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# Numerical Investigation on Buckling Behavior of Cold-Formed Steel Built-up Box Slender Columns

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***Abstract— In construction industry, builders and engineers are more interested in application cold-formed steel (CFS) sections in place of conventional materials not only as the non-structural components but also the structural members of the commercial and residential buildings. As the structural members, the literatures endorsed that built-up CFS sections have higher strength than single detached sections. The objective of this paper is to analyze the buckling behaviors of CFS built-up box slender columns by means of FE software ANSYS 2020 R1 grounded on the recent experimental models and compares the outputs for design optimization. Face-to-face built-up box slender columns were connected with fillet weld joint spacing of 500 mm and analyzed for Eigenvalue buckling loads. Numerical results by ANSYS 2020 R1 were within the range of allowable compressive loads and global buckling governs for slender columns.***

***Keywords: numerical investigation, built-up box slender columns, cold-formed steel, eigenvalue buckling, and fillet-welded connections.***

## I. INTRODUCTION

During the past century, wood and timber were applied as the primary materials for construction. The excessive use of these materials has great impact on conservation of forests and effects on global warming. Builders and engineers, however, have substituted hot-rolled steel (HRS) in place of these conventional materials; there have been tranquil challenges for them. HRS can be manufactured at high temperature and has lower strength at their smallest shapes. Cold-formed steel (CFS), conversely, can be manufactured at room temperature, enhances the material handling more simplified and having high strength-to-weight ratio, which attract to be substituted in place of them.

According to Steel Framing Industry Association (SFIA) Market Data Report 2018, CFS manufacturers conveyed using 282,355 total tons (raw tons before processing) of steel in the first quarter of 2018, which grew up from 272,305 total tons reported in the previous quarter of 2017. This showed that demand for cold-formed steel framing (CFSF) products grow up in construction industry [1]. As the structural members, the literatures endorsed that built-up CFS have higher strength than single detached sections. In construction, deformation or the sudden changes of structural members' shapes are caused due to material failure and structural instability called buckling, which is the loss of stability of a component and is usually independent of material strength and which is one of the two limit states for compression members, columns. Buckling may be local, distortional or global or combination of two or more buckling modes [2].

## II. LITERATURES REVIEW

The loss of stability generally occurs within the elastic range of the material. End conditions of the member, eccentricity of the load, geometric imperfections and the slenderness ratio are the influential factors to buckle the compressive members [2]. Though CFS is widely used as non-structural components, design guidelines to be applied as structural members are inadequate because of their complex nature and behaviors. As the structural members, the literatures endorsed that built-up CFS sections have higher strength than single detached sections. Through recent investigations, moreover, the researchers were more captivated on bending and flexural behaviors of built-up beams rather than columns. Mon and Selvam (2021) recommended to compare the modes of buckling among the built-up box, sigma and I sections through uniaxial compression loads for global buckling as the vertical structural members [3]. The buckling characteristics depend on the shape and the slenderness ratio of their geometric profiles. Reyes et al. (2011) investigated front-to-front built-up box with seam welded condition and suggested the application of modified slenderness ratio in place of slenderness ratio for the sections with thickness 1.5 mm and 2.0 mm if the welded spacing is less than or equal to 600 mm [4]. According to Krishanu et al (2019), there has been no previous work described any built-up box CFS sections of front-to-front connection through bolts or screws, under axial compression [5]. ANSYS and ABAQUS are the most advantageous FEA solvers for researchers to predict the approximate data with the experimental results. FEM for buckling analysis was prolonged to consent for any combinations of continuous restrains, which are uniform throughout the element, effect on the analysis of symmetric beam-columns with moment gradient by Hancock and Trahair (1978) [6]. Schafer (1997) established the numerical modeling of ultimate strength of cold-formed steel members with the application of finite element software ABAQUS [7]. Schafer and Peköz (1998) specified the influence of geometric imperfection and residual stresses for load carrying capacity in cold-formed members [8]. Laim et al (2013) studied the failure modes of different types of CFS single and built-up members as C, Box, Double Box and I sections with numerical software ABAQUS [9]. Sreedhar Kalavagunta (2019) applied STAAD.pro structural analysis software to investigate load carrying capacity and critical stresses of CFS C sections [10]. The numerical data proved approximately to American design results. G.Beulah Gnana Ananthi (2016) applied ABAQUS software to assess the non-linear analysis of CFS built-up box double angle columns with pinned-end condition under compression load [11]. Marsel Garifullina (2018) applied ABAQUS to examine non-linear analysis of CFS channel section C columns under compressive loads and calculated the load bearing capacity and influence of imperfections on load bearing members [12]. The approaches for the models of 36 built-up columns were incorporated as reported by Anbarasu et al [13]. This pointed out the research questions of how to combine single detached sections as built-up BOX columns and the extent of reliability of design evaluation processes by FE software ANSYS. This research focuses on the reliability of numerical approach on CFS built-up box slender columns for design evaluation. The prediction of numerical method has been carried out with ANSYS 2020 R1 software.

## III. MODES OF BUCKLING

Buckling occurs when axially loaded member loses its stability and which is one of the challenges for engineers and builders considering cold-formed steel design. Steel yielding is the major design consideration for hot-rolled steel (HRS) members where as buckling becomes the leading concern for all forms of cold-formed steel sections due to their low thickness to width ratio. The buckling characteristics depend on the shape and the slenderness ratio of their geometric profiles. Buckling phenomena, normally, can be classified into three types as Local (L), Distortional (D) or Global (G) modes (Fig. 1). Any of these modes may lead to excessive deformation and, finally, to fail.

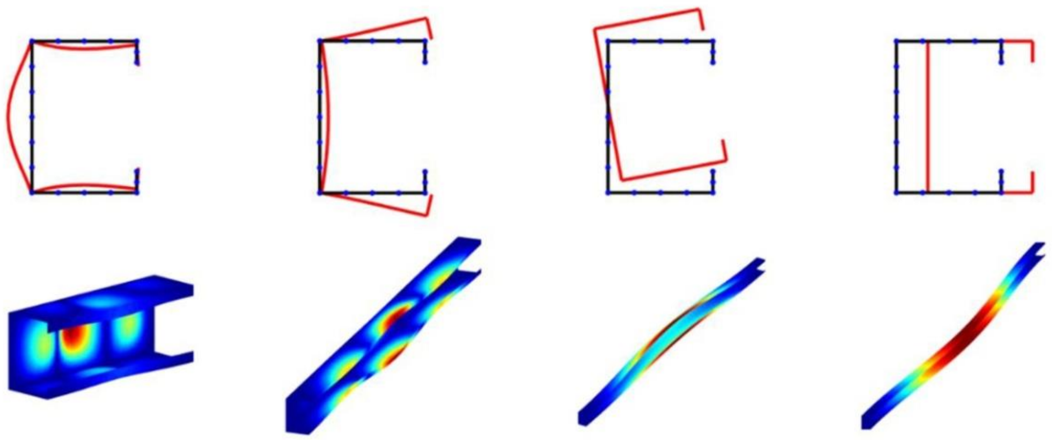


**Figure 1** Types of Pure Buckling Modes [14]

**Local buckling** – involves principally plate bending of the elements; and, with respect to the cross-section deformations, the fold lines of the elements do not translate but merely rotate as each compression element buckles out-of-plane. The half-wavelength of local buckling, i.e., the length at which the buckling shape repeats along the member length, is usually shorter than or equal to the largest dimension of the member under compressive stress. Buckling that involves significant distortion of the cross-section, but this distortion includes only rotation, not translation, at the internal fold lines (e.g., the corners) of a member. The half-wavelength of the local buckling mode should be less than or equal to the largest dimension of the member under compressive stress [15].

**Distortional buckling** – involves deformations which visually appears as a combination of local and global buckling, where part of the cross-section (e.g., the flange) responds rigidly by twisting or translating about a point (e.g., the flange/ web junction) and another part of the cross-section (e.g., the web) undergoes plate bending. The half-wavelength of distortional buckling falls between the half-wavelengths of local and global buckling. It is possible that a member that is fully braced from global buckling (i.e., no global buckling) may still be subjected to distortional buckling[15].

**Global buckling -** Buckling that does not involve distortion of the cross-section, instead translation (flexure) and/or rotation (torsion) of the entire cross-section occurs. Global or "Euler" buckling modes: flexural, torsional,

torsional-flexural for columns and lateral-torsional for beams, occur as the minimum mode at long half-wavelengths [15]. Global buckling is characterized by a distorted longitudinal axis of the member. Unlike distortional buckling, global buckling does not deform the cross-section of the element. Overall (global) column buckling may be Flexural buckling, Torsional buckling or Flexural-Torsional buckling. Flexural buckling is bending about a principal axis. If the geometric section of a slender column is a doubly symmetric shape (I-section), closed shape (square or rectangular tube), closed cylindrical shape, or point-symmetric shape (Z-shape or cruciform) and is axially loaded, it may fail by overall flexural buckling. For singly symmetric shapes, flexural buckling is one of the possible failure modes. If a column section is other than the above-discussed shapes but is connected to other parts of the structure such as wall sheathing material, the member can also fail by flexural buckling. Torsional buckling is twisting about shear center. Generally, closed sections will not occur torsional buckling because of their large torsional rigidity. For open thin-walled sections, conversely, three modes of failure are considered in the analysis of overall instability (flexural buckling, torsional buckling, and flexural–torsional buckling). Flexural–torsional buckling is bending and twisting of column section occurs simultaneously.

## IV. NUMERICAL METHOD

Numerical method is the analyzing and implementation of algorithms to solve numerically the problems of continuous mathematics with the application of mathematics and physics phenomena with the aid of computing machines. Numerical analysis is the presentation of numerical methods to solve problems. Finite element method (FEM), finite strip method (FSM), finite difference method (FDM) and finite volume method (FVM) are the most pertinent methods for numerical analysis. FEM and FSM are the most common methods in many fields of engineering and research, which allow efficient and precise modeling the behavior of physical, mechanical, thermal and other complex systems especially stress and structural analysis.

### A. Finite Element Method- FEM

FEM is a numerical technique to perform finite element analysis (FEA) for a complex system with the use of partial differential equations (PDEs). ANSYS and ABAQUS are the most advantageous FEA solvers to predict the approximate data with the experimental results. FEM for buckling analysis was prolonged to consent for any combinations of continuous restrains, which are uniform throughout the element, effect on the analysis of symmetric beam-columns with moment gradient by Hancock and Trahair (1978) [6]. Schafer (1997) established the numerical modeling of ultimate strength of cold-formed steel members with the application of finite element software ABAQUS [7]. Schafer and Peköz (1998) specified the influence of geometric imperfection and residual stresses for load carrying capacity in cold-formed members [8]. M. E. Aghoury et al (2020) compared the compressive strength of pinned-pinned axial loads through the back-to-back CFS sigma sections columns by means of experimental and numerical analysis by ANSYS [16]. Prabhakaran.S (2020) investigated the behavior of cold-formed steel battened columns by means of numerical application, ANSYS [17]. Laim et al (2013) studied the failure modes of different types of CFS single and built-up members as C, Box, Double Box and I sections with numerical software ABAQUS [9]. G.Beulah Gnana Ananthi (2016) applied ABAQUS software to assess the non-linear analysis of CFS built-up box double angle columns with pinned-end condition under compression load [11]. Marsel Garifullina (2018) applied ABAQUS to examine non-linear analysis of CFS channel section C columns under compressive loads and calculated the load bearing capacity and influence of imperfections on load bearing members [12].

### B. Finite Strip Method- FSM

Finite strip method (FSM) is one of the techniques of structural analysis for statics, stability, buckling and vibrations of thin-walled structural members [18][19]. It is applicable to analyze the structures in strips instead of elements in FEM. The comparison of these two methods is illustrated in (Fig. 3.15). Timoshenko and Woinowsky-Krieger (1959) explained the classical plate theory assumptions on which FSM formulation is originated [20]. For strip displacement in longitudinal deviations, continuous harmonic series functions are employed whereas simple polynomial functions for transverse variations. This approach is the main difference from FEM, which employs polynomial functions for both directional variations of the elements translation. CUFSM, Constrained and Unconstrained Finite Strip method, [18] and Thin-Wall [21] are the most renowned computer programs. The CUFSM was initiated and created to analyze elastic buckling prediction for thin-walled structures where as the Thin-Wall application is Semi Analytical Finite Strip Method (SAFSM). Z. Li et al (2010) applied CUFSM to investigate the buckling modes of CFS columns [22].

## V. OBJECTIVES

The objective of this paper is to predict linear and nonlinear buckling behaviors of CFS built-up box slender columns by means of ANSYS 2020 R1 based on the recent experimental models and compare the results with experimental and analytical outputs.

## VI. MATERIALS AND METHODOLOGY

### A. Geometry And Material Properties

In this numerical investigation on built-up box columns, the focus is on compressive members, slender columns. According to Krishanu et al (2019) [5], there has been no previous work described any built-up box CFS sections of front-to-front connection through bolts or screws, under axial compression. The experimental investigation was done to two groups of 8 single CFSS and 8 built-up box columns, which were connected with self-drilling screws. The initial imperfections of tested built-up box specimens B75 were applied in two groups as displayed in Table 1 and the cross section in Fig 1. In that research, the experiment was concentrated on studs and slender columns. For specimen label B75-L500-1, B represented built-up box column, 75 was nominal web dimension, L was height of specimen, 500 was nominal height and 1 the number of tested member.

**Table 1:** Cross Sectional Dimensions of B75 [5]

| Specimen | Web, $d_w$ | Flange, $b_f$ | Lip, $C$ | Height, $H$ | Radius, $R$ | Thickness, $t$ |
|---|---|---|---|---|---|---|
| Studs | | | | | | |
| B75-L500-1 | 76.1 | 39.8 | 15.1 | 500.4 | 1.5 | 1.0 |
| B75-L500-2 | 75.2 | 38.5 | 14.2 | 498.7 | 1.5 | 1.0 |
| B75-L500-3 | 74.7 | 41.6 | 14.8 | 499.6 | 1.5 | 1.0 |
| B75-L500-4 | 77.2 | 40.2 | 14.2 | 502.4 | 1.5 | 1.0 |
| Slender | | | | | | |
| B75-L1500-1 | 77.4 | 41.2 | 14.4 | 1500.9 | 1.5 | 1.0 |
| B75-L1500-2 | 76.4 | 40.6 | 14.6 | 1502.6 | 1.5 | 1.0 |
| B75-L1500-3 | 75.4 | 39.7 | 15.3 | 1507.4 | 1.5 | 1.0 |
| B75-L1500-4 | 75.2 | 38.7 | 15.1 | 1511.4 | 1.5 | 1.0 |

*All of the measurements are in millimeter (mm).

To make comparison with the experimental findings, the analysed model dimensions are used as the nominal dimensions of tested specimens that mean the materials are assumed as geometric perfection. To create models with ANSYS 2020 R1 design modeler, CFSS are joined together with fillet weld conditions with spacing of 500 mm. Depending on the welded spacing, the nominal height of specimens are 600 mm for stud, 1150 mm for medium and 1700 mm for slender columns however 500 mm for studs and 1500 mm for slender were applied in the experimental research. The objective of this analysis is to evaluate the degree of reliability for buckling of built-up box columns through experimental versus FEA software, ANSYS. The nominal dimensions of modeling specimens are summarized in Table 2 and the cross sectional model is illustrated in Fig 2. The yield strength and Young's Modulus were assumed as 250 MPa and 200 GPa. Poisson's ratio was assumed as 0.3.

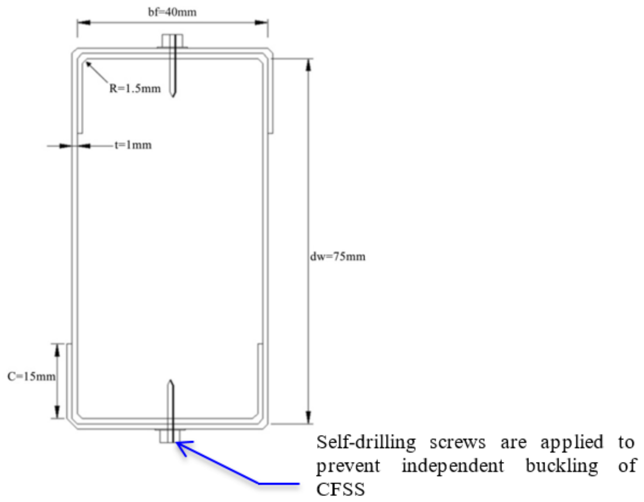


**Figure 1:** Nominal cross-section of CFS built-up box section [5]

**Table 2:** Nominal Dimensions of Modeling Specimens

| Specimen | Web, $d_w$ | Flange, $b_f$ | Lip, $C$ | Height, $H$ | Radius, $R$ | Thickness, $t$ |
|---|---|---|---|---|---|---|
| Slender Column | | | | | | |
| B75-L1700-1 | 75 | 40 | 15 | 1700 | 1.5 | 1.0 |

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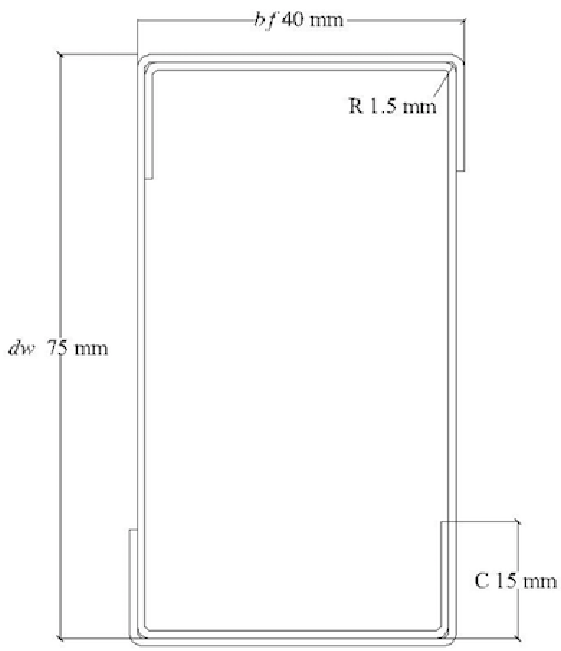


**Figure 2:** Nominal cross-section of CFS built-up box model

### B. Finite Element Mesh

Selection of finite element meshing prior to structural analysis is the critical step for the convergence of the model. A linear 4 nodes shell element mesh with the size of 5 x 5 mm were used whereas the end plates of 8 nodes solid models were with the size of 6 x 6 x 6 mm. Typical finite element mesh for all types built-up box columns are illustrated in Fig 3.

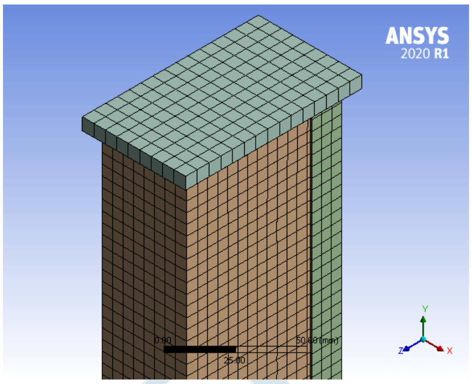


**Figure 3:** Typical mesh model of built-up box column

### C. Boundary Conditions And Load Application

The centroids of the built-up columns were assumed as the center of gravity for axial compression loads. The reaction ends of the columns were modeled as fixed end and the load end as the free one. The translation and rotation at the bottom ends of the columns were restrained in all directions. The loads were applied at the center of the upper free ends along the negative Y direction.

### D. Contact Modeling

"Surface to surface" contact was applied for the interaction between the cross sectional edges of the columns and solid end plates of the geometric models. The edges of the cross section at the both ends performed as the contact bodies and the inner surfaces of the end plates as the target ones. MPC formulation is used as bonded contact and hence there were no penetrations between the contact surfaces.

## VII. RESULTS AND DISCUSSION

Table 3 displays the linear and non-linear buckling load of all types of built-up columns in 10 modes of deformation.

**Table 3:** Linear and Non Linear Buckling Loads & Modes of Built-up Box Columns

| Types of Columns | Modes | Linear Buckling Load (kN) | Non-Linear Buckling Load (kN) | Mode of Buckling |
|---|---|---|---|---|
| **Built-up Box Slender Columns B75-L1700-1** | 1 | 17.24 | 17.22 | Global Buckling |
| | 2 | 53.75 | 53.08 | Local Buckling |
| | 3 | 53.79 | 53.12 | Local Buckling |
| | 4 | 54.92 | 54.87 | Global Buckling |
| | 5 | 64.90 | 64.85 | Local Buckling |
| | 6 | 64.94 | 64.89 | Local Buckling |
| | 7 | 64.99 | 64.96 | Local Buckling |
| | 8 | 65.04 | 64.99 | Local Buckling |
| | 9 | 65.29 | 65.35 | Local Buckling |
| | 10 | 65.33 | 65.40 | Local Buckling |

Data in Table 3 illustrates the comparison of linear and nonlinear buckling of built-up box slender columns. The first mode of slender columns, the failure load is 17.24 kN in linear and 17.22 kN in nonlinear and global buckling occurs in their minor axis. In the second mode, the loads increase three times and it governed by local buckling mode. Global

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buckling occurs only in their 1st and 4th modes while the remaining modes by local one. By comparing the load bearing capacity among these modes, the 1st mode, in slender columns is lowest, 17.24 kN with global buckling. Fig 4 displays the pre-stress linear buckling of CFS built-up box slender columns in 1st mode.

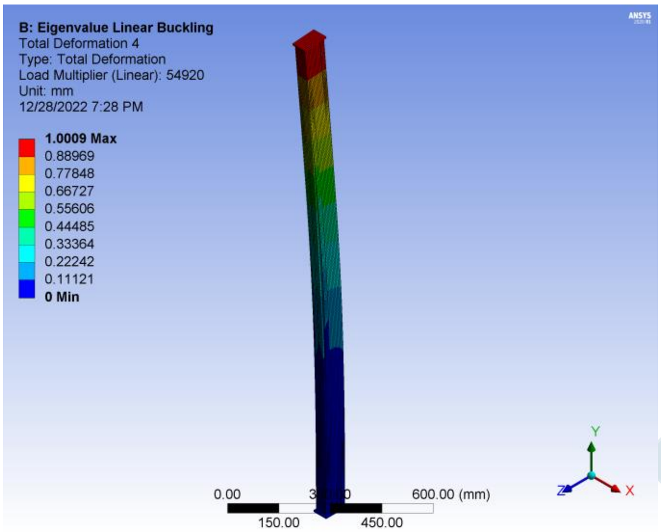


**Figure 4:** 1st mode of buckling of built-up box slender column

Table 4 configures the buckling loads and failure modes of this built-up model studs and slender columns by means of numerical, experimental and analytical (AISI & AS/NZS design results) approaches. Krishanu et al (2019) [4] demonstrated the experimental and analytical results.

**Table 4:** Linear and Non Linear Buckling Loads & Modes of Built-up Box Columns

| Specimen | Numerical Results - $F_{FE}$ (kN) | Mean Experimental Results- $F_E$ (kN) | Mode of Buckling (1st Mode) | $F_{FE}/F_E$ | AISI & AS/NZS Design Results | | |
|---|---|---|---|---|---|---|---|
| | | | | | $F_{AISI}$ (kN) | $F_{FE}/F_{AISI}$ | $F_E/F_{AISI}$ |
| Slender (B75-L1150-1) | 17.24 | 90.55 | Global | 0.20 | 73.1 | 0.25 | 1.24 |

The table distinguishes the results by three methods of design approaches and correlates how they are varied, compliance and interrelated each other. There are not much differences between the modes of buckling in both cases whereas a bit variances for failure load of slender columns. In analyzing slender column by means of FEA software, the prediction output is only 20% of mean value of experimental grade while 25% of analytical result. These correlation values endorse that design evaluation for this type of built-up slender column is safe and secure by use of FE software, ANSYS. As the FE models in this ANSYS presentation were built-up with fillet-welded connections nonetheless the experimental and analytical approaches were based on self-drilling screws type, it is recommended to associate the use of screw connection by numerical study.

## REFERENCES

[1] Market Data Report 2018, *Steel Framing Industry Association (SFIA)*, USA, 2016.

[2] 2 Wei-Wen Yu and Roger A. LaBoube, "Cold-Formed Steel Design", Fourth edition, John Wiley &Sons, Inc, Handbook, New Jersey, 2010.

[3] Mon, T. Y., and Selvam, J., "Buckling Behaviors of Cold-Formed Steel Built-Up Columns under Axial Compression Tests: Review Paper", *International Journal of Recent Technology and Engineering*, 2021; 10(1): pp. 7-11. http://dx.doi.org/10.35940/ijrte.A5593.0510121

[4] Reyes, W., and Guzmán, A., "Evaluation of the slenderness ratio in built-up cold- formed box sections", *Journal of Construction Steel Research, Volume 67(6)*, pp. 929-935, 2011.

[5] Krishanu Roy et al. "Compression Tests on Cold-Formed Steel Built-up Box Sections", *the 2019 World Congress on Advances in Structural Engineering and Mechanics*, Jeju Island, Korea. September 2019; 17-21.

[6] Hancock, G.J., and N.S. Trahair, "Finite Element analysis of the lateral buckling of continuously restrained beam-columns," *Institution of Engineers*, vol. CE 2 (2), pp. 120-127, 1978.

[7] Schafer, B.W., "Cold-formed steel behavior and design: analytical and numerical modeling of elements and members with longitudinal stiffeners," 1997, PhD thesis, Cornell University: USA.

[8] Schafer, B.W. and T. Peköz, "Computational modeling of cold-formed steel: characterizing geometric imperfections and residual stresses," *Journal of Constructional Steel Research*, vol. 47(3), pp. 193-210, 1998.

[9] L. Laim, J. P. C. Rodrigues and L. S. da Silva, "Experimental and numerical analysis on the structural behavior of cold-formed steel beams", *Journal of Thin Walled Structures*, vol. 72, pp. 1-13, 2013.

[10] Sreedhar Kalavagunta, "Theoretical study of axially compressed cold-formed steel sections," 9th International Conference on Steel and Aluminum Structures (ICSAS19) Bradford, UK, pp. 3-5, July 2019.

[11] G.Beulah Gnana Ananthi, "Nonlinear finite element bending analysis of Cold-Formed Steel of Z section beams", *KSCE Journal of Civil Engineering*, pp.1-13, 2016.

[12] Marsel Garifullina, "Computational Analysis of Cold-Formed Steel Columns with Initial Imperfections," *Procedia Engineering*. vol. 117, pp. 1073-1079, 2018.

[13] Anbarasu, M.; Kanagarasu, K.; Sukumar, S., "Investigation on the behavior and strength of cold-formed steel web stiffened built-up battened columns," *Mater. Struct.*, vol. 48, pp. 4029–4038, 2015.

[14] João Alfredo de Lazzaria and Eduardo deMiranda Batistaa, "DistortionalGlobal Buckling Interaction Relevance in Cold-Formed Steel Lipped Channel Columns", Latin American Journal of Solids and Structures, vol. 17, pp. 1-30, Nov 2020.

[15] Direct Strength Method (DSM) Design Guide CF06-1, American Iron and Steel Institute (AISI). June 2006.

[16] Mohamed EI Aghoury et al. "Compressive Strength of Axially Loaded Built-up Sigma Cold-Formed Sections Columns", Future Engineering Journal, vol. 1, pp. 2314-7237, Mar 2020.

[17] Prabhakaran.S., "Numerical study on behavior of cold-formed steel built-up battened," International Research Journal of

Engineering and Technology, vol. 7, pp. 3127-3176, May 2020.

[18] Schafer, B. W., and Ádány, S., 2006. Buckling analysis of cold-formed steel members using CUFSM: Conventional and constrained finite strip methods. In: *18th International Specialty Conference on Cold-Formed Steel Structures: Recent Research and Developments in Cold-Formed Steel Design and Construction, Johns Hopkins University*, United States, 39–54.

[19] Nguyen, V.V., "Direct strength method for the design of cold-formed steel sections under localized loading," 2017, Ph.D. Thesis, University of Sydney, Australia.

[20] Timoshenko, S. P.; Woinowsky-Krieger, S. Theory of plates and shells. New York: McGraw-Hill, 1959.

[21] Nguyen, V. V., Hancock, G. J., Pham, C. H., "Development of the ThinWall-2 Program for buckling analysis of thin-walled sections under generalized loading," In: INTERNATIONAL CONFERENCE ON ADVANCES IN STEEL STRUCTURES, vol.8., 2015, Lisboa, Portugal. Proceedings, Lisboa: ICASS, 2015.

[22] Z. Li, B. W. Schafer, "Buckling Analysis of Cold Formed Steel Members with General Boundary Condition Using CUFSM: Conventional and Constrained Finite Strip Methods", 12th International Specialty Conference on Cold Formed Steel Structures USA, 3-4 November 2010.