector plate (d/S) influence the strength of the columns. The effect of yield stress ($\sigma_y$) and Young's modulus of elasticity (E) of the material are taken care in the calculation of connector plate slenderness ratio. With the addition of connectors in the columns, the failure mode shifted from combined overall flexural buckling about minor axis and distortional mode to interference of combined local, minor axis overall flexural buckling and distortional buckling modes. From the ultimate loads of all the columns with number of connectors 2,3 and 4, it is inferred that the occurrence of local buckling reduces the increase in percentage of load carrying capacity. The percentage increase in the ultimate load of the column with different depth such as 50 mm, 75 mm and 100 mm connectors over fully opened section ranges from 12.36 to 27.55%. For the column with closed connector, the ultimate load increased by a maximum of 30.34%.

## 8. SUMMARY AND CONCLUSIONS

The behaviour and ultimate strength of intermediate length cold formed steel stiffened channel columns with connectors are investigated by varying the depth and spacing of connectors and presented in this paper. The ends of the columns are considered as pinned. The specimens are modeled using ANSYS FE analysis software. Buckling analysis is carried out on the model and local, distortional modes are extracted to incorporate initial imperfections. The model includes material and geometric non linearities. The FE analysis is validated with the experimental results. Later, the FE analysis is extended by varying the depth and spacing of connectors. The load-deflection and failure modes are compared. The following conclusions are derived from the study:

- This study proved that the provisions of connectors increase the ultimate strength of the section.
- The ultimate strength increases with increase in depth and number of connectors.
- Among the different depth of connectors, the connector having 50 mm showed better improvement in ultimate strength.
- This investigation has shown that the use of connectors at proper depth and spacing do help increasing not only load carrying capacity but also vary mode of failure.
- The effect of increase in connectors from 2 to 4 for ultimate load is less compared to single connector for all the three depth of connectors.
- For open sections, the design capacity predicted by AS/NZ, DSM and IS 801-1975 codal provisions are unconservative.

- Since the distortional buckling mode governs the ultimate load of the intermediate length columns, it must be taken care in the design equations, which is not considered in IS 801-1975.

This investigation has also shown that further research is needed in the interaction of connectors in the ultimate load to be add in the design codal provisions for intermediate length columns.

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