

Evaluation of Reduction in Compressive Strength of Singly Symmetric CFS Members Due To Shift in Effective Centroid

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Abstract - Cold formed steel members are becoming increasingly popular within the construction industry due to their superior strength to weight ratio and ease of fabrication as opposed to hot rolled steel members. Cold-formed Lipped channel columns may buckle in three distinct modes, namely local buckling, distortional buckling and overall buckling. The main effect of local buckling is the redistribution of the longitudinal stress which causes the greatest portion of the load is carried near the plate junctions. Local buckling of plate elements of singly symmetric columns, such as channel section, causes overall bending of the column when the member is compressed between pinned ends. A uniformly compressed channel section undergoes shift in the line of action of the internal force resultant when the section locally buckles between pinned ends. In the design of such members it is necessary to account this shift of the effective centroid caused by local buckling. The purpose of this thesis is to estimate the reduction in strength due to shift of effective centroid of lipped channel compression members. Systematic parametric study using non-linear finite element analysis of the model which will be calibrated with available test results in the literature is used in this project. After comparing the FEM column ultimate strength with the strength predicted by the DSM, The DSM does not specify different procedures of pinned and fixed columns. i.e, as per DSM both pinned and fixed column should fail at same load. The finite element analysis clearly shows that the reduction between these are as high as 39%.

Key Words: Cold-formed column, Support conditions, Local buckling, Steel structures, Design rules.

1. INTRODUCTION

Cold-formed steel (CFS) structural members offers economical solution compared to hot-rolled members due to their high strength to weight ratio, ease of fabrication and construction. Further, the increased yield strength, post-buckling strength and suitability for a wide range of applications are the key advantages of CFS members. The market for these sections includes the secondary cladding and purlin applications as well as primary applications as beams and columns of industrial and housing systems under moderate loading conditions where common hot-rolled

sections would be under-stressed and hence operate at less than the full efficiency. The cold-formed steel structures has become increasingly popular in building construction all over the world. These sections are essentially of thin-plate elements with moderate to very high flat width to thickness ratio of the web or flange plate components. Such members are susceptible to local buckling at relatively low compressive stresses due to axial compression, shear, bending or bearing. However, a considerable reserve of post-local buckling strength exists due to the possibility of membrane actions after local buckling.

The main effect of local buckling is to cause a redistribution of the longitudinal stress in which the greatest portion of the load is carried near the plate junctions. The redistribution produces increased stresses near the plate junctions and high bending stresses as a result of plate flexure, leading to ultimate loads below the squash load of the section. However, in singly symmetric cross sections, the redistribution of longitudinal stress caused by local buckling also shift the line of action of the internal resultant force. When the section is compressed between pinned ends, which is referred to as the "shift of the effective centroid", This introduces overall bending due to eccentricity and reduction in the load carrying capacity. Overall bending induced by local buckling can significantly reduce the column strength and needs to be considered in design of such members. This leads to a beam column design approach, in which the applied moment is calculated as a product of the axial force and its eccentricity. The design eccentricity is found by determining the effective widths of each component plate and thus an effective cross-section with distinct centroid, referred to as the effective centroid. The design eccentricity is determined as the distance from the effective centroid to the applied force.

1.1 OBJECTIVES

- To study the buckling behaviour of cold formed lipped channel members compressed between fixed and pinned ends.
- To review and compare the various design provisions adopted for the CFS members.
- To quantify the reduction in column strength because of the combined local and overall bending for pinned column.
- Evaluate the accuracy of various design procedures adopted for CFS members such as DSM, MDSM etc.

1.2 NEED FOR STUDY

- Local buckling is an extremely important facet of cold formed steel sections on account of the fact that the very thin elements used will invariably buckle before yielding.
- Local buckling and cross-section distortion must be treated as an essential part of member design.
- Modifications to the design equation for the CFS members may be required for more economical and safe designs.

2. METHODOLOGY

The finite element non-linear analysis program ABAQUS version 6.13 was used to stimulate the ultimate loads, axial shortenings and failure modes of fixed ended cold-formed lipped channel columns. In the finite element model, the cross-section dimensions, material properties and initial geometric imperfections are selected from the column tests conducted by Ben young and Kim J.R Rasmussen were modelled and analysed.

The numerical simulation consisted of two stages. In the first stage, an eigen value elastic buckling analysis is performing on a perfect geometry to establish probable buckling modes of a column. In the second stage, a non-linear analysis by incorporating both geometric and material non-linearities is performing to obtain the ultimate load. Performing the parametric study to evaluate the strength of members by finding out the parameters that affect their strength.

The CUFSM (provides a method to examine all the instabilities in a CFS members) software is using to find out the corresponding buckling load (P_{cr1}). Then using CUTWP for finding out the length. After deciding the specimen thickness and length the actual strength is finding out from the FEA. Quantifying the reduction in column strength because of the combined local and overall bending for pinned column. Then Comparing various design provisions adopted for the CFS members with these FEA results. Evaluating the accuracy of various design procedures adopted for CFS members such as DSM, MDSM etc.

3. PARAMETRIC STUDY

It is shown in the previous chapter that FEM closely predicted the column strengths and the behaviour of the tested channels. Hence the finite element model was used for an extensive parametric study of lipped channel member. Currently, the non-dimensional elastic local buckling slenderness ratio, λl is the only parameter included in the equation for evaluating the non-dimensional strength. One of the aims of this study was to find the influence of parameters, other than the non-dimensional elastic local buckling slenderness ratio such as the actual section dimensions, the yield strength of the material (f_y), and the web depth to flange width ratio (h/b) on the normalized ultimate strength of the columns, which fail by yielding after

only local buckling. For the different values of the studied parameters, the thickness of the specimen (even if nonstandard) was chosen by trial and error, to obtain results for different specific desired values of λl . For this first varying the h/b as 0.5, 0.75, 1.0 and identifying the specimens. Then finding out the thickness of specimen in such a way that P_{ul} / P_y as 0.30, 0.50, 0.70, by using the equation in Kumar and Kalyan (2014)10.

In the case of local buckling:

for $\lambda l \leq 0.60$, $P_{ul} / P_y = 1.00$

for $\lambda l > 0.60$, $P_{ul} / P_y = [1 - \alpha_1 (P_{cr1} / P_y)^\beta] (P_{cr1} / P_y)^\beta \leq P_{ul, max} / P_y$

where $\alpha_1 = 0.27(2 - \mu)$

$\beta = (1/100)(50 - 7\mu) \geq 0.35$

$\mu = \max[h/b, (b/h)0.6]$

In the case of overall buckling:

For $\lambda c \leq 1.5$, $P_{ne} = [0.658 (\lambda c)^2] P_y$

For $\lambda c > 1.5$, $P_{ne} = [0.877 / \lambda c^2] P_y$

where $\lambda c = [P_y / P_{cre}]^{(1/2)}$

$P_y = A_g \cdot F_y$

In the case of distortional buckling:

for $\lambda d \leq 0.561$, $P_{ul - DSM} = P_y$

for $\lambda d > 0.561$, $P_{ul - DSM} = [1 - 0.25(P_{crd} / P_y)^{0.6}] (P_{crd} / P_y)^{0.6} P_y$

The lipped channel column cross-section dimensions and length were suitably chosen for buckling interaction between the local, distortional and global buckling modes. To ensure nearly coincident local, distortional and global buckling stresses (P_{cr1} , P_{crd} and P_{cre}), it was necessary to perform educated trial and error buckling analysis using the CUFSM software. The CUFSM (provides a method to examine all the instabilities in a CFS members) software is used to find out the corresponding buckling load (P_{cr1}). Then using CUTWP for finding out the length. After deciding the specimen thickness and length the actual strength is found out from the FEA.

4. MODELLING AND ANALYSIS

The ABAQUS, CUFSM and CUTWP software is used to model and analysis the elements. The global buckling analysis (flexural-torsional, lateral-torsional, etc) of thin-walled members can be an involved task. In finite element analysis using shell elements, the global buckling load need not be accurate due to interaction of other buckling modes. CUTWP provides the thin-walled cross-section properties necessary in such analysis and provides classic stability solutions as well.

The specimens considering for the analysis is shown below:

Table -1: Specimen dimensions for lipped channel sections

| Specimen | Lips (mm) | Flanges (mm) | Web (mm) | Thickness | Length |
|------------------|-----------|--------------|----------|-----------|--------|
| 150x150x15x1.068 | 15 | 150 | 150 | 1.068 | 4301 |
| 150x100x15x1.581 | 15 | 100 | 150 | 1.581 | 2996 |
| 150x100x15x2.543 | 15 | 100 | 150 | 2.543 | 2149 |
| 150x200x15x2.577 | 15 | 200 | 150 | 2.577 | 3239 |
| 150x200x15x8.463 | 15 | 200 | 150 | 8.463 | 2360 |

4.1 BOUNDARY CONDITION AND METHOD OF LOADING

The channel columns compressed between fixed ends, pinned ends as reported in the experiments are simulated in finite element analysis. The fixed-ended boundary condition was modelled by restraining all the degrees of freedom of the nodes at both ends, except for the translational degree of freedom in the axial direction at the top end of the column. This is due to the load applied at the top end of the column. The nodes other than the two ends were free to translate and rotate in any directions. The loading method used in the finite element analysis (FEA) was identical to that used in the tests. The displacement control method was used for the analysis of the columns. Axial compressive load was applied to the column by specifying a displacement to the nodes at the top end of the column. The maximum displacement of 6 mm was applied.

5. RESULT AND DISCUSSIONS

The lipped channel 150x150x15x1.068 of fixed ended specimen analysis result is as follows:

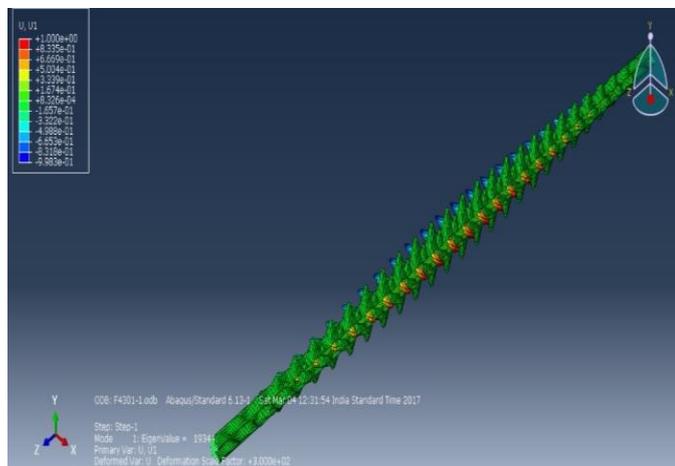


Fig -1: Fixed end condition local buckling mode of 150x150x15x1.068

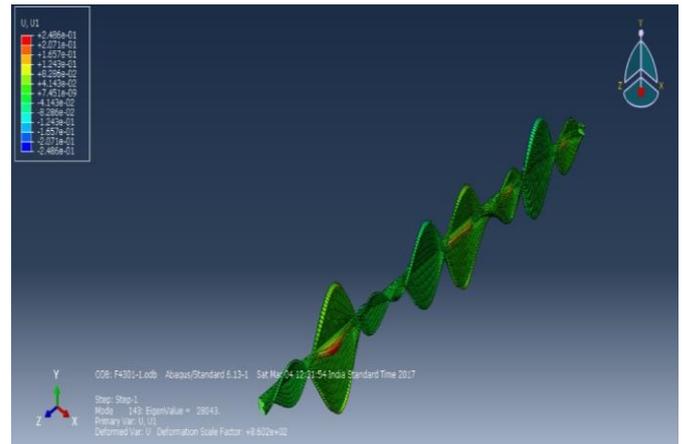


Fig -2: Fixed end condition distortional buckling mode of 150x150x15x1.068

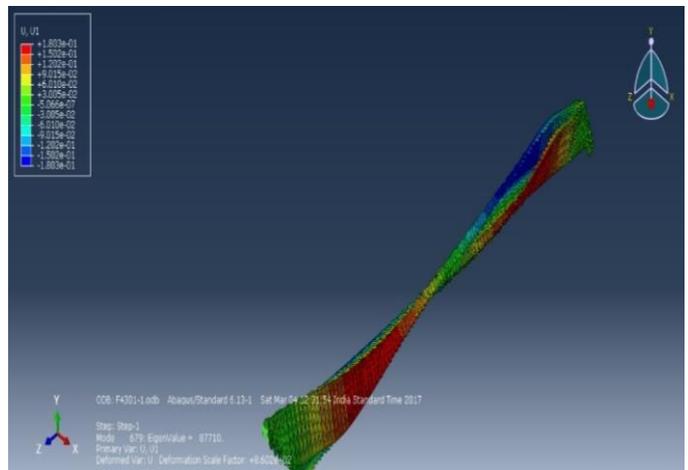


Fig -3: Fixed end condition overall buckling mode of 150x150x15x1.068

The lipped channel 150x150x15x1.068 of pinned ended specimen analysis result is as follows:

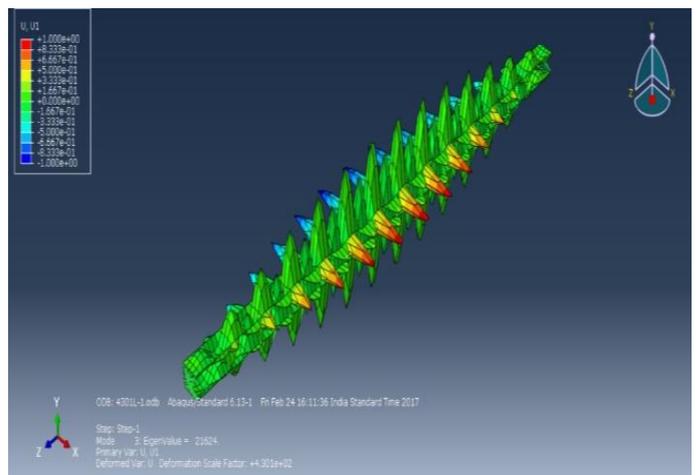


Fig -4: Pinned end condition local buckling mode of 150x150x15x1.068

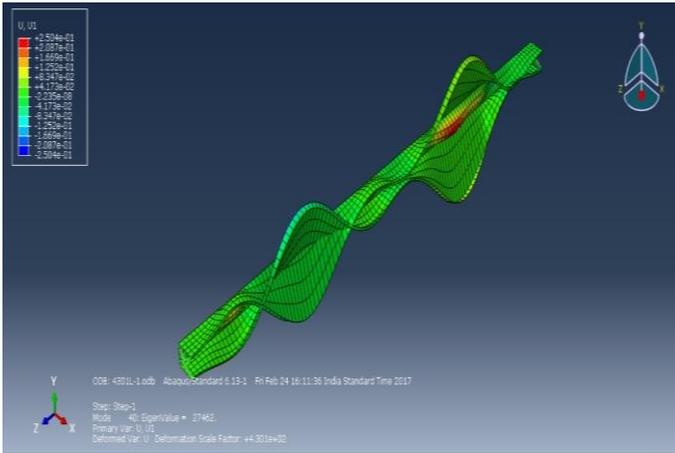


Fig -5: Pinned end condition distortional buckling mode of 150x150x15x1.068

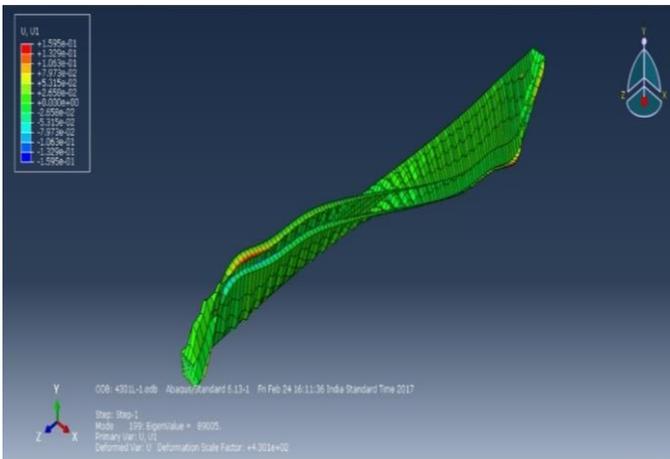


Fig -6: Pinned end condition overall buckling mode of 150x150x15x1.068

5.1 LOAD VS DISPLACEMENT CURVE FROM NON-LINEAR ANALYSIS

The specimen discusses the result of non-linear finite element analysis in the form of load versus axial deformation plot. Load vs deformation for specimens are presented in below figures. The load displacement curves for each specimen is compared with the fixed end and pinned end conditions. The result is as follows:

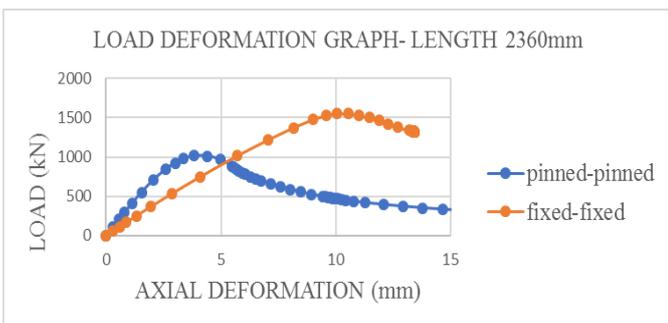


Chart -1: Load displacement graph of effective length 2360mm

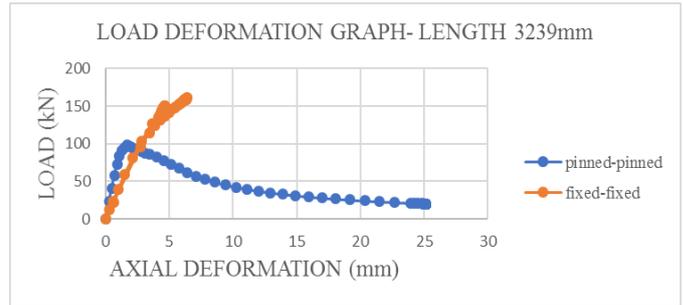


Chart -2: Load displacement graph of effective length 3239mm

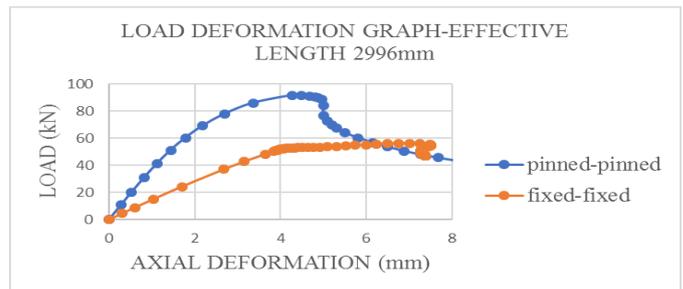


Chart -3: Load displacement graph of effective length 2996mm

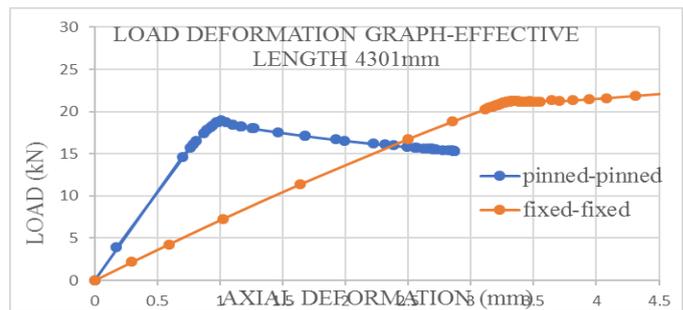


Chart -4: Load displacement graph of effective length 4301mm

Table -2: Ultimate load of each specimen

| Length | P _{FEA-pinned} | P _{FEA-fixed} | P _{FEA-fixed} - P _{FEA-pinned} | % Difference |
|--------|-------------------------|------------------------|--|--------------|
| 4301 | 18922 | 26278 | 7356 | 28 |
| 2996 | 56301 | 91623 | 35323 | 38 |
| 3239 | 97916 | 160737 | 62821 | 39 |
| 2360 | 1014700 | 1552570 | 537870 | 34 |

5.2 STRENGTH EVALUATION USING DSM

The strength of the channels are calculated using DSM formula and tabulated in the table below.

In the case of local buckling:

$$P_{ul} / P_y = [1 - 0.15(P_{cr1} / P_{ne})^{0.4}][P_{cr1} / P_{ne}]^{0.4} P_{ne}$$

In the case of overall buckling:

$$\text{For } \lambda_c \leq 1.5, P_{ue} = [0.658 (\lambda_c)^2] P_y$$

For $\lambda_c > 1.5$, $P_{ue} = [0.877 / \lambda_c^2] P_y$

where $\lambda_c = [P_y / P_{cre}]^{1/2}$

$P_y = A_g * F_y$

In the case of distortional buckling:

for $\lambda_d \leq 0.561$, $P_{ud-DSM} = P_y$

for $\lambda_d > 0.561$, $P_{ud-DSM} = [1 - 0.25(P_{crd} / P_y)^{0.6}] (P_{crd} / P_y)^{0.6} P_y$

The buckling value from direct strength method is tabulated as below:

Table -3: Ultimate strength of each specimen

| Section | P_{ul} | P_{ud} | P_{ue} | $P_{mini} (P_{ul}, P_{ud} \& P_{ue})$ |
|--------------------|----------|----------|----------|---------------------------------------|
| 150x150x15x1.06787 | 40481 | 65022 | 76915 | 40481.341 |
| 150x100x15x1.5814 | 94866 | 117171 | 150277 | 94865.785 |
| 150x200x15x2.5765 | 254931 | 210349 | 373728 | 210349.155 |
| 150x200x15x8.463 | 13079300 | 158548 | 1718314 | 1586564.168 |

5.3 STRENGTH EVALUATION USING MODIFIED DSM

The Kumar and kalyan (2012,2014) proposed modification to DSM. This section discusses the strength evaluation using MDSM. The Actual strength under interaction to all buckling mode using MDSM is as follows:

$$P_{ulde} / P_y = 0.15 + P_{ul} / P_y \times P_{ud} / P_y \times P_{ue} / P_y \leq \text{minimum of } (P_{ul} / P_y, P_{ud} / P_y, P_{ue} / P_y)$$

Comparing this result with the buckling values getting from DSM equation and actual strength under interaction of all buckling mode using MDSM.

The ultimate strength from the MDSM and FEA is tabulated as follows:

Table -4: Actual strength calculation of each specimen

| $P_{ulde-MDSM}$ | $P_{FEA-pinned}$ | $P_{FEA-fixed}$ | $P_{FEA-pinned} / P_{ulde}$ | $P_{FEA-fixed} / P_{ulde}$ |
|-----------------|------------------|-----------------|-----------------------------|----------------------------|
| 40481.36 | 18922.2 | 26277.8 | 0.46 | 0.64 |
| 63572.29 | 56300.8 | 91623.4 | 0.88 | 1.44 |
| 147975.50 | 97916.3 | 160737 | 0.66 | 1.08 |
| 158548.29 | 1014700 | 1552570 | 6.39 | 9.79 |

6. CONCLUSIONS

The study in this report clearly reveals that there is significant reduction in the strength for pinned column due to the shift in effective centroid. The arrived conclusions are as follows:

- A systematic finite element analysis result are presented in this study. Initially the finite element model is validated using the experimental results reported by young and Rasmussen. It is concluded that finite element model can accurately predict the strength of CFS compression member.
- Direct strength method does not specify different procedures of pinned and fixed columns. i.e, as per DSM both pinned and fixed column should fail at same load. The finite element analysis clearly shows that the reduction between these are as high as 39%
- The significant difference between pinned and fixed column is due to shift in effective centroid. The study clearly concludes that the modifications to DSM are required based detailed study.
- The comparison of actual strength from FEA to the values obtained from DSM shows that strength from DSM are much higher than actual strength. This leads to unsafe design of column.
- DSM gives very high percentage of error in pinned column as it does not account for shift in centroid.
- MDSM predictions are better than DSM. Still it need modification to amount for shift in centroid.

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