A PARAMETRIC STUDY: TO INVESTIGATE NONLINEAR STRUCTURAL BEHAVIOUR OF CFS BUILT-UPBATTENED COLUMNS

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ABSTRACT

This study presents parametric study performed to investigate nonlinear structural behaviour of all the three categories (based on column slenderness) of CFS built-upbattened columns. The parametric study is conducted by varying the critical parameters viz, global column slenderness, different geometries, plate slenderness (b/t ratio) and yield stress using the FE model validated. This extended study helps to apply the FEA results to verify the design strengths evaluated by DSM and EWM of AISI and European code specifications (EC3).
KEYWORDS: nonlinear structural members, CFS built-up battened columns, direct strength method, effective width method

INTRODUCTION

CFS sections are commonly adopted since they offer numerous advantages such aslightweight structures, high strength-to-weightratio, high stiffness, ease of erection & construction and so on. The use ofhot-rolled steel sections in construction of steelstructures becomes uneconomical when subjected to light/moderate loading, & for short spanned structuralmembers (Example: Joists, purlins, girts, rooftrusses, complete framing of one and two storey residential, commercial & industrial structures). Therefore investigating behaviour of CFS framing members is very important to reduce cost of construction. The hot rolled steel sections are formed under high temperatures whereas the CFS sections are rolled at ambient temperatures. Hence, this facilitates the manufacturing of CFS sections. The CFS possesses a sharper edge which offers more precise dimensions than the hot rolled sections. In general, CFS has higher yield strength and tensile strength than hot rolled, which makes CFS less likely to fracture under pressure.

The slender compression members subjected to axial compressive load will undergo lateral deformation known as buckling. As the load is applied gradually on the member, the axial shortening will be available. When a critical load is achieved, however, the part buckles sideways. This buckling action will induce bigger deformations, causing the part to collapse. The design criteria for compression members is determined by the load at which buckling occurs. Recognizing various buckling modes is required for design of CFS compression members. Light gauge CFS sections havebeen widely used in India as primary structural load-bearing elements inresidential, industrial & commercial buildings in recent times.

COLD-FORMEDSTEEL BUILT-UP COMPRESSION MEMBERS

The CFS built-up columns are generally assembled by connecting two or more sectionstogether by means of connectors. The connectors may be either battens or lacings. The main advantage of doubly symmetric section is shear centrecoincides with centroid of section. The use of doubly symmetric section is to avoid the flexural/torsional buckling. Engineers and designers face problems in using CFS battened built-up members in construction, because of lack of adequate knowledge about the behaviour and design specifications for CFS built-up battened compression members.

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OBJECTIVES OF THE RESEARCH

To investigate nonlinear structural behaviour of CFS built-up battened columns under axial compression loading.

LITERATURE REVIEW

Anil Kumar & Kalyanaraman (2010) have investigated the appropriateness of DSM in predicting axial capacities of three types of columns. The test results of plain channel sections, rectangular hollow sections and I sections from various studies are considered. Then the adequacy of DSM is checked by comparing the CUFSM-EWM and the experimental results. The DSM is found to be accurate for the three types of columns.

Dinis & camotim (2011) have reported the numericalinvestigation over elastic & elastic–plasticpost-buckling behaviour of CFS lipped channelcolumns affected by distortional/globalbuckling modeinteraction. Numerical investigation iscarried out by using ABAQUSsoftware. Further, effects of initial imperfections that affect the failure modes are studied.

In the same way, Georgieva et al. (2012) have compared the experimental buckling capacities of four CFS built-up innovative cross-sectionsformed by Σ, Z, channel & track profiles with the DSM predictions. It is concluded that the DSM approach could be used for the composed members if the method includes the provisions formembers which are sensitive to global-distortional bucklinginteraction.

Kang et al. (2013) have carried out axial compression tests on two CFS built-up columns withdifferent orientation, one with lipped C-channels facing each other (rectangular columns) and the other facing away (I-shaped columns) welded together. The I-shaped sections show uncertain buckling capacities than rectangular columns calculated by AISI-2001 due to the impacts of orientation.

Li et al. (2014) have made axial compressiontests also on CFSbuilt-up box sectioncolumns formed byconnecting the flanges of two lippedchannels by self-drilling screws. Further, numerical investigation is carried out using ANSYS. The effects of structural behaviour, fastener spacing and installation error on the load carryingcapacity of the built-upmembers too are examined. Finally, a strength estimation method is proposed which is found to be reliable for built-up I & box sectioncolumns.

Zhang & Young (2015) have examined the behaviour of CFS builtup open section columns possessing edge and web stiffeners. The parametric study is made in a way to research effectiveness of the edge & web stiffeners in built-up open sections. The results show that current DSM along with the modified DSM, utilising rational buckling analysis, could be employed fordesign of CFS built-upopen sectioncolumns.

Maia et al. (2016) have exhibited the numerical & experimental analysis of doubleangle members connected by battenplates under concentric and eccentric axial compression. The 2 design hypotheses are compared to results obtained, such as non-compositeaction and composite action. The research is focused on the number of battens provided. It is concluded that the use of more number of batten plates does not increase strength of system.

Cardoso et al. (2017) have carriedout the numerical investigation on CFS lipped channelcolumns under axial load to propose the equations for calculating the distortional buckling stresses using energy approach method. Two assumed different buckling mode shapes are used to conduct the analytical analysis. In first shape, stiffened flange is assumed as rigid whereas, in second shape, the flange plate is assumed as flexible. The parametric study is carried out with different plate slenderness for further validation of the proposed equations. From comparison of obtainedresults of parametric study with the results calculated from generalised beam theory software, it is concluded that proposed equation gives the reliable results.

Ting (2018) have addressed the issues in screw spacing in CFS built-up channel sections. There are 30 built up columns ranging from stub columns to slender columns which aretested experimentally undercompression. FE modelling is also carried out, which shows thatFE results

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are in good agreementwith test results. A parametricstudy is also conducted with 144 column models and the results show that the stub columns exhibit unconservative results by 10%.

Cai et al. (2019) have made an experimental investigation on CFS elliptical tubular stub columns to study their behaviour. Numerical analysis is carried out using ABAQUS software and validation is further done with test results. The parametric study is extended covering a wide range ofcross-17 section geometries. Theresults obtained are compared with design strengths predicted by the existing DSM. In the comparison, results calculated using the existing DSM scatters less. Therefore the design equations are proposed for predicting accurate design strengths of CFS elliptical tubular stub columns.

Aruna et al. (2020) have tested CFS built-up closedcolumns axially. The flange and web portion of columns are formed with intermediate stiffeners. FEM is validated with the test results & employed for parametric study. The results of parametric study arethen compared with DSM in NAS. Itis found that current DSM is not good in predicting capacity of CFSbuilt-up closed columns. Thus, by modifying the current design rules, improved equationsare proposed.

Akshay Mangal Mahar et al. (2021) describe a computational approach for calculating critical buckling stress ofbuilt-up cold-formed steel columns linked with discretefasteners. The fasteners are represented as 3-dimensional beam components, & their influence is integrated into spline finite stripframework, advancing compound strip approach. Despite the fact that this approach has already been published in literature, this research introduces yetanother strong framework for evaluating buckling load of compound cold-formed steelcolumns with arbitrarily positioned fasteners. The suggested formulations are simple yet rigorous, and they have been validated using numerical findings based on finite elements.

The study by Muthuraman Mohan et al. (2022) is concerned with lack of research addressing behavior of built-upcolumns. The suitable built-up column section is selected in accordance with the AISI-S100:2007 specification. Thirty-six specimens were developed and evaluated by altering web, flange, lip dimensions, chord spacing, & battened width while exposed to axialcompression. Comparing 36 experimentally buckled specimens with Finite Element Method model and two ASI-recommended direct strength methods (DSMs). The proposal's four eligible components were chosen, & validation research was carried out. Based on the study's key results, the proposed design guideline & corrected DSM value are appropriate for designing back-to-back stiffened columns.

Jing-Ren Wu et al. (2022) studied the behavior of back-to-backchannel sections composed of S700 steelwith a yield strength of 700 MPa.Compressive tests on such membersare performed to validate finite element models. Following that, using the previously proven numerical modeling technique, a numerical parametric study of buckling resistance of axially loadedcold-formed steel back-to-backchannel sections is performed. The effects ofstiffeners & the number of boltson buckling resistance are specificallyexplored. Furthermore, the parametric analysis findings are compared with codified buckling resistance derived by effective width approach used in Eurocode 3 Part 1-3 to assess the dependability of the standardised design process for buckling resistance.

P. Sangeetha et al. (2022) conducted axial compression experimental testing on builtup cold-formed columns constituted of a mix of intermediate & closer stiffeners. Twelve columns were tested tofailure, with or without intermediate & closer stiffeners. Theexperimental results attempt to quantify influence of cross-section, intermediate, and closer stiffeners on overall performance for the built-up column, including strength, strain, & failure modes. ANSYS software was used to create the Finite element model, which was verified using experimental findings. The built-up column strength predicted by American Iron and Steel Institute (AISI) design equations agreed well with the ultimate load ofbuilt-up columns determined experimentally and numerically. Based on the findings of this investigation, a suggestion is made to DSM for CFSbuilt-up columns with intermediate & closer stiffeners.

Under axial compression, Manikandan Palanisamy et al. (2023) explore distortional buckling strength of a partly closed cold-formedsteel (CFS) channel section with intermediate web stiffeners & outward lips. In general, a closed CFS cross section has greater torsional resistance

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than an open cross section. In the building business, however, an open cross section is more common. Despite popularity of CFS open sections, distortional buckling can impair their load-carrying ability. According to the results of the parametric analysis, the use of spacer plates can enhance the axial capacity of stiffened CFS channel sections by up to 32%. The findings of the finite element approach were compared to design strengths estimated using direct strength method (DSM).

RESEARCH METHODOLOGY

In the initial stage of the research, the testing on the CFS built-upcolumns is conducted in laboratory for determining load carrying capacity of sections. The tests are carriedout on 28 CFS built-up battenedcolumns with different grade of CFS materials. The specimens chosen are based on the parameters such as plate slenderness, global column slenderness and different geometry. The axial load capacities and deformed shapes are obtained for all the tested specimens. Thetest results obtained for specimens are compared with design strengths of AISI specifications using DSM and EWM and EC3 specifications. These results are used in numerical modelling as a reference in the formulation of reliable numerical model. The numerical models arethen generated and validated with testresults using the commercial program ABAQUS. Based on the measured findings, the dimensions of chord of CFS built-up sections are incorporated in FE models. In the FEM, the material characteristics acquired from the tensile coupons are used. According to the ABAQUS handbook, measured stress-strain curve is translated into the real stress-straincurve. Nonlinear FE approaches take into account material nonlinearity, geometric nonlinearity, & geometric defects. The FE models have been validated against the tests and have been shown to be correct in terms of strength, failure mechanisms, & deformed features. The verified FE model is used to conduct a parametric analysis on ultimate compressive resistance of built-up battenedcolumns. In final stage of research, a total of 228 FE models are analysed for parametric study. The factors which influence the parameters are globalcolumn slenderness, different geometries, plate slenderness & yield stress of built-up battened columns. The ultimate axialcompressive loads obtained from FE analysis are compared with design strengths of AISI (2016) and EC3 specifications to assessaccuracy of the current designrules.

EXPERIMENTAL ANALYSIS

The validated FE model is used to carryout the parametric studyfor identifying the ultimate compressive resistance as well as the nonlinear structural performance of the built-up battened columns. In the parametric study, 228 built-up battenedcolumns are examined. Variable factors include global column slenderness, alternative geometries, plate slenderness, & yield stress of built-up battened columns. To cover a wide range of slenderness by reflecting all column types, the global column slenderness is varied from 20 to 200. The specimens are made up of four distinct section sizes with thicknesses ranging from 1.2 mm to 1.6 mm. The dimensions of the chords satisfy the geometric limitations as prescribed in AISI specifications. In this parametric study, the yield stress fy is varied as 250, 350 and 450 MPa. The spacing between the batten plate chosen for current study is within limits proposed by AISI: S100 (2016) in section I1.2 and EN1993-1-3 (2006) in section 6.4.4 for chord slenderness. The typical geometrical details of the specimens are shown in Figure 1. It is worth mentioningthat there are no guidelines available in literature and the current design codes of CFS members to calculate the dimension of the batten plate. Therefore the present study chooses the depth of end batten to be greater than the distance between the CG of the chords as specified in clause 7.7.2.3 of IS 800:2007. The depth of the intermediate batten is fixed as 3/4th of the depth of the end batten.

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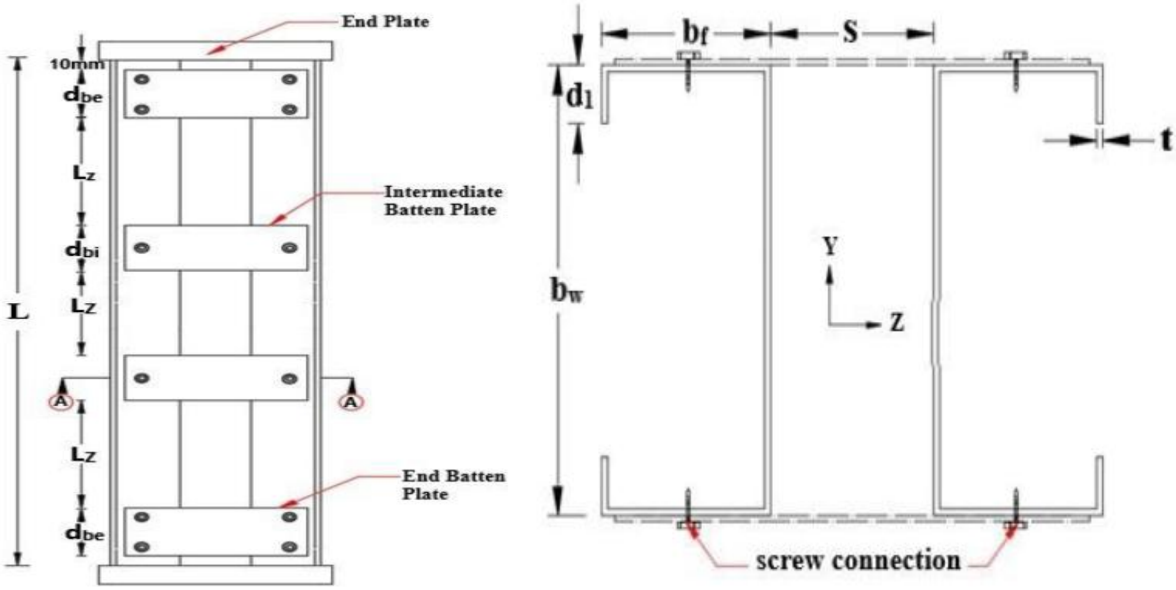

FIGURE 1 TYPICAL DETAILS OF THE SPECIMEN

Table 1: shows cross-sectional dimensions of CFS built-up battened columns considered for parametric study.

TABLE 1: DETAILS OF THESPECIMENS

COLUMN SERIES	B_W(mm)	B_F (mm)	D_1 (mm)	T (mm)	SPACING BETWEEN THECHANNELS 'S'mm)	DEPTH OF END BATTEN 'D_{BE}'(mm)	DEPTH OF INTERMEDIATEBATTEN 'D_{BI}' (mm)
120-50-15-1.6	120	50	15	1.6	55	100	75
150-60-15-1.6	150	60	15	1.6	55	100	75
120-50-15-1.2	120	50	15	1.2	55	100	75
150-60-15-1.2	150	60	15	1.2	55	100	75

The column sections are labelled based on depth of channel section, width of flange of channel, depth of the lip followed by thickness, global column slenderness & total number of battens. Forexample, in label "120-50-15-1.6-20-4", 120 indicates the depth of the web of channel, 50 indicates the breadth of flange, 15 indicates the depth of lip, 1.6 indicates thickness of section, 20 indicates global column slenderness and 4 indicates total number of battens.

DESIGN GUIDELINES IN ACCORDANCE WITH THE AISI-S100-2016 DIRECT STRENGTH METHOD

It necessitates calculating the elastic bucklingload in local, global, & distortional buckling modes. Finite strip or FE analysis may be used to calculate elastic buckling load. The nominal compressive strength of column section has been determined to be the lowest possible value of Pne, Pnl, and Pnd. Appendix 1 has a sample DSM calculation. The experimental investigation reveals that the DSM1 produces safe results for the specimens tested, whereas the DSM2 produces unsafe results for allspecimens because elastic buckling loadscalculated by CUFSM software do not account for the effect of discrete fasteners along the length of the specimens. As a result, the DSM2 technique, which takes into account elastic buckling load from CUFSM, is not employed in the parametric research.

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EFFECTIVE WIDTH METHOD

The EWM provides the modified slender approach for calculating axialstrength of CFS built-up columns. Using the values of effective area of column sections and critical buckling stresses, the member axial capacities are calculated for all the sections.

PARAMETRIC RESULTS

RESULTS OF DSM

The statistical comparison is presented in Table 2. The mean value of PFEA/PDSM is found to be 1.29 with corresponding standard deviation of 0.257. The reliability index, β value of PFEA/PDSM, is 2.88. It is clear thatcurrent DSM equations are generally conservative in predicting strength of built-up battened columns. From the results, it is found that currentDSM equations are adequate enough for predicting the strength of built-up battened columns which fail predominantly in local buckling. However, itis found that DSM formula are quite conservative for those columns that fail by interaction of the local & the flexural buckling & the conservatism increases by increasing the global column slenderness. It is observed that on the whole, current DSM predictions are reasonably good in predicting load carryingcapacity of the CFS built-up battenedcolumns. Further, calculation of critical elastic buckling loads from FE analysis is challenging for the practical design. Therefore the design equation is not proposed in the current study for the DSM.

RESULTS OF EWM

The design strength (PAISI) calculated for 228 parametric sections using EWM as per AISI and FEA results (PFEA) is compared and the statistical parameters are presented in Table 2. The value of mean & standarddeviation of PFEA/PAISI is 1.38 and 0.267 respectively. From Table 2 and Figure 2, it is observed that current design curve predictions aresafe, but they display inconsistently scattered trend in the inelastic region. Therefore there is ascope for improvement in the existing design curve of AISI for the fair prediction of accurate designstrength for built-up battened columns.

DISCUSSION

CORRELATION BETWEEN FEA RESULTS AND THE PROPOSED DESIGN STRENGTH OF AISI

As demonstrated in Figure 3, ultimate axial capacities derived from numerical parametric research are compared to design strength anticipated by the present and proposed AISI codes. According to Figure 3, the axial compression resistance estimated by existing AISI requirements is too conservative.

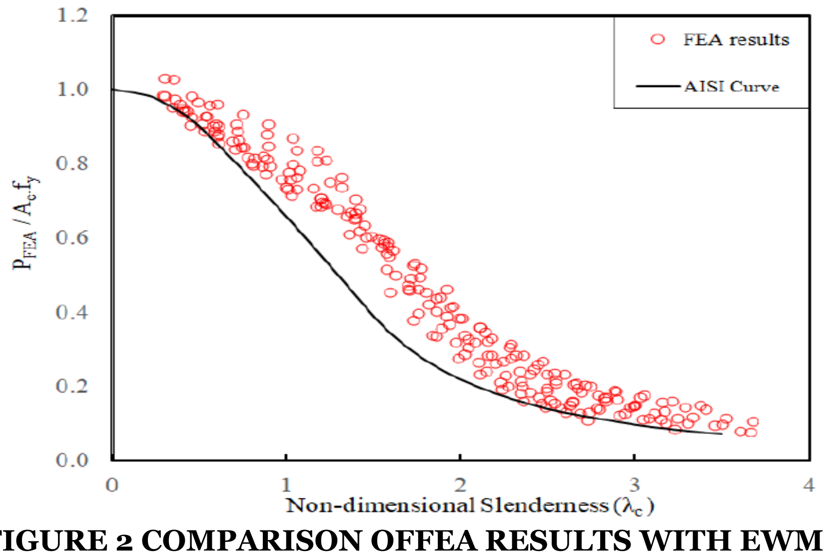

FIGURE 2 COMPARISON OFFEA RESULTS WITH EWM

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TABLE 2 COMPARISONOF FEA RESULTS WITH THE CURRENTAND THE PROPOSEDDESIGN STANDARDS

	DESIGN STRENGTHPREDICTED BY THE CURRENTDESIGN RULES				DESIGN STRENGTH PREDICTED BY THE PROPOSED EQUATIONS	
	PFEA/ PDSM	PFEA/ PAISI	PFEA/PEC3-I	PFEA/PEC3-II	PFEA/P#AISI	PFEA/P#EC3-I
Mean	1.29	1.38	1.42	0.93	1.16	1.25
Standard deviation	0.257	0.267	0.320	0.193	0.175	0.231
Capacity reduction factor(φ_c)	0.85	0.85	0.85	0.85	0.85	0.85
Reliability index(β)	2.88	3.28	3.04	1.81	2.97	2.87

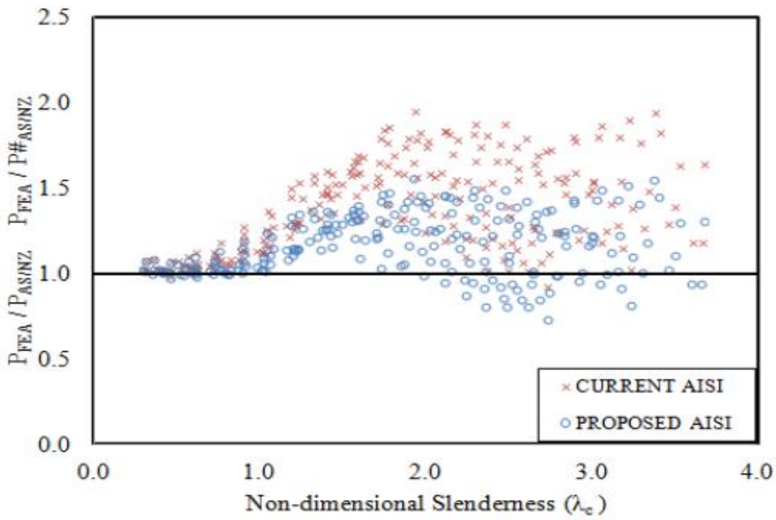

FIGURE 3: COMPARISON OFFEA RESULTS WITH THE CURRENT AISI AND THE PROPOSED AISI

The proposed equation of AISI specification prediction is reliable and safe since mean valueof the proposed PFEA/P#AISI is 1.16 which is lesser than mean value of current AISI predictions. The standard deviation of PFEA/P#AISI is 0.175. Further, the reliability index, β for the proposed equation of AISI specification, is 2.97 which have crossed target reliability value (β0) of 2.5. Hence it has been proven that the proposed design rules give safe, reliable and consistent results than the existing design as shown in Figure 3.

CORRELATION BETWEEN FEA RESULTS AND THE PROPOSED DESIGN STRENGTH OF EC3-I

As proposed EC3-I equations give consistent and safe results since mean value of the proposed PFEA/P#EC3-I, is 1.25 which is lesser than the mean value of the current EC3 predictions. Further, reliability index β for the proposed EC3 is 2.87 which has crossed the target reliabilityindex value (β0) of 2.50. From Figure 4, it is proved that the proposed design rule of EC3 gives safe & consistent results than existing design.

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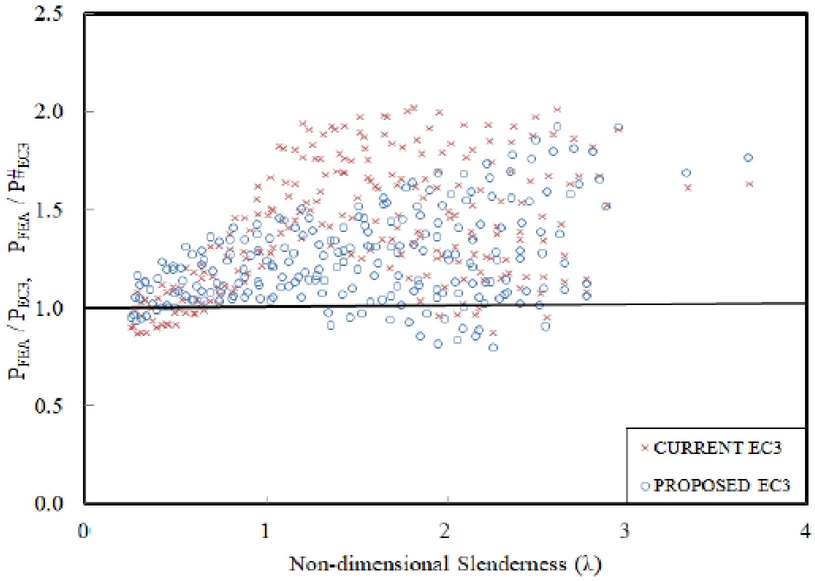

FIGURE 4 COMPARISON OF FEARESULTS WITH THE CURRENT EC3-I AND THE PROPOSED EC3-I

MODIFIED DESIGN RULES FOR AISI AND EC3-I APPROACH

PROPOSED DESIGN RULES FOR AISI

Figure 5 plots the comparison ofFEA results with the current AISI and the proposed AISI designcurves. The current design curve predicts the safe results as an overall, but it is also shown that the results are more conservative, particularly in the in-elastic region. Even though reliability index value is higher than target reliability index value, results are not consistently scattered. Hence the modified design equation isproposed for the EWM of AISI (2016) as given in Equations (1)-(3).

$$F_n = \left(0.720^{\lambda c^{1.8}}\right)F_{y,}\;\; For \lambda_c \leq 1.0 \;\ldots\ldots\ldots\ldots\ldots(1)$$

$$F_n = \left(0.720^{\lambda c^{2.1}}\right)F_{y,}\;\; For\ 1.0 < \lambda_c \leq 1.5 \;\ldots\ldots\ldots(2)$$

$$F_n = \left(\frac{1.10}{\lambda_c^2}\right)Fy, For \lambda_c \geq 1.5 \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Theproposed design curve is developed byfitting into data points obtained as shown in Figure 5.

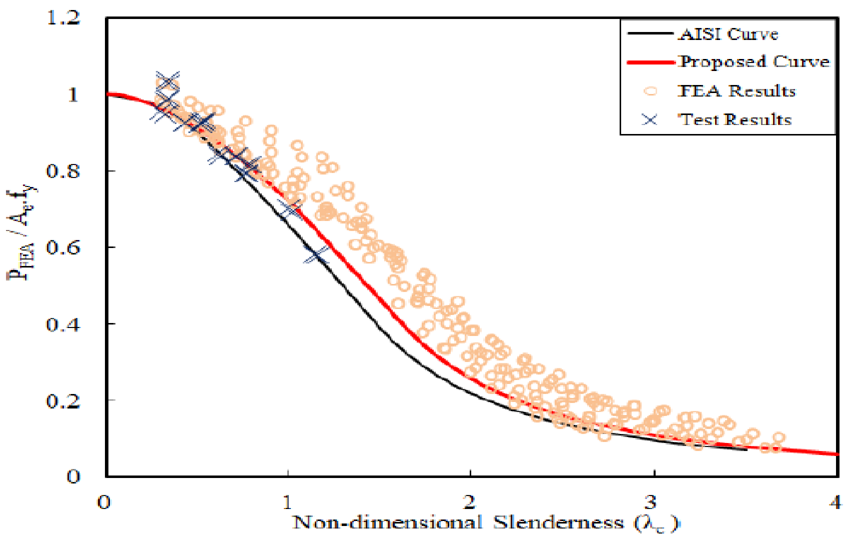

FIGURE 5 COMPARISON OF FEARESULTS WITH THE CURRENT AISI (2016) AND THE PROPOSED AISI (2016)

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A similartechnique is also used for curve proposal by the other researchers such as Gunalan & Mahendran (2013), Zhang & Young (2018a); Anbarasu & Dar (2020a). Since the AISI S100:2016 & AS/NZ 4600:2018 standards areidentical to each other, anymodification proposed to AISI-S100:2016 design rule can beapplied to AS/NZ 4600-2018 design rules as well.

PROPOSED DESIGN EQUATIONS FOR EC3-I

Figure 6 compares axial compression resistance derived from FE analysis to present and planned design curves in the EC3 code framework. The existing EC3 forecasts are proven to be dispersed and unconservative, especially at low non-dimensionalslenderness of the built-up battenedcolumns. It also predicts medium slenderness far too conservatively. This leads to the conclusion that there is a scope for further improvement in the design curves.

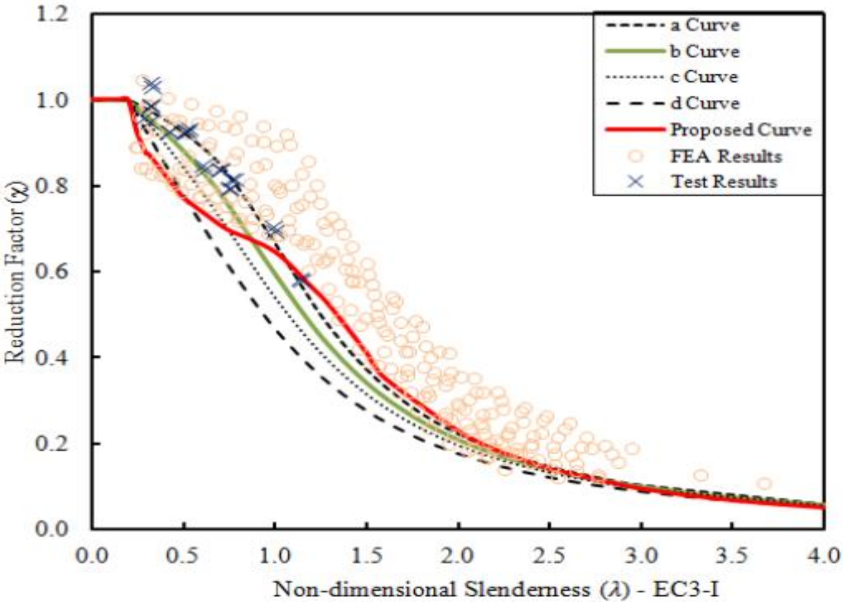

FIGURE 6 COMPARISON OF FEA RESULTS WITH THE CURRENTEC3-I AND THE PROPOSED EC3-I

Therefore new design equations are proposed to obtain safe, lessscattered, reliable & fairly accurate load carrying capacity of CFS built-up battened columns as given by Equation (4).

$$X = \begin{cases} 1.0 \quad For\bar{\lambda} \leq 0.2 \\ 1.025 + \left(0.15 - 0.99\bar{\lambda}\right) \ 0.2 < \bar{\lambda} \leq 0.3 \\ \left(\frac{0.646}{\bar{\lambda}\ 0.25842}\right) \ For 0.3 < \bar{\lambda} \leq 1.0 \\ \left(\frac{3.535}{\bar{\lambda}\ 1.842}\right) - \left(\frac{2.872}{\bar{\lambda}\ 2.089}\right) \ For 1.0 < \bar{\lambda} \leq 1.3 \\ \left(\frac{1.097}{\bar{\lambda}\ 2.419}\right) \ For 1.3 < \bar{\lambda} \leq 1.6 \\ \left(\frac{1.0525}{\bar{\lambda}\ 2.196}\right) \ For\bar{\lambda} > 1.6 \end{cases} \quad (4)$$

The proposedcurve is a multi-stagecurve as given in Equation (4), basedon the non-linear regressionanalysis using least square method, which is also shown in Figure 6. It develops equation by areduction factor (χ) beingfunction of non-dimensionalslenderness (λ). Similartechnique is also used forcurve proposed by the other researchers like Anbarasu & Dar (2020b); Devi and Singh (2020).

CONCLUSIONS

This paper has presented the detailed parametric study carried outon the CFS built-up battened columns. The effect of the variation of slenderness parameters, global column

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slenderness, yield stress and thickness is detailed. The ultimate loadbearing capacity of CFSbuilt-up battened columns determined by parametric research are compared to the design strength anticipated by AISI and EC3 design regulations. The parametric analysis findings show that the present design rule requirements have limitations in forecasting the design strength of CFS built-up battened columns. When findings are compared, it is discovered that the suggested EWM design equations and the proposed Eurocode designequations are appropriate for computing axial capacities of the CFS built-up battened columns. Furthermore, the applicability of the suggested design equations was validated using reliability analysis and comparison of test data with FEA findings available in the literature (Kherbouche & Megnounif, 2019).

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