COLD-FORMED STEEL COMPRESSION MEMBERS: A REVIEW

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Abstract - *The cold-formed steel structural or non-structural members usage has increased in the past few years in various constructional activities. It is used due to its lightweight, easy installations, erection and economy. A built-up column is composed of two or more channels together to form a single entity that is connected either by battens or lacings. The three fundamental buckling modes, local, distortional and global are depended on the cross-sectional shape of the cold-formed steel members. Many experimental and numerical analyses have been done on differently shaped channels like single-channel sections, back-to-back channels, face-to-face channels, and Z-shape by various researchers. Different parametric studies were conducted on the effect of slenderness ratio, spacing of channels, batten width, channel spacings, screw spacings, and lacing slenderness on the ultimate capacity of columns under axial compression. In most cases, the experimental results are compared with the numerical results that are obtained from the finite element models developed in software like Abaqus and Ansys. The obtained buckling capacities of the column are compared with American iron and Steel Institute (AISI), Australian Standards (AS) or New Zealand Standards (NZ) and Eurocode standards.*

Key Words: Buckling, Built-up column, Cold-formed, Finite element

1.INTRODUCTION

Cold steel (CFS) is much better than wood and hot metal parts in modern construction because of their lightweight, durable and easy to install and save construction costs. They are produced by rolling or pressing the steel sheets to form into desired shapes. Built-in columns are widely used in steel construction especially when the working length is large and the compression strength is simple. For carrying heavy loads and using large panels in both profiles, two or more CFCs are connected by self-tapping screws, welds or bolts to form sections designed to function effectively as building components. They consist of two or more components that are connected by lacing platens or battens. For the designing of CFS built-up members, the available design standards, specifications and guidelines are insufficient. The major benefits of the CFS include high durability, lightweight, and high strength to average weight. The main purpose of this review is to study the past and present research works carried out on CFS columns.

2. LITERATURE SURVEY

2.1 Cold-formed steel built-up I-Section

Stone et al. [1], evaluated to examine the behaviour of the cold-formed steel built-up I section. They are commonly used in the applications of framing for windows, doorways, and shear walls. In this investigation, they considered two C-sections oriented back- to - back to form an I shaped cross-section. The studs were connected with two self-drilling screws spaced at specific intervals. To the end of each built-up stud, a cold-formed steel track section was connected which was running perpendicular, connected by a single self-drilling screw through each flange of the C- section. These 32 specimens were tested. From the analysis, it was found that for thicker materials modified slenderness ratio was not necessary for computing the axial capacity. From the result, the current design specifications were conservative in providing the ultimate capacity of the built-up studs.

Zhang and Young et al. [3], conducted a series of column tests of Cold-formed Steel I-shaped Open Sections with edge and web stiffeners. The test specimens were brake-pressed at first from high strength zinc-coated steel sheets. A back-to-back I-connection was provided by self-tapering screws to form an I-shaped section with edge and web stiffeners. About 21 column specimens were tested at first and secondly, the test strength was compared with design strengths calculated according to the design codes. The members used for the experiment had a nominal thickness of 0.48mm, 1.00 and 1.2 mm with a column length varying from 300 to 3200 mm with an increment of 600mm. To obtain the tensile properties at both flat and corner portions of the sections Tensile coupon tests were conducted. Due to local, distortional, flexural buckling and the interaction of these buckling nodes made the columns failed. The column specimen's failure modes and ultimate strengths were discussed. The design strength of I- shaped open section columns was calculated using the direct strength method in the North American Specification and the Australian/New Zealand Standard. They examined the reliability of the direct strength approach for I-shaped open sections using reliability analysis.

Li et al. [6], examined a series of axially compressed tests on built-up box sections composed of 2 C-sections assembled by self-driving screws on their flanges. As the first step, the differences in global, local and distortional buckling behaviour between the single-channel and built-up sections were considered. The effect of fastener spacing and installation error on the ultimate load-carrying capacity of the built-up members was considered. Based on the experimental investigation and analytical study a strength estimation method for built-up members under axial compression was found. The obtained capacity from the strength estimation method was compared to the experimental results.

Fratamico et al [9], presented an experimental investigation on the global and collapse behaviour of built-up cold-formed steel columns connected back-to-back, assembled with 16 different CFs channel sections. Using the self-drilling screw fasteners at specified spacing along the length of the column the channel sections are connected to the web. Concentric compression, displacement controlled, monotonic loading tests on 32 specimens were done up to 17 position transducers monitoring displacements. The common mode of failure was the local-global interaction. The stud-to-track end state was determined to be semi-rigid but closer to a fixed condition than initially assumed. Using the South-well method the end rigidities were modelled. Based on the test results for the built-up CFS column new DSM formulas were discussed. The DSM predicted values were compared with the test using the existing strength equations published in AISI S100-16. When isolated-global buckling occurs the composite action is created through web screws.

Roy et al. [21], Numerical analysis and experimental procedures were done to find the behaviour of screw-fastened back-to-back built-up aluminium alloy stub columns under compression. To examine the material properties of the section a tensile coupon test was conducted to get the initial imperfections of the sections using a laser scanner before the test. From the 15 test reports the failure modes such as load axial shortening, load lateral displacement and load axial strain relationships were found. For validation, a non-linear finite element model was modelled against the test results. To study the effect of modified slenderness, screw number and thickness of the section on the axial strength of built-up columns a parametric study on 216 models was done. It was found that the section thickness affected the axial strength of the columns. In the built-up back-to-back column, the screw spacing had a limited effect on its axial strength shown in Fig: 1. The experimentally and numerically obtained axial strength was compared with the guidelines given by Aluminium Design Manual (ADM), American Iron and Steel Institute (AISI), Australian and New Zealand Standards (AS/NZ), Eurocode 9(EC 9) and Eurocode 3 (EC 3).

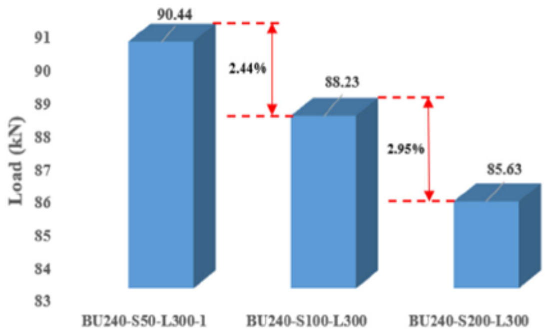

Fig -1: Effect screw spacing

2.2 Cold-formed steel built-up C-Section

Roy, et al. [10], Conducted the test to find the effect of screw spacing on the axial strength of back-to-back built-up cold-formed steel un-lipped channel sections. About 95 finite element models were analysed with varying column lengths from stub to slender. The model was validated with the results obtained from the back-to-back built-up cold-formed steel lipped channel sections. To conduct the parametric study verified finite element models were used to find the effect of screw spacing on these columns. The obtained results were compared against built-up lipped channel sections and it showed that the axial strength of the un-lipped built-up sections was 31% lesser on average than the built-up lipped channel sections. The strength of the column predicted from the finite element analysis was compared against the design strengths calculated by The American Iron and Steel Institute (AISI) and the Australian and New Zealand Standards (AS/NZ). The American Iron and Steel Institute (AISI) and the Australian and New Zealand Standards (AS/NZ) were found to be over-conservative by around 15% for built-up columns that failed due to overall buckling for short, intermediate and slender columns, but un-conservative by around 8% for built-up columns that failed due to local buckling for stub columns.

Roy et al. [11], investigated the axial strength of the back-to-back gapped cold-formed steel channel sections under compression. The results of 40 experimental tests were adopted considering a wide range of non-dimensionless slenderness from stub to slender columns. A non-linear finite element was modelled in Abaqus software were compared with the experimental results which showed a good agreement with the test results and are shown in Fig: 2. 84 models were used to study the load- axial strain, failure modes, load-axial shortening, and deformed shapes. The effect of channel spacings on the axial strength was determined. To assess their material qualities tensile couple tests were conducted on specimens. They also compared the experimental strength computed using the American Iron and Steel Institute (AISI), an Australian and New Zealand Standards (AS/NZ). They also concluded that the test and FEA results were up to 53% greater than the design strength of such columns due to non-dimensional slenderness.

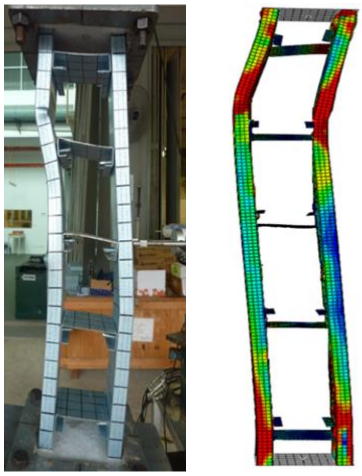

Fig -2: Experimental and analytical comparison of failure modes of column

Vijayanand and Anbarasu [8], described the findings of a numerical and theoretical investigation of the buckling behaviour and ultimate capacity of cold-formed steel built-up sections under axial compression. The built-up sections were formed by two identical lipped channels that were positioned back-to-back and connected with spacers. Abaqus software was used to develop the finite element model. The numerical model was compared with the experimental results. A parametric study was conducted after obtaining the validation by changing the overall slenderness ratio, depth and number of spacers. A comparison was done between the column strength which was calculated by theoretical and numerical methods. The strength predicted using the Direct Strength Method (DSM) and Effective Width Method (EWM) as per North American Specifications (AISI-S100:2007) for cold-formed steel members is compared to the strength derived using numerical analysis.

2.3 Cold-formed steel built-up Box Section

Roy et al. [14], conducted experimentally and numerically to examine the behaviour of face to face built-up cold-formed steel channel sections under compression. The experiment was conducted on 36 specimens covering a wide range of slenderness from stub to slender columns to discuss the failure modes, axial capacity, load axial shortening, load-lateral displacement and load-axial strain relationship. From the analysis, the CFS built-up stub and short columns failed through local buckling while intermediate and slender columns failed by global or the combination of local and global buckling. While considering the effect of fastener spacing it was found that fastener spacing has a negligible effect on column strength of stub and short columns. While considering the intermediate and slender column when the fastener spacing was doubled, the axial strength reduced by 15-20% for the former and approximately 20% on average respectively. A non-linear finite element model was made which included non-linear material properties and geometric imperfections. The finite element results showed good agreement with the experimental results. Both the test and finite element results were compared against the standard design codes. From the study, it was found that both FEA and test results were generally conservative by around 15%, but AISI & AS/NZS and Eurocode (EN 1993-1-3) can be un-conservative by 8% on average for face-to-face built-up columns failed due to the local buckling.

Roy, et al. [15], investigated the axial capacity of built-up CFS box sections by experimental method. In this study to form built-up sections, two identical lipped channels were connected with the flanges with self-drilling screws. 16 experimental tests were conducted with varying slenderness from short to slender columns as evaluation. Fig. 3 shows the details of a cross-section of the built-up columns. To find the load-axial relationship and failure modes in built-up columns 8 tests were conducted and the remaining on single-channel sections were done. A non-linear finite element model was generated considering the material non-linearities, initial imperfections and modelling of intermediate fasteners for built-up box and single channel sections.

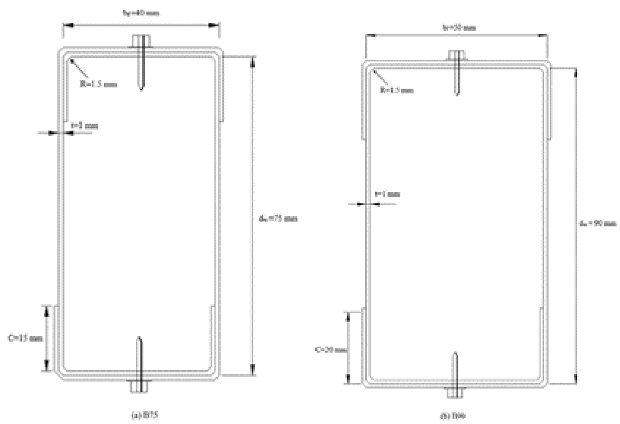

Fig -3: Nominal cross-sections of CFS built-up box sections (a) B75, (b) B90

Kherbouche and Megnounif [12], investigated 2 types of cross-sections built-up closed and open sections made by two channels joined by battens plates. At first, a non-linear finite element model was created and the results obtained showed good agreement against the experimental results like ultimate strength, the type of deformed shapes at failure, and lateral displacement. Secondly, a DSM approach where the local, distortional, or global buckling was obtained numerically by using the finite element method software. While comparing the experimental results with the DSM approach gave a satisfactory degree of accuracy.

Yang et al. [18], conducted experimental and numerical studies on the fire resistance of cold-formed steel (CFS) columns with built-up box shape sections. To obtain the stress-strain relationship of steel plates from 20 to 800 °C a series of coupon tensile tests were done before the fire resistance testing of the columns. The load-bearing capacity of the columns was conducted first at ambient temperature and later on, the fire resistance tests were performed for eight specimens considering different load ratios and axial restraining stiffness. Later on, numerical models were created, including heat transfer and structural analysis were developed to replicate the fire resistance behaviour, which was later verified with test results. Lastly, parametric analysis was done to investigate the influence of load ratio, axial restraint, and rotational restraint on the fire resistance behaviour of the column. According to the findings, the major failure mode of the specimen occurred was the combination of local and global flexural buckling. Furthermore, as the load ratio and axial restraining stiffness increased, the critical temperature and failure time decreased significantly. Furthermore, even a moderate level of rotational restriction could improve the column's fire-resistance characteristics.

Li et al. [22] investigated the distortional buckling behaviour of built-up closed sections. A concentric axial loading was conducted on 12 C-sections, 12 U-sections and 24 built-up closed sections assembled with self-drilling screws at their flanges. The mechanical properties, failure modes, and buckling modes were examined. Using the current Design strength Method, the research showed how to calculate the ultimate capacity of CFS built-up closed section columns and estimate the critical buckling stress. The obtained design strength was compared with the test results and concluded that it can be used for the column design of CFS built-up closed section columns.

Nie et al. [19], examined the compression behaviour of 30 specimens of built-up closed box sections of two-channel sections of various cross-sections, lengths and thicknesses. To evaluate the accuracy of the equation in code a parametric study was conducted for a wide range of parameters. When the specimen was subjected to axial compression it was subjected to local buckling initially. When the concentric axial compression was considered for the long and medium columns there were flexural buckling occurred along the weak axis, while the failure mode for the short column under concentric axial compression had excessive buckling without global buckling. Moreover, while considering the specimen subjected to eccentric axial compression about the strong and weak axes, the flexural torsional buckling and the flexural buckling occurred respectively. When the slenderness ratio of the column and the web height to thickness, the ratio increased the concentric axial compression strength of the column decreased.

2.4 Cold-formed steel section Battened columns

Muthuraman et al. [16], examined the axial loading of pin-jointed cold-formed steel column sections by numerical and theoretical analysis. About 44 models were modelled in Abaqus and were analysed under axial compression. By considering different batten numbers and slenderness ratios the numerical and theoretical studies were done. The ultimate loads for the lipped channels were analysed using two methodologies for the lipped channel sections and were compared to obtain the effective section proposed. While considering the slenderness ratio from 20 to 60 from the direct strength method the buckling mode and the failure load were approximately showing good agreement with the FEM results. Moreover, when the slenderness ratio was beyond 60 it failed to predict the buckling load and failure mode of the column. Hence concluded that with the increase in slenderness ratio of the column the ultimate load-carrying capacity of the section is decreased. While considering the comparative study the distortional buckling of the column depends on the post-buckling strength of the section. It is found that the prediction of buckling mode and column failure load was shown stable and roughly relevant to the FEM results based on the findings.

Dabaon et al. [7], investigated the non-linear behaviour and design of built-up steel section battened columns. To simulate the structural performance of the axially loaded columns, non-linear 3-D finite element models were built. In this model, the non-linear properties of the flat and the corner portions of the channels, as well as initial geometric imperfections, real geometries and boundary conditions are taken into account. For comparison, the column strength, failure modes, deformed shapes at failure, load lateral displacement and load-axial strain relationships obtained from the finite analysis was compared with test results and their comparison showed a good agreement. To investigate the effects on the strength of built-up column and its behaviour due to the change in column cross-section, column lengths, column local and overall slenderness and cold-formed steel strengths parametric study was conducted which were validated with the experimental results for which the experimental set up is shown in Fig: 4. In addition, the parametric study's anticipated column strengths were compared to design strengths derived using the North American Specification, Australian/New Zealand Standard, and European Code for cold-formed steel columns. From the results, it was concluded that built-up cold-formed steel battened columns failing mainly due to local buckling were shown with unconservative specifications moreover, failing due to elastic flexural buckling of the column were shown as conservative.

Fig -4: Experimental set-up for built-up battened column

Ananthi et al. [20], explained the behaviour of stainless steel battened built-up columns by finite element analysis that included the material non-linearity and initial geometric imperfections. As a parametric study 132 validated finite element model was used to study the effect of slenderness, different cross-sectional and batten depth on the axial strength of the built-up columns in which two different grades of steel were considered like Austenitic EN1.4004, and Ferritic EN1.4003. From the results of the parametric investigation, the study revealed that the distortional-flexural buckling caused the failure of the majority of the short, intermediate and long columns. The result of axial strength obtained from the parametric study was compared to design power calculated by the different standard codes.

Dar et al. [17], studied the axial compression loading behaviour of built-up cold-formed steel columns in terms of peak axial compressive strengths, mode of failure, post-peak resistance and lateral drift. A toe-to-toe arrangement of unstiffened channel sections is used as the chord members connected with batten plates are used in the analysis. For analysing the parametric study 230 models incorporated with geometric imperfections and non-linear material properties were generated in Abaqus. Thus, the modelled developed were calibrated against the test results on cold-formed steel battened columns with plain channels in the back-to-back position. The major parameters modified in the numerical models are the width-to thickness ratios of chords, overall column slenderness ratios, and the toe-to-toe spacing of chords. The results found that the chord width to thickness ratios had a strong influence on the peak axial stresses of short columns, but only a little influence on the peak axial stresses of long columns. Also, excessive lateral displacements can be prevented by keeping the overall column slenderness to 75. The numerical results are compared to the expected design strengths of North American Standards (NAS) and Eurocode (EC3). Both of these standards are found to be unreliable in estimating the axial strengths of short built-up columns with axial strengths of 15–30%. Finally, design guidelines for built-up battened CFS columns with toe-to-toe channel chords are suggested, which are also verified through reliability analysis.

2.5 Cold-formed steel section Laced columns

Dar et al. [13], found the performance of built-up cold-formed steel (CFS) columns under monotonically increasing axial compression loading. For the research, five specimens were considered in which four CFS angle sections were connected using a lacing system. In the test specimens, the width-to-thickness ratios and slenderness ratios of chord and lacing elements, as well as the height of columns, were modified. The major examined factors were column strengths, axial load vs. displacement response, mechanism of failure and deformed configurations. A finite model was created in Abaqus software and was validated with the test results. The chord width to thickness ratio and the lacing slenderness affected the behaviour of built-up laced CFS columns. The column strength curves for built-up laced CFS columns were created using the test findings. The result found that maximum lacing slenderness was limited to 80 and the value of the ratio of 120 or higher resulted in premature buckling of columns, thereby controlling the axial load capacity. Finally, the findings of this investigation were compared to the design strength projections for CFS sections made by North American Standards and European Standards. From the results, it was found that to avoid the lateral displacements in a larger amount the overall slenderness ratio and the chord width to thickness ratio should be limited to about 60 and 40 respectively.

Kalochairetis et al. [5], conducted experimental and numerical methods to investigate the in-plane response of scaled Z- laced built-up columns under the axial compression applied at the ends with considerable eccentricities. The chord profile and the density of the lacings are varied to find the impact of the capacity of the column, magnitude and the direction of the eccentricity. A numerical model was developed which contained the effect of initial geometric imperfections and thermally residual stress. Both the test and numerical were in good agreement. From the results, it was found that due to the action of concentrated moments the axial capacity of the system was lowered drastically. The local imperfections had a major impact on the effect on the specimens of local buckling of different intermediate panels.

Davaran and Hoveidae [2] Investigated the effect of mid-connection details on the elastic-plastic behaviour of built-up sections of the bracing systems. The buckling and post-buckling behaviour of single-span models of crossed braced systems of the single storey is studied by using finite element analysis. The overall behaviour of the bracing system was affected by the centre connection detail of cross bracings obtained from the results. Here one diagonal member from each section is made dis-continuous and the other is continuously passing through the connection in the common mid-connection details of built-up sections. To join the discontinuous and continuous a rectangular gusset plate is adopted diagonals in practice. In this method, the diagonal member from each section is made dis-continuous and the other is continuous. Using the non-linear static finite element analysis, the buckling and post-buckling behaviour of the single-span and single-storey models were examined. The strength and ductility of the section were improved with the proposed connection detail and also found that in common mid-connection detail of the discontinuous diagonal member provided with two cover plates on both sides improved partially the overall behaviour of the system.

Bonab et al. [4], assessed the static behaviour of laced columns for which 18 tests were conducted on columns from the pairs of U-section provided with various lengths and distances between the main chords. The behaviour of the built-up column in the plane parallel to the lacing planes was studied with a test set-up arranged in such a way that the buckling occurred in the plane itself. The theoretical and experimental results showed a good agreement with each other. From the results, the SSRC method showed more errors with overestimating the results while Engesser's method showed minor errors and was conservative when compared to Bleich's and Paul's methods. The result showed that the geometrical imperfections affected the ultimate capacity of the laced columns even though the number of variations was the same.

3. CONCLUSION

Cold-rolled sections are utilised for purlins, girts, wind bracings, roof truss, wall frames, and portal frames in India, indicating that they are effective structural constructions. Cold-formed steel sections are most effective with constructions with moderate loads and spans, where they can be less expensive than hot-rolled components and easier to construct due to their lightweight and rigidity. From most of the results, it was found that the stub and short column failed due to local buckling while in the case of intermediate and slender columns failed due to global or the combination of local and global buckling. It was found that the ultimate load capacity was inversely proportional to the slenderness ratio (L/r ratio). While considering the built-up column with the laced system the overall slenderness ratio and the chord width to thickness ratio should be limited to about 60 and 40 respectively to avoid lateral displacements in a larger amount. It was also found that the ultimate capacity of the laced column was also affected by geometrical imperfections even though the number of variations was the same, the ultimate capacity was different. While considering the effect of fastener spacing it was found that fastener spacing has a negligible effect on column strength of stub and short columns. While considering the intermediate and slender column when the fastener spacing was doubled, the axial strength reduced by 15-20% for the former and approximately 20% on average respectively. Thus, the study made on the various sections of built-up columns in different loading conditions helps in understanding their behaviour different before their usage for constructional purposes.

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