Research Article

Determination of Modelling Error Statistics for Cold-Formed Steel Columns

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In this article, an attempt has been made to estimate the Modelling Error (ME) associated with compression capacity models available in international standards for different failure modes of compression members fabricated from Cold-Formed Steel (CFS) lipped channel sections. For the first time, a database has been created using test results available in the literature for compression capacities of CFS lipped-channel sections. The database contains details of 273 numbers of compression member tests which have failed in different failure modes, namely, (i) flexural, torsional, flexural-torsional, local, and distortion buckling and (ii) failure by yielding. Only those sources, which report all the details, required to compute the capacities using different standards are included in the database. The results of experimental investigations carried out at CSIR-Structural Engineering Research Centre, Chennai, are also included in this test database. The international codes of practice used in calculation of compression capacities of the database columns considered in this paper are ASCE 10-15 (2015), AISI S100-16 (2016), AS/NZS 4600: 2018 (2018), and EN 1993-1-3:2006 (2006). The ASCE, AISI, AS/NZS, and EN design standards have different design guidelines with respect to the failure modes, e.g., ASCE 10-15 (2015) standard provides stringent criteria for maximum width to thickness ratio for stiffened and unstiffened elements. Hence, guidelines for the distortional buckling mode are not provided, whereas the AISI S100-16 (2016) and AS/NZS 4600: 2018 (2018) standards consider separate guidelines for distortional buckling mode and EN 1993-1-3:2006 (2006) standard considers combined local and distortional buckling mode. Further, the sample size for each design standard is varying depending on the design criteria and failure mode. Studies on statistical analysis of ME suggest that the compression capacity predicting models for flexural-torsional buckling mode are associated with large variation irrespective of the design standard. Similar observations are made for the flexural buckling model as per EN 1993-1-3:2006 (2018) standard and distortional buckling models as per AISI S100-16 (2016) and AS/NZS 4600: 2018 (2018) standards. The compression capacities for test database sections are evaluated by neglecting the partial safety factors available in design standards. The probabilistic analysis to determine statistical characteristics of compression capacity indicates the importance of consideration of ME as a random variable. Hence, the ME results will be useful in code calibration studies and may have potential reference to design practice.

1. Introduction

The exponential growth in all sectors, viz. industrial, housing, transportation, communication, services, has increased the demand of power supply by many folds. In order to cater to this increased demand, the transmission line towers have to support larger and heavier conductors in bundle configuration, Juette and Zaffanella [1]. This makes the tower configurations taller and wider, and hence, the

tower system would become heavier. Conventionally, the transmission line towers are fabricated using Hot-Rolled Steel (HRS) angle sections. To reduce the tower weights, it is necessary either to consider eco-friendly alternate sustainable materials (viz., GFRP sections) or to produce lighter steel sections with higher strengths. Generally, CFS sections are used for achieving higher strengths for the structure and structural members without compromising on overall drift requirements.

For CFS sections, the influence of cold work on mechanical properties of structural steel was investigated at Cornell University by Chajes et al. [2], Karren [3], Karren and Winter [4], and Winter and Uribe [5]. It was found that the changes in mechanical properties of CFS are due to cold stretching caused mainly by strain hardening and strain aging, occurring predominantly in the bent portions of the CFS sections. The effect of cold working increases the yield stress by a minimum of 15% [6].

Some of the advantages of CFS sections as against HRS sections are as follows:

- (i) Cold rolling process produces any desired shape of cross section over longer lengths
- (ii) High strength to weight ratio can be achieved in CFS sections
- (iii) The connection methods that can be used for CFS sections are same as those for the HRS sections
- (iv) Since CFS sections/members are lighter and stronger, they can be easily transported and erected
- (v) Pregalvanised or precoated CFS sections have high resistance to corrosion

The abovementioned advantages of CFS members enable engineers to design cost effective transmission line towers. The CFS members can be fabricated to closely fit the design requirements. Recommendations for the design of plain and lipped angles, produced by cold-forming process for transmission towers, were given by Gaylord and Wilhoite [7]. These recommendations are included in ASCE 10-15 [8] standard. Some of the other international standards providing design guidelines for the use of CFS sections are AISI S100-16 [9], AS/NZS 4600: 2018 [10], EN 1993-1-3:2006 [11], and IS 801 [12]. These codes recommend equations/models for prediction of compression and tension capacities of CFS members failing in different modes depending on geometrical, material, and boundary condition details. In this paper, the focus is on estimation of ME associated with equations specified in ASCE 10-15 [8], AISI S100-16 [9], AS/NZS 4600: 2018 [10], and EN 1993-1-3:2006 [11] standards for compression capacity estimation of CFS members. Some of the highlights of the international design standards considered are as follows. (i) The ASCE 10-15 [8] standard provides design guidelines for CFS sections for transmission line towers. In this standard, the CRC curve is used for the estimation of compression capacity without embedding any partial safety factor. (ii) The AISI S100-16 [9], AS/NZS 4600: 2018 [10], and EN 1993-1-3:2006 [11] standards are providing design guidelines for CFS section for general building structures.

The JCSS probabilistic model code [13] states that the models used in calculation of structural responses are usually not complete and exact, so the actual outcomes cannot be predicted without error. The variables used in model functions are associated with possible uncertainties which accounts for random effects that are neglected in the models, and uncertainties arise due to simplification in the mathematical relations.

As has been already pointed out, the focus of this paper is to establish the ME associated with the compression capacity

formulae given in ASCE 10-15 [8], AISI S100-16 [9], AS/NZS 4600: 2018 [10], and EN 1993-1-3:2006 [11] codes. In order to estimate the same, a database of experimental capacities of columns (pinned ended), made of CFS lipped channel sections failing in different modes, is created for the first time. This database includes experimental results for CFS lipped channel columns obtained from the literature along with the test results of three nominally similar columns tested at CSIR-SERC. A brief review of the literature on column tests, probabilistic analysis, and determination of reliability index for CFS lipped channel sections is presented here.

Number of researchers have conducted experiments on CFS lipped channel columns to study the influence of residual stress, cross-sectional dimensions, yield type (gradual or sharp) of stress strain curve, forming methods (press brake or cold rolling), local buckling, load application (concentric or eccentric), etc: Weng and Pekoz [14], Weng and Lin [15], Dat [16], Mulligan [17], Loughlan [18], Loughlan and Rhodes [19], Young and Rasmussen [20], Chilver [21], Pekoz [22], Zaras and Rhodes [23], Rokade et al. [24], Miller and Pekoz [25], Moldovan [26], Sivakumaran [27], Thomasson [28], Chou et al. [29], Pu et al. [30], Dundu [31]. The compression capacity results obtained from abovementioned experimental studies for CFS lipped channel sections are used in creation of database.

From the review of literature, it has been noted that recent research is directed towards experimental and analytical investigations on built-up CFS channel sections under axial compression. Ting et al. [32] have carried out numerical and experimental investigations to study the buckling behaviour of back to back built-up CFS channel sections covering stub columns to slender columns. The geometric imperfections were measured using equipment with LVDT (0.01 mm accuracy) and considered in finite element modelling. It is observed that the FEA and test results were in good agreement and conservative with the calculated strengths as per AISI and AS/NZS standards for short, intermediate, and slender columns which failed through a combination of local and global buckling and/or global buckling. Whittle and Ramseyer [33] have conducted experimental compression tests on closed-section, built-up members formed of intermediately welded CFS channel sections, and the test capacities were compared to theoretical buckling capacities based on the AISI specifications modified slenderness ratio. Use of the modified slenderness ratio was exceedingly conservative. Capacities based on the unmodified slenderness ratio provisions were less conservative. Ye et al. [34, 35] presented the results of experimental and numerical investigations carried out on CFS plain and lipped channels under axial compression to study the interaction of local and overall flexural buckling. The measured initial geometric imperfections and material properties are used in development of finite element models. The finite element and experimental results were compared to the compression capacity calculated using Eurocode and direct strength method. It was observed that the Eurocode provides conservative predictions for the compressive capacity of plain and lipped channel sections, while the direct strength method predictions are more accurate for lipped

channels. It has been stated that these studies represent the state of the art.

Balaji Rao and Appa Rao [36] carried out studies on probabilistic analysis of strength of steel imperfect columns. Based on these studies, a characteristic strength equation is proposed which will be useful in rational design of imperfect columns. The researchers have estimated ratios of load carrying capacity to the yield load of column (ME) using CRC, AISC—ASD, AISC—PD, AISC—LRFD, SSRC Curve 2, IS 800: 1984, Lui and Chen [37], and Rondal and Maquiao [38] formulae/model functions.

The determination of reliability index for CFS elements or members is presented in several research reports of the University of Missouri-Rolla [39–43] and Supomsilaphachai et al. [44], where both the basic research data as well as the reliability index inherent in the AISI Specification are presented in great detail. The entire set of data for HR steel and CFS, was reanalysed by Ellingwood et al. [45]; Galambos et al. [46]; and Ellingwood et al. [47] using (a) updated load statistics and (b) a more advanced level of probability analysis which was able to incorporate probability distributions and to describe the true distributions more realistically.

From the review of the literature, presented above, it is found that studies dealing with ME estimation for CFS compression members are scanty. However, while estimating the ME care is taken to neglect the use of any partial factors embedded in the codal equation. The main objectives of this paper are (i) creation of database for compression capacities of CFS lipped-channel sections from the test results available in literature, (ii) estimation of ME for database results for the various failure modes as per ASCE 10-15 [8], AISI S100-16 [9], AS/NZS 4600:2018 [10], and EN 1993-1-3: 2006 [11] standards, (iii) studies on statistical characteristics of ME estimated at step (ii), and (iv) fitting a statistical distribution for the ME.

The details of experimental investigations carried out at CSIR-Structural Engineering Research Centre, Chennai, which included in test database are provided in next section.

2. Compression Tests on CFS Lipped Channels Carried Out at CSIR-SERC

At CSIR-SERC, Chennai, experimental investigations were carried out to study the buckling behaviour and to evaluate the compression capacity of axially loaded CFS lipped channel compression members (leg member of a X-braced tower panel). The scope of these experimental investigations consist of measurement of sectional dimensions for the procured lipped channels to study the imperfection associated with the CFS sections, coupon tests for determining the mechanical properties of CFS, and element level studies on axially loaded compression members to observe the buckling failure mode and to evaluate the capacity. The details for abovementioned experimental investigations are summarised as below:

2.1. Sectional Dimensions. The sectional dimensions are verified for each specimen of 3.0 m length with the help of

Vernier calliper (least count 0.01 mm) at seven locations (starting from one end at 0.0 m to every 0.5 m) along the length, and thicknesses are verified using micrometer screw gauge (least count 0.001 mm) at both the ends. The details of dimension measurements for two number of sample specimens are given in Table 1. The tolerance limit for profile dimensions as per IS: 811-1987 [48] is ± 0.5 mm and for the thickness of strip used in making of cold formed section is ± 0.5 mm as per IS: 1852-1985 [49]. It is observed that the sectional dimensions and member thicknesses are within the tolerance limits. To measure the straightness, the specimens were placed horizontally on a plane surface and a long precision ruler was used as a reference plane.

2.2. Coupon Tests. The material properties were determined by tensile coupon tests. The coupons were cut from the centre of web of CFS lipped channel sections of the same batch as per ASTM Standard E8/E8M—15a [50] and tested as per ASTM Standard E6—15 [51] in a 100 Ton Universal Testing Machine (UTM). An extensometer of 50 mm gauge length was used to measure the longitudinal strain. The displacement control for load application is kept at 0.5 mm/min, and the inbuilt data acquisition system of UTM with 1 Hz sampling frequency was used to record the load and strain values during the test. The stress-strain curve obtained along with the coupon specimen details are presented in Figure 1. As the material is gradually yielding material, the yield stress was determined by the 0.2% offset method [52]. The tension coupon test set up for CFS and the coupon test specimen after failure is shown in Figure 2.

2.3. Element-Level Tests. The element-level compression tests were carried out on lipped channel sections LC $90 \times 50 \times 20 \times 3.15$ mm (Lipped Channel – Web depth $\times$ Flange width $\times$ Lip depth $\times$ Thickness). The tests were categorized as concentrically loaded members corresponding to leg members in a latticed tower panel. The tests were conducted using 250 Ton capacity displacement control UTM with spherical joints and ball bearing head at the top end and fixed base at the bottom. The CFS lipped channel specimens fabricated were of 2.225 m in length and connected with specially made fixtures at ends using 3 numbers of 16 mm diameter bolts as shown in Figure 3. This is in order to simulate the exact member end condition for leg member of a X-braced panel. During the tests, the lateral displacements of flanges and web were measured using displacement dial gauges (0.01 mm least count). The linear foil strain gauges were instrumented across the cross section of specimens to measure the longitudinal strain variations throughout the load application. The test responses for dial and strain gauges were acquired using HBM data logger. In order to measure the strains and displacement responses at critical location, specimens were instrumented at maximum lateral displacement sections, i.e., mid length of the specimens. The test set-up and the three tested specimen's photos are shown in Figure 4. As the end fixtures are made of 16 mm thick HRS plates and the specimen thickness is 3.15 mm, the stiffness of end fixtures is higher compared to the specimen. Hence, it is

TABLE 1: Dimension measurement details of two number of CFS lipped channel specimens.

Specimen	Section No	Distance	Web (mm)	Flange1 (mm)	Flange2 (mm)	Lip1 (mm)	Lip2 (mm)	Thk1 (mm)	Thk2 (mm)
1	1	0.00	90.42	50.00	49.79	19.90	20.50	3.25	3.25
	2	0.50	89.77	50.03	50.03	20.24	20.45	—	—
	3	1.00	90.26	50.36	50.29	19.68	20.43	—	—
	4	1.50	89.75	50.44	50.47	19.58	19.55	—	—
	5	2.00	89.91	49.96	50.40	19.60	19.86	—	—
	6	2.50	89.94	50.29	50.34	19.52	19.55	—	—
	7	3.00	90.47	49.65	50.50	20.09	20.24	3.25	3.40
	Average		90.07	50.10	50.26	19.80	20.08	3.25	3.33
2	1	0.00	89.52	50.44	49.70	20.05	19.54	3.22	3.20
	2	0.50	90.46	50.46	49.80	20.05	19.60	—	—
	3	1.00	90.26	50.30	50.44	20.25	19.80	—	—
	4	1.50	90.39	50.18	49.93	20.22	19.94	—	—
	5	2.00	89.52	49.81	50.03	19.77	19.81	—	—
	6	2.50	89.64	49.89	49.58	19.70	20.44	—	—
	7	3.00	90.04	49.55	49.93	19.86	19.56	3.17	3.60
	Average		89.98	50.09	49.92	19.98	19.81	3.20	3.40
Minimum dimension required			90.00	50.00	50.00	20.00	20.00	3.15	3.15

FIGURE 1: Stress-Strain plot and tension coupon details.

assumed that the end condition of test specimen will act as pin ends. Accordingly, the effective length for analysis is considered between centre to centre of the end connection. The test specimens have failed in flexural-torsional buckling mode and the observed test capacities are 119, 118, and 113 kN with an average compression capacity of 116.67 kN. The capacities calculated using the assumed effective length and as per ASCE 10-15 [8] and AISI S100-16 [9], AS/NZS 4600:2018 [10] are in good agreement with the test capacity. This observation shows that the effective length determined assuming pinned end conditions is satisfactory. However, it is to be noted that exact determination of effective length is difficult. The results of test capacities and codal predictions for the test specimens are presented in Table 2. The capacity predictions are based on the design standards under consideration and calculated for effective length equal to the centre to centre of bolted connection (1915 mm) and without considering the safety or partial safety factors present in model equations.

The specimen details and results of above compression tests along with results of compression tests available in the literature for CFS lipped channel pinned columns considered in creation of database is presented in the next section.

3. Database of Compression Capacity for CFS Lipped Channel Members

In this study, for the first time, a test database is created from the experimental details available in the literature for the CFS lipped channel compression members. Table 3 provides the details of database created. Further, it gives information on the test data exclusion criteria used in filtering the test data of each study considered. It also indicates the reference data number for particular referenced compression members from the detailed test database presented in Table 4 and Figure 5.

The selection of test compression members, obtained from the literature, for the ME estimation was based on the following criteria:

- (1) The member is a CFS lipped channel section
- (2) The test results are close to the calculated capacities ($\pm\%$ variations used)
- (3) The member is concentrically loaded during the test
- (4) The member tested with pinned end condition on both ends
- (5) The member is not having any perforations along the length
- (6) The member is not having any intermediate stiffeners in web

A total number of 577 compression members' test details available in the literature are used in the creation of test database. Out of this 273 compression members (120 columns and 153 stub columns) are filtered using above-mentioned criteria and used in test database. The detailed test database (refer Table 4 and Figure 5) includes test compression member details like out-to-out cross-section dimensions (lipped channel section web depth, flange width, and lip depth), thickness of section, corner radius (inner), length of the member, material properties (Young's modulus, yield, and ultimate strength), test load, type of compression member (column or stub column), torsion

FIGURE 2: Test details of coupon tests carried out in this investigation. (a) Test set-up (b) Tested specimens.

indicator, and forming method (press brake or roll forming). While creating the test database, it is noticed that not all the required details were available and were assumed appropriately as follows:

- (a) In some of the references, the material properties like Young's modulus and/or ultimate strength details were not available which were taken from the standards based on the value of yield strength and country/region in which the tests were conducted.
- (b) The pinned end condition was assumed at both ends for some of the compression members for which the details were not available.
- (c) For the compression members where it was not clearly mentioned that the torsional buckling is allowed, it is assumed to be allowed. This assumption provides calculated results in a more realistic behaviour.
- (d) In one of the references, the member length was not indicated for the stub columns. Though it is not required for calculating the section capacity, the same was assumed as three times the web depth. This is just to indicate in the test database.

Further, to estimate ME, initially the test database for CFS lipped channel compression members has been filtered through the geometric proportion criteria stipulated for each code separately which is explained in next section. Then the database compression members are further filtered for the limiting maximum slenderness ratio. The limiting maximum slenderness ratio for tower leg members (axially loaded compression members in transmission tower) is given as 120 in ASCE standard. Though this limitation is not present in AISI, AS/NZS, and EN standards, the same is applied in this study as ASCE standard provides design guidelines for "Design of Latticed Steel Transmission Structures," whereas the other standards are applicable for general steel structures. This philosophy of limiting slenderness ratio to the axially loaded compression members is based on the fact that the overall deformation of transmission line towers is governed by the stiffness of leg members. Large deformations resulting with higher slenderness ratios of lower stiffness members may cause disturbance to the safe clearance limits of electrical conductors with the tower profile.

Before estimating the ME associated with different codal equations, a brief overview of codal clauses that would help in discussing the results of statistical analysis are presented in the next section.

Note - All dimension are in mm.

FIGURE 3: Fabrication details of the compression element and details of the end fixtures.

FIGURE 4: Test details of compression tests carried out in this investigation. (a) Test set-up (b) Tested specimens.

4. Codal Provisions for Estimation of Compression Capacity of CFS Columns

In this section, a brief review of design guidelines for CFS sections available in International design standards, i.e.,

ASCE 10-15 [8], AISI S100-16 [9], AS/NZS 4600: 2018 [10], and EN 1993-1-3:2006 [11] are presented (refer Table 5). The design guidelines of AISI and AS/NZS standards are similar and hence presented in a single column (refer Table 5). The design guidelines covered here focus on increase in strength

TABLE 2: Results of experimental investigation, column capacity in torsional-flexural buckling mode.

Design standard	Calculated compression capacity (kN)	Average test compression capacity (kN)	Difference in compression capacity (kN)	% Difference
ASCE 10-15 (2015)	120.14		3.47	2.97
AISI S100-16 (2016) & AS/NZS 4600: 2018 (2018)	112.84	116.67	−3.83	−3.28
EN 1993-1-3:2006 (2006)	98.34		−18.33	−15.71

TABLE 3: Test database for cold-formed lipped channel compression members.

Sr. no.	Author(s)	Year	No. of compression members				Criterion [#]	Ref. data no. in database
			Tested		Data used in this study			
			Column	Stub column	Column	Stub column		
1	Weng and Pekoz	1990	68	25	30	13	1	1 to 43
2	Dat	1980	60	20	26	11	1, 2	44 to 69 and 263 to 273
3	Mulligan	1983	21	36	13	25	1, 3	70 to 81, 196 and 171 to 195
4	Loughlan and Rhodes	1979, 1980	33	—	7	—	3	82 to 88
5	Young [@]	1998	15	6	10	2	2, 3, 4	89 to 100
6	Rokade et al.	2010	3	—	3	—	—	101 to 103
7	Miller and Pekoz	1994	—	31	—	18	5	104 to 121
8	Moldavan	1994	37	27	18	11	1	121 to 139 and 140 to 150
9	Sivakumaran	1987	—	48	—	6	5	151 to 156
10	Thomasson	1978	46	—	14	—	6	157 to 170
11	Chilvers ^{\$}	1954	—	28	—	16	1	197 to 212
12	Pekoz ^{\$}	1977	—	19	—	12	1	213 to 224
13	Zaras and Rhodes*	1987	—	6	—	2	1	225 to 226
14	Pu	1998	—	36	—	36	—	227 to 262
15	Dundu	2014	9	3	9	3	—	273 to 285

[#]Criterion used to exclude some of the test compression members given in reference. [@]—Some of the test compression members of this reference are considered in test database, finally they were excluded based on very high ME or no match in calculated and experimental results. ^{\$}—The data are taken from Mulligan [17] as the original reference is not available. *The data are taken from Chou et al. [29] as the original reference is not available.

due to cold working, limiting geometrical proportions, and column capacity prediction models for different failure modes.

Considering the above codal provisions, the database CFS lipped channel sections are filtered for limiting criteria, and then the compression capacities are calculated for the estimation of ME. The ME estimation procedure and statistical properties of ME for database CFS lipped channel sections is presented in the next section.

5. Modelling Error Estimation Methodology

The mathematical relations or model functions used to predict the capacity of the compression member are based on the simplifying assumptions and/or neglected random effects for some of the parameters involved in the prediction equation [13]. Hence, the model function may not completely describe the physical phenomenon under consideration. This in combination with lack of complete knowledge of the modeller causes the difference in the actual and predicted compression member capacities. The difference in capacity can be quantified using ME analysis. Accordingly, the ME should be defined as the ratio of actual capacity to calculated capacity. It may be possible that the test capacity may not be the true capacity as there may be some unavoidable errors involve in the test and measurement procedure, but even then, it provides close estimate to the true

capacity. In this study, the ME is taken as the ratio of test to calculated capacity of compression member. Further, in ME analysis, the model functions are considered for various modes of failure viz. flexure, flexure-torsion, local and distortion buckling, and yielding of section based on ASCE 10-15 [8], AISI S100-16 [9], AS/NZS 4600: 2018 [10], and EN 1993-1-3:2006 [11] standards as described in above section.

Accordingly, after passing through the filtering criteria as discussed in “Database of Compression Capacity for CFS Lipped Channel Members”, the member compression capacity has been calculated for the balance test database members for governing failure modes given in each design standard after removing the safety or partial safety factors present in the model function. Then the ME estimated taking the ratio of test capacity as per database with the calculated capacity. The results of calculated ME and its statistical properties for the test database compression members in various failure modes as per abovementioned design standards are presented in Table 6. The histograms of ME for various failure modes with respect to design standards are shown in Figures 6–8. Further, Chi-square goodness-of-fit test has been performed on ME for selection of statistical distributions, and the results of this test are provided in Table 7. The failure modes considered for column members are flexure, flexure-torsion, and local and distortion buckling and for stub columns failure by yielding and local and distortion buckling.

TABLE 4: Test database of axially loaded cold-formed steel lipped channel section compression members.

S. No.	W (mm)	F (mm)	L (mm)	T (mm)	R (mm)	Length (mm)	F_y (N/mm ²)	F_u (N/mm ²)	P_{Test} (kN)	E (N/mm ²)	Type of comp. member	Torsion allowed	Forming method
1	80.06	41.86	17.93	3.02	3.96	254.00	278.22	366.00	166.43	203.255	SC	Y	R
2	80.06	41.86	17.93	3.02	3.96	685.80	278.22	366.00	143.74	203.255	C	Y	R
3	80.06	41.86	17.93	3.02	3.96	990.60	278.22	366.00	134.84	203.255	C	Y	R
4	80.06	41.86	17.93	3.02	3.96	1295.40	278.22	366.00	126.83	203.255	C	Y	R
5	80.06	41.86	17.93	3.02	3.96	1600.20	278.22	366.00	87.67	203.255	C	Y	R
6	77.90	41.38	18.16	2.44	3.96	254.00	357.25	428.63	155.75	203.255	SC	Y	R
7	77.90	41.38	18.16	2.44	3.96	254.00	357.25	428.63	161.98	203.255	SC	Y	R
8	77.90	41.38	18.16	2.44	3.96	685.80	357.25	428.63	134.39	203.255	C	Y	R
9	77.90	41.38	18.16	2.44	3.96	990.60	357.25	428.63	129.94	203.255	C	Y	R
10	77.90	41.38	18.16	2.44	3.96	1295.40	357.25	428.63	105.91	203.255	C	Y	R
11	77.90	41.38	18.16	2.44	3.96	1600.20	357.25	428.63	75.65	203.255	C	Y	R
12	76.15	44.60	17.63	1.91	5.56	254.00	379.57	527.43	130.83	203.255	SC	Y	R
13	76.15	44.60	17.63	1.91	5.56	254.00	379.57	527.43	133.06	203.255	SC	Y	R
14	76.15	44.60	17.63	1.91	5.56	254.00	379.57	527.43	131.72	203.255	SC	Y	R
15	76.15	44.60	17.63	1.91	5.56	685.80	379.57	527.43	112.59	203.255	C	Y	R
16	76.15	44.60	17.63	1.91	5.56	982.98	379.57	527.43	99.24	203.255	C	Y	R
17	76.15	44.60	17.63	1.91	5.56	1295.40	379.57	527.43	72.98	203.255	C	Y	R
18	76.15	44.60	17.63	1.91	5.56	1600.20	379.57	527.43	56.52	203.255	C	Y	R
19	76.15	44.60	17.63	1.91	5.56	1917.70	379.57	527.43	43.17	203.255	C	Y	R
20	76.84	41.15	15.49	2.21	3.96	254.00	264.58	348.36	104.58	203.255	SC	Y	P
21	76.84	41.15	15.49	2.21	3.96	254.00	264.58	348.36	104.58	203.255	SC	Y	P
22	76.84	41.15	15.49	2.21	3.96	680.72	264.58	348.36	80.10	203.255	C	Y	P
23	76.84	41.15	15.49	2.21	3.96	990.60	264.58	348.36	77.88	203.255	C	Y	P
24	76.84	41.15	15.49	2.21	3.96	1295.40	264.58	348.36	71.20	203.255	C	Y	P
25	76.23	41.45	15.37	1.80	3.96	254.00	250.11	344.98	82.33	203.255	SC	Y	P
26	76.23	41.45	15.37	1.80	3.96	254.00	250.11	344.98	78.77	203.255	SC	Y	P
27	76.23	41.45	15.37	1.80	3.96	254.00	250.11	344.98	79.21	203.255	SC	Y	P
28	76.23	41.45	15.37	1.80	3.96	685.80	250.11	344.98	71.65	203.255	C	Y	P
29	76.23	41.45	15.37	1.80	3.96	990.60	250.11	344.98	69.42	203.255	C	Y	P
30	76.23	41.45	15.37	1.80	3.96	1295.40	250.11	344.98	57.85	203.255	C	Y	P
31	76.23	41.45	15.37	1.80	3.96	1600.20	250.11	344.98	49.84	203.255	C	Y	P
32	76.23	41.45	15.37	1.80	3.96	1905.00	250.11	344.98	43.17	203.255	C	Y	P
33	127.94	63.27	22.30	3.00	3.18	431.80	210.77	351.05	201.59	203.255	SC	Y	P
34	127.94	63.27	22.30	3.00	3.18	1397.00	210.77	351.05	152.19	203.255	C	Y	P
35	127.94	63.27	22.30	3.00	3.18	1905.00	210.77	351.05	135.28	203.255	C	Y	P
36	127.94	63.27	22.30	3.00	3.18	2286.00	231.50	357.66	123.71	203.255	C	Y	P
37	127.94	63.27	22.30	3.00	3.18	2794.00	231.50	357.66	99.24	203.255	C	Y	P
38	67.18	34.98	15.82	1.63	2.39	254.00	230.47	276.50	58.74	203.255	SC	Y	P
39	67.18	34.98	15.82	1.63	2.39	787.40	230.47	276.50	49.84	203.255	C	Y	P
40	67.18	34.98	15.82	1.63	2.39	1041.40	230.47	276.50	46.28	203.255	C	Y	P
41	67.18	34.98	15.82	1.63	2.39	1320.80	220.89	310.67	35.60	203.255	C	Y	P
42	67.18	34.98	15.82	1.63	2.39	1574.80	220.89	310.67	30.71	203.255	C	Y	P
43	67.18	34.98	15.82	1.63	2.39	1752.60	220.89	310.67	27.59	203.255	C	Y	P
44	44.20	42.93	18.92	2.29	3.94	2209.80	305.02	434.37	40.18	203.255	C	Y	R
45	44.20	42.93	18.92	2.29	3.94	1905.00	305.02	434.37	54.29	203.255	C	Y	R
46	44.20	42.93	18.92	2.29	3.94	1752.60	305.02	434.37	59.41	203.255	C	Y	R
47	44.20	42.93	18.92	2.29	3.94	1600.20	305.02	434.37	71.20	203.255	C	Y	R
48	44.20	42.93	18.92	2.29	3.94	1447.80	305.02	434.37	89.00	203.255	C	Y	R
49	44.20	42.93	18.92	2.29	3.94	1295.40	305.02	434.37	102.35	203.255	C	Y	R
50	44.20	42.93	18.92	2.29	3.94	1143.00	305.02	434.37	109.03	203.255	C	Y	R
51	44.20	42.93	18.92	2.29	3.94	990.60	305.02	434.37	131.28	203.255	C	Y	R
52	43.76	42.49	18.71	1.85	4.15	2156.46	304.95	421.39	40.27	203.255	C	Y	R
53	43.76	42.49	18.71	1.85	4.15	2044.70	304.95	421.39	39.16	203.255	C	Y	R
54	43.76	42.49	18.71	1.85	4.15	2044.70	304.95	421.39	35.60	203.255	C	Y	R
55	43.76	42.49	18.71	1.85	4.15	1295.40	304.95	421.39	68.98	203.255	C	Y	R
56	43.76	42.49	18.71	1.85	4.15	1295.40	304.95	421.39	71.20	203.255	C	Y	R
57	43.76	42.49	18.71	1.85	4.15	990.60	304.95	421.39	80.10	203.255	C	Y	R
58	43.76	42.49	18.71	1.85	4.15	685.80	304.95	421.39	86.78	203.255	C	Y	R

TABLE 4: Continued.

S. No.	W (mm)	F (mm)	L (mm)	T (mm)	R (mm)	Length (mm)	F_y (N/mm ²)	F_u (N/mm ²)	P_{Test} (kN)	E (N/mm ²)	Type of comp. member	Torsion allowed	Forming method
59	44.20	42.93	18.92	2.29	3.94	2540.00	330.10	429.05	34.27	203.255	C	Y	P
60	44.20	42.93	18.92	2.29	3.94	2082.80	330.10	429.05	44.28	203.255	C	Y	P
61	44.20	42.93	18.92	2.29	3.94	1600.20	330.10	429.05	70.53	203.255	C	Y	P
62	44.20	42.93	18.92	2.29	3.94	1295.40	330.10	429.05	96.12	203.255	C	Y	P
63	44.20	42.93	18.92	2.29	3.94	990.60	330.10	429.05	117.48	203.255	C	Y	P
64	43.76	42.49	18.71	1.85	4.15	2260.60	308.33	413.90	36.49	203.255	C	Y	P
65	43.76	42.49	18.71	1.85	4.15	1981.20	308.33	413.90	46.73	203.255	C	Y	P
66	43.76	42.49	18.71	1.85	4.15	1752.60	308.33	413.90	49.84	203.255	C	Y	P
67	43.76	42.49	18.71	1.85	4.15	1447.80	308.33	413.90	62.08	203.255	C	Y	P
68	43.76	42.49	18.71	1.85	4.15	990.60	308.33	413.90	85.89	203.255	C	Y	P
69	43.76	42.49	18.71	1.85	4.15	685.80	308.33	413.90	89.89	203.255	C	Y	P
70	156.57	81.10	18.11	1.14	2.78	1600.20	223.30	319.90	43.61	203.255	C	Y	P
71	155.98	81.08	17.04	1.14	2.72	1905.51	220.14	317.22	46.28	203.255	C	Y	P
72	156.97	81.08	17.04	1.16	2.76	3075.94	220.14	317.22	36.49	203.255	C	Y	P
73	155.37	81.20	17.63	1.15	2.81	3073.40	220.14	317.22	37.38	203.255	C	Y	P
74	156.57	80.49	18.29	1.22	2.95	1905.00	223.72	310.81	52.51	203.255	C	Y	P
75	231.57	81.25	17.27	1.14	2.72	1829.05	224.55	321.49	42.72	203.255	C	Y	P
76	231.98	81.13	17.48	1.14	2.82	2416.05	223.30	319.90	38.94	203.255	C	Y	P
77	232.18	81.13	17.37	1.12	2.69	2997.20	223.30	319.90	33.82	203.255	C	Y	P
78	230.58	81.25	18.44	1.23	2.94	2413.76	227.78	306.95	48.06	203.255	C	Y	P
79	222.05	114.20	19.94	1.21	2.90	1906.78	219.24	307.91	54.74	203.255	C	Y	P
80	222.83	113.69	19.46	1.21	3.00	2516.38	244.04	319.63	53.85	203.255	C	Y	P
81	222.66	114.00	19.13	1.22	2.99	2518.66	233.23	311.22	52.51	203.255	C	Y	P
82	153.95	62.79	25.37	0.80	0.00	1905.00	242.00	360.00	21.80	201.000	C	Y	P
83	153.95	62.89	25.60	0.81	0.00	1600.20	242.00	360.00	23.04	201.000	C	Y	P
84	152.02	62.97	25.57	0.80	0.00	1295.40	242.00	360.00	23.62	201.000	C	Y	P
85	152.30	49.28	17.74	1.64	0.00	1905.00	233.00	360.00	65.83	208.000	C	Y	P
86	178.23	61.85	24.62	1.63	0.00	1905.00	233.00	360.00	75.39	208.000	C	Y	P
87	177.93	61.62	24.77	1.64	0.00	1600.20	233.00	360.00	75.84	208.000	C	Y	P
88	176.73	61.98	25.71	1.64	0.00	1295.40	233.00	360.00	80.29	208.000	C	Y	P
89	90.00	50.00	20.00	3.15	3.15	1915.00	350.00	471.00	119.00	219.800	C	Y	P
90	90.00	50.00	20.00	3.15	3.15	1915.00	350.00	471.00	118.00	219.800	C	Y	P
91	90.00	50.00	20.00	3.15	3.15	1915.00	350.00	471.00	113.00	219.800	C	Y	P
92	92.00	37.00	12.00	1.91	2.40	276.00	358.00	450.00	192.90	203.255	C	Y	R
93	151.00	34.00	8.00	0.93	2.40	453.00	309.00	360.00	38.20	203.255	C	Y	R
94	92.00	37.00	11.00	2.14	2.40	276.00	358.00	450.00	193.60	203.255	C	Y	R
95	92.00	37.00	12.00	2.15	2.40	276.00	358.00	450.00	194.60	203.255	C	Y	R
96	92.00	37.00	11.00	2.14	2.40	276.00	358.00	450.00	213.60	203.255	C	Y	R
97	152.00	35.00	8.00	0.89	2.40	456.00	309.00	360.00	43.30	203.255	C	Y	R
98	152.00	35.00	8.00	0.87	2.40	456.00	309.00	360.00	42.60	203.255	C	Y	R
99	152.00	34.00	8.00	0.91	2.40	456.00	309.00	360.00	43.30	203.255	C	Y	R
100	92.00	37.00	12.00	1.92	2.40	276.00	366.00	450.00	165.40	203.255	C	Y	R
101	92.00	36.00	12.00	1.91	2.40	276.00	366.00	450.00	184.00	203.255	C	Y	R
102	92.00	37.00	12.00	1.91	2.40	276.00	366.00	450.00	182.90	203.255	C	Y	R
103	92.00	37.00	12.00	1.92	2.40	276.00	366.00	450.00	158.80	203.255	C	Y	R
104	92.00	37.00	12.00	1.91	2.40	276.00	366.00	450.00	182.60	203.255	C	Y	R
105	152.00	35.00	8.00	0.90	2.40	456.00	302.00	360.00	40.20	203.255	C	Y	R
106	152.00	35.00	8.00	0.89	2.40	456.00	302.00	360.00	39.60	203.255	C	Y	R
107	152.00	35.00	8.00	0.89	2.40	456.00	302.00	360.00	37.00	203.255	C	Y	R
108	152.00	35.00	8.00	0.89	2.40	456.00	302.00	360.00	38.20	203.255	C	Y	R
109	152.00	35.00	8.00	0.89	2.40	456.00	302.00	360.00	41.00	203.255	C	Y	R
110	85.80	56.00	15.00	1.90	2.90	1080.00	213.00	360.00	66.71	210.000	C	N	P
111	85.60	57.20	16.40	1.90	2.90	1080.00	213.00	360.00	67.69	210.000	C	N	P
112	86.20	55.40	17.00	1.90	2.90	2000.00	213.00	360.00	51.99	210.000	C	N	P
113	87.20	55.50	17.00	1.75	2.60	2000.00	213.00	360.00	49.05	210.000	C	N	P
114	96.00	65.50	20.00	1.75	2.60	1480.00	213.00	360.00	69.65	210.000	C	N	P
115	94.00	65.80	20.00	1.75	2.60	1480.00	213.00	360.00	71.61	210.000	C	N	P
116	99.80	64.50	19.80	1.85	2.80	2000.00	213.00	360.00	64.75	210.000	C	N	P

TABLE 4: Continued.

S. No.	W (mm)	F (mm)	L (mm)	T (mm)	R (mm)	Length (mm)	F_y (N/mm ²)	F_u (N/mm ²)	P_{Test} (kN)	E (N/mm ²)	Type of comp. member	Torsion allowed	Forming method
117	99.00	66.50	20.50	1.90	2.90	2000.00	213.00	360.00	69.65	210.000	C	N	P
118	96.00	72.00	21.20	3.00	4.50	1120.00	211.00	360.00	156.96	210.000	C	N	P
119	97.70	70.30	22.10	3.00	4.50	2000.00	211.00	360.00	123.61	210.000	C	N	P
120	97.50	70.00	21.60	3.00	4.50	2000.00	211.00	360.00	130.47	210.000	C	N	P
121	136.50	55.50	24.50	3.00	4.50	1700.00	211.00	360.00	186.39	210.000	C	N	P
122	121.00	83.20	25.00	3.00	4.50	1700.00	211.00	360.00	167.75	210.000	C	N	P
123	121.80	82.70	25.20	3.00	4.50	1700.00	211.00	360.00	150.09	210.000	C	N	P
124	119.30	85.50	25.10	3.00	4.50	2000.00	211.00	360.00	143.23	210.000	C	N	P
125	121.30	84.60	25.60	3.00	4.50	2000.00	211.00	360.00	154.02	210.000	C	N	P
126	121.00	86.10	25.50	1.90	2.90	2000.00	213.00	360.00	94.18	210.000	C	N	P
127	121.00	86.10	25.50	1.90	2.90	2000.00	213.00	360.00	96.14	210.000	C	N	P
128	82.50	57.00	16.00	1.80	2.70	295.00	213.00	360.00	77.50	210.000	SC	N	P
129	82.00	57.00	17.00	1.80	2.70	296.00	213.00	360.00	77.50	210.000	SC	N	P
130	97.00	66.00	21.00	1.85	2.80	350.00	213.00	360.00	87.31	210.000	SC	N	P
131	95.00	67.00	21.00	1.90	2.90	350.00	213.00	360.00	96.14	210.000	SC	N	P
132	97.00	70.00	23.00	3.00	4.50	348.00	211.00	360.00	200.12	210.000	SC	N	P
133	97.00	70.00	23.00	3.00	4.50	348.00	211.00	360.00	192.28	210.000	SC	N	P
134	114.00	84.00	27.00	3.10	4.70	397.00	211.00	360.00	214.84	210.000	SC	N	P
135	115.00	88.00	26.00	3.10	4.70	399.00	211.00	360.00	213.86	210.000	SC	N	P
136	121.00	88.00	26.00	3.10	4.70	400.00	211.00	360.00	208.95	210.000	SC	N	P
137	120.00	87.00	26.00	1.90	2.90	400.00	213.00	360.00	119.68	210.000	SC	N	P
138	123.00	86.00	25.00	1.90	2.90	400.00	213.00	360.00	117.72	210.000	SC	N	P
139	85.70	34.90	9.50	1.60	3.20	200.00	340.60	443.60	84.55	205.000	SC	Y	R
140	85.70	34.90	9.50	1.60	3.20	200.00	340.60	443.60	84.70	205.000	SC	Y	R
141	85.70	34.90	9.50	1.60	3.20	200.00	340.60	443.60	86.75	205.000	SC	Y	R
142	147.28	36.18	10.09	1.29	2.58	265.00	262.20	336.00	54.30	210.000	C	Y	R
143	147.28	36.18	10.09	1.29	2.58	265.00	262.20	336.00	54.40	210.000	C	Y	R
144	147.28	36.18	10.09	1.29	2.58	265.00	262.20	336.00	53.25	210.000	C	Y	R
145	300.46	101.56	20.23	0.63	1.50	2690.00	391.00	482.00	16.00	216.000	C	N	R
146	300.98	101.98	21.24	0.64	1.50	2690.00	395.00	490.00	16.20	216.000	C	N	R
147	300.48	101.78	20.64	0.64	1.50	2690.00	398.00	483.00	15.50	216.000	C	N	R
148	301.30	101.50	20.85	0.65	1.50	2690.00	288.00	384.00	14.50	216.000	C	N	R
149	301.68	102.38	21.14	0.94	1.50	2690.00	464.00	552.00	36.90	216.000	C	N	R
150	301.58	102.38	20.94	0.94	1.50	2690.00	460.00	545.00	35.00	216.000	C	N	R
151	301.18	102.48	20.54	0.94	1.50	2690.00	460.00	546.00	37.10	216.000	C	N	R
152	300.22	101.52	20.46	0.96	1.50	2690.00	475.00	549.00	34.50	216.000	C	N	R
153	302.20	102.90	21.75	1.45	1.50	2690.00	382.00	463.00	76.60	216.000	C	N	R
154	302.96	102.86	21.63	1.43	1.50	2690.00	379.00	466.00	70.00	216.000	C	N	R
155	302.56	102.56	22.18	1.38	1.50	2690.00	395.00	467.00	71.30	216.000	C	N	R
156	303.38	103.18	24.79	1.39	1.50	2690.00	393.00	478.00	73.00	216.000	C	N	R
157	302.00	103.60	25.00	1.40	1.50	2690.00	380.00	470.00	57.00	216.000	C	N	R
158	302.18	102.58	22.49	1.39	1.50	2690.00	381.00	474.00	69.00	216.000	C	N	R
159	82.60	41.63	9.86	1.22	2.59	303.53	225.92	300.27	46.28	203.255	C	Y	P
160	116.69	41.50	9.88	1.22	2.64	304.29	225.92	300.27	44.72	203.255	C	Y	P
161	154.18	42.06	9.65	1.22	3.09	278.38	225.92	300.27	45.17	203.255	SC	Y	P
162	79.86	81.71	17.22	1.20	1.87	457.71	230.06	315.01	58.74	203.255	SC	Y	P
163	79.40	81.58	17.27	1.21	1.76	457.71	230.06	315.01	60.52	203.255	SC	Y	P
164	151.41	81.94	17.30	1.20	1.97	456.69	230.06	315.01	57.85	203.255	SC	Y	P
165	150.83	82.25	16.92	1.20	1.93	456.69	230.06	315.01	60.52	203.255	SC	Y	P
166	228.19	81.64	17.50	1.20	1.87	559.31	230.06	315.01	56.96	203.255	SC	Y	P
167	227.81	81.86	17.55	1.19	2.14	685.04	230.06	315.01	56.96	203.255	C	Y	P
168	299.97	81.86	17.30	1.19	1.98	558.80	230.06	315.01	56.96	203.255	SC	Y	P
169	300.74	82.04	17.63	1.19	2.41	913.64	238.60	321.42	53.40	203.255	C	Y	P
170	299.72	81.79	17.32	1.20	1.98	558.04	230.06	315.01	56.07	203.255	SC	Y	P
171	80.72	114.10	19.13	1.14	2.52	647.70	223.30	319.90	51.18	203.255	SC	Y	P
172	80.16	114.20	19.20	1.14	2.67	647.19	223.30	319.90	52.51	203.255	SC	Y	P
173	114.88	114.10	19.23	1.13	2.65	646.94	224.55	321.49	52.96	203.255	SC	Y	P
174	114.50	114.00	19.25	1.14	2.57	647.19	224.55	321.49	53.40	203.255	SC	Y	P

TABLE 4: Continued.

S. No.	W (mm)	F (mm)	L (mm)	T (mm)	R (mm)	Length (mm)	F_y (N/mm ²)	F_u (N/mm ²)	P_{Test} (kN)	E (N/mm ²)	Type of comp. member	Torsion allowed	Forming method
175	281.18	145.36	34.21	1.55	2.20	891.29	412.02	546.72	138.62	203.255	SC	Y	P
176	281.43	146.15	33.40	1.55	2.41	891.54	412.02	546.72	139.73	203.255	SC	Y	P
177	224.23	113.79	19.35	1.22	2.94	646.94	368.06	490.09	67.64	203.255	SC	Y	P
178	223.65	115.09	18.95	1.28	2.94	647.70	198.64	290.07	61.41	203.255	SC	Y	P
179	223.24	114.88	19.51	1.29	3.08	647.95	198.64	290.07	64.97	203.255	SC	Y	P
180	331.72	114.88	19.05	1.27	2.94	762.00	198.64	290.07	60.52	203.255	SC	Y	P
181	330.71	115.39	19.05	1.28	2.94	971.30	203.19	291.38	62.30	203.255	C	Y	P
182	440.94	113.69	19.18	1.24	2.77	761.75	201.19	290.41	55.63	203.255	C	Y	P
183	441.45	113.69	19.10	1.25	2.56	1295.15	202.08	291.24	49.84	203.255	C	Y	P
184	114.71	113.79	19.76	1.23	2.99	2518.66	236.60	313.56	48.95	203.255	C	Y	P
185	152.40	50.80	12.70	1.22	1.22	457.20	293.24	449.99	55.18	203.255	C	Y	P
186	146.05	63.50	25.40	2.95	2.95	438.15	274.70	360.00	231.40	203.255	SC	Y	P
187	127.00	63.50	12.70	2.03	2.03	381.00	293.24	449.99	113.48	203.255	SC	Y	P
188	101.60	57.15	9.53	2.03	2.03	304.80	245.42	360.00	106.36	203.255	SC	Y	P
189	88.90	50.80	9.53	2.03	2.03	266.70	304.06	449.99	109.47	203.255	SC	Y	P
190	101.60	44.45	15.88	3.25	3.25	304.80	317.90	449.99	226.06	203.255	SC	Y	P
191	76.20	38.10	9.53	3.25	3.25	228.60	324.11	449.99	159.76	203.255	SC	Y	P
192	69.85	25.40	12.70	1.63	1.63	209.55	327.21	449.99	64.53	203.255	C	Y	P
193	69.85	25.40	12.70	2.03	2.03	209.55	330.31	449.99	86.33	203.255	C	Y	P
194	47.63	22.23	6.35	1.22	1.22	142.88	347.26	449.99	34.09	203.255	SC	Y	P
195	44.45	25.40	6.35	1.22	1.22	133.35	376.61	449.99	41.03	203.255	SC	Y	P
196	254.00	88.90	19.05	1.22	1.22	762.00	183.69	360.00	42.19	203.255	C	Y	P
197	203.20	101.60	19.05	1.22	1.22	609.60	186.72	360.00	45.39	203.255	SC	Y	P
198	152.40	101.60	19.05	1.22	1.22	457.20	191.40	360.00	41.21	203.255	SC	Y	P
199	101.60	101.60	19.05	1.22	1.22	304.80	183.69	360.00	41.96	203.255	SC	Y	P
200	50.80	50.80	9.53	1.22	1.22	152.40	192.92	360.00	32.31	203.255	SC	Y	P
201	84.00	27.00	7.49	0.56	0.48	350.01	301.58	449.99	14.42	203.255	C	Y	P
202	81.99	26.49	5.74	0.56	0.48	270.00	301.58	449.99	12.19	203.255	C	Y	P
203	29.39	27.20	8.20	0.56	0.48	267.97	301.58	449.99	14.60	203.255	C	Y	P
204	30.10	27.61	5.59	0.56	0.48	204.98	301.58	449.99	13.39	203.255	C	Y	P
205	152.70	153.19	35.99	1.50	2.01	499.87	226.82	360.00	88.56	203.255	SC	Y	P
206	152.81	152.91	54.51	1.50	2.01	499.87	226.82	360.00	100.13	203.255	SC	Y	P
207	152.81	152.91	19.61	1.50	2.01	499.87	226.82	360.00	93.01	203.255	SC	Y	P
208	152.50	63.70	31.09	1.50	2.01	499.87	226.82	360.00	88.11	203.255	SC	Y	P
209	152.50	63.70	10.01	1.50	2.01	499.87	226.82	360.00	70.31	203.255	C	Y	P
210	152.50	63.70	16.61	1.50	2.01	499.87	226.82	360.00	75.65	203.255	C	Y	P
211	151.00	30.78	10.01	1.50	2.01	299.97	226.82	360.00	49.84	203.255	C	Y	P
212	151.00	30.78	4.29	1.50	2.01	299.97	226.82	360.00	43.52	203.255	C	Y	P
213	148.70	48.85	19.39	0.97	1.96	449.10	288.70	360.00	43.99	202.500	C	Y	P
214	148.70	73.71	19.78	0.97	2.26	449.50	288.70	360.00	41.88	202.500	SC	Y	P
215	102.70	53.00	13.20	3.00	3.50	300.00	417.00	516.75	230.00	203.255	SC	Y	R
216	102.70	53.00	13.20	3.00	3.50	300.00	417.00	516.75	229.00	203.255	SC	Y	R
217	102.70	53.00	13.20	3.00	3.50	300.00	417.00	516.75	230.00	203.255	SC	Y	R
218	102.70	53.00	13.20	3.00	3.50	300.00	417.00	516.75	243.00	203.255	SC	Y	R
219	102.70	53.00	13.20	3.00	3.50	300.00	417.00	516.75	241.00	203.255	SC	Y	R
220	102.70	53.00	13.20	3.00	3.50	300.00	417.00	516.75	236.00	203.255	SC	Y	R
221	102.70	53.00	13.20	3.00	3.50	300.00	417.00	516.75	207.00	203.255	SC	Y	R
222	102.70	53.00	13.20	3.00	3.50	300.00	417.00	516.75	233.00	203.255	SC	Y	R
223	102.70	53.00	13.20	3.00	3.50	300.00	417.00	516.75	229.00	203.255	SC	Y	R
224	102.70	53.00	13.20	3.00	3.50	300.00	417.00	516.75	238.00	203.255	SC	Y	R
225	98.40	52.00	16.00	1.20	2.80	360.00	192.90	344.50	40.70	203.255	SC	Y	P
226	98.40	52.00	16.00	1.20	2.80	360.00	192.90	344.50	42.60	203.255	SC	Y	P
227	98.40	52.00	16.00	1.20	2.80	360.00	192.90	344.50	43.20	203.255	SC	Y	P
228	98.40	52.00	16.00	1.20	2.80	360.00	192.90	344.50	40.80	203.255	SC	Y	P
229	98.40	52.00	16.00	1.20	2.80	360.00	192.90	344.50	39.10	203.255	SC	Y	P
230	98.40	52.00	16.00	1.20	2.80	360.00	192.90	344.50	41.90	203.255	SC	Y	P
231	98.40	52.00	16.00	1.20	2.80	360.00	192.90	344.50	42.70	203.255	SC	Y	P
232	98.40	52.00	16.00	1.20	2.80	360.00	192.90	344.50	42.50	203.255	SC	Y	P

TABLE 4: Continued.

S. No.	W (mm)	F (mm)	L (mm)	T (mm)	R (mm)	Length (mm)	F_y (N/mm ²)	F_u (N/mm ²)	P_{Test} (kN)	E (N/mm ²)	Type of comp. member	Torsion allowed	Forming method
233	97.60	52.00	16.00	0.80	2.00	360.00	171.30	310.05	19.70	203.255	SC	Y	P
234	97.60	52.00	16.00	0.80	2.00	360.00	171.30	310.05	21.00	203.255	SC	Y	P
235	97.60	52.00	16.00	0.80	2.00	360.00	171.30	310.05	20.30	203.255	SC	Y	P
236	97.60	52.00	16.00	0.80	2.00	360.00	171.30	310.05	20.70	203.255	SC	Y	P
237	97.60	52.00	16.00	0.80	2.00	360.00	171.30	310.05	19.60	203.255	SC	Y	P
238	97.60	52.00	16.00	0.80	2.00	360.00	171.30	310.05	20.90	203.255	SC	Y	P
239	97.60	52.00	16.00	0.80	2.00	360.00	171.30	310.05	21.10	203.255	SC	Y	P
240	97.60	52.00	16.00	0.80	2.00	360.00	171.30	310.05	20.30	203.255	SC	Y	P
241	102.70	53.00	13.20	3.00	3.50	300.00	417.00	516.75	239.00	203.255	SC	Y	R
242	102.70	53.00	13.20	3.00	3.50	300.00	417.00	516.75	236.00	203.255	SC	Y	R
243	102.70	53.00	13.20	3.00	3.50	300.00	417.00	516.75	236.00	203.255	SC	Y	R
244	102.70	53.00	13.20	3.00	3.50	300.00	417.00	516.75	234.00	203.255	SC	Y	R
245	98.40	52.00	16.00	1.20	2.80	360.00	192.90	344.50	41.70	203.255	SC	Y	P
246	98.40	52.00	16.00	1.20	2.80	360.00	192.90	344.50	41.70	203.255	SC	Y	P
247	98.40	52.00	16.00	1.20	2.80	360.00	192.90	344.50	41.80	203.255	SC	Y	P
248	97.60	52.00	16.00	0.80	2.00	360.00	171.30	310.05	20.40	203.255	SC	Y	P
249	97.60	52.00	16.00	0.80	2.00	360.00	171.30	310.05	20.80	203.255	SC	Y	P
250	97.60	52.00	16.00	0.80	2.00	360.00	171.30	310.05	20.30	203.255	SC	Y	P
251	43.76	42.49	18.71	1.85	4.15	304.80	308.33	413.40	94.25	203.255	SC	Y	P
252	43.76	42.49	18.71	1.85	4.15	304.80	308.33	413.40	92.47	203.255	SC	Y	P
253	43.76	42.49	18.71	1.85	4.15	304.80	308.33	413.40	101.68	203.255	SC	Y	P
254	43.76	42.49	18.71	1.85	4.15	304.80	330.10	421.39	105.47	203.255	SC	Y	R
255	43.76	42.49	18.71	1.85	4.15	304.80	330.10	421.39	98.79	203.255	SC	Y	R
256	44.20	42.93	18.92	2.29	3.94	177.80	304.95	429.04	133.50	203.255	SC	Y	P
257	44.20	42.93	18.92	2.29	3.94	177.80	304.95	429.04	125.94	203.255	SC	Y	P
258	44.20	42.93	18.92	2.29	3.94	304.80	304.95	429.04	127.27	203.255	SC	Y	P
259	44.20	42.93	18.92	2.29	3.94	304.80	304.95	429.04	123.27	203.255	SC	Y	P
260	44.20	42.93	18.92	2.29	3.94	304.80	305.02	434.35	137.06	203.255	SC	Y	R
261	44.20	42.93	18.92	2.29	3.94	304.80	305.02	434.35	125.94	203.255	SC	Y	R
262	300.00	75.00	20.00	2.00	3.00	500.00	242.79	344.88	119.31	200.766	SC	Y	R
263	300.00	75.00	20.00	2.00	3.00	750.00	242.79	344.88	114.08	200.766	C	Y	R
264	300.00	75.00	20.00	2.00	3.00	1000.00	242.79	344.88	109.86	200.766	C	Y	R
265	300.00	75.00	20.00	2.00	3.00	1250.00	242.79	344.88	114.96	200.766	C	Y	R
266	300.00	75.00	20.00	2.50	3.75	500.00	282.26	372.20	159.79	203.058	SC	Y	R
267	300.00	75.00	20.00	2.50	3.75	750.00	282.26	372.20	166.97	203.058	C	Y	R
268	300.00	75.00	20.00	2.50	3.75	1000.00	282.26	372.20	182.36	203.058	C	Y	R
269	300.00	75.00	20.00	2.50	3.75	1250.00	282.26	372.20	164.73	203.058	C	Y	R
270	300.00	75.00	20.00	3.00	4.50	500.00	258.94	350.42	156.14	206.308	SC	Y	R
271	300.00	75.00	20.00	3.00	4.50	750.00	258.94	350.42	161.37	206.308	C	Y	R
272	300.00	75.00	20.00	3.00	4.50	1000.00	258.94	350.42	178.18	206.308	C	Y	R
273	300.00	75.00	20.00	3.00	4.50	1250.00	258.94	350.42	146.37	206.308	C	Y	R

Dimensions of lipped channel sections. W —web depth in mm. F —flange width in mm. L —Lip depth in mm. T —thickness in mm. R —corner radius (inner) in mm. Lipped channel section characteristics. Forming methods. P —press brake methods. R —cold roll forming method. P_{Test} —test capacity of section in kN. Material properties. F_y —yield strength of steel in N/mm². F_u —ultimate strength of steel in N/mm². E —modulus of elasticity in N/mm². Compression member characteristics. Type of comp. member. C—column, SC—Stub column. Torsion allowed, Y—yes, N—no. Length in mm—centre to centre length for pinned end columns/stub columns.

The algorithm for estimation of ME and determination of its statistical characteristic is given as follows:

- (1) Prepare the test database for ME estimate with exclusion criteria
- (2) Filter the test database members (columns and stub columns) for geometric proportions criteria and maximum slenderness ratio limit
- (3) Calculate capacities for different governing failure modes for various standards by not considering the

safety or partial safety factors present in the model function

- (4) Calculate ME as ratio of test to calculated capacity
- (5) Plot histograms for ME and calculate statistical properties
- (6) Perform Chi-square goodness-of-fit test for selection of statistical distribution for ME

The probabilistic analysis is carried out for simulation of compression capacity of a typical CFS lipped channel

FIGURE 5: Lipped channel section.

column from the database considering ME as a random variable. The details of probabilistic analysis and its statistical characteristics are provided in the next section.

Considering the above ME statistics for different buckling failure modes of CFS lipped channel columns, probabilistic analysis is carried out on compression capacity as discussed in the next section.

6. Probabilistic Analysis of Compression Capacity

The aim of this section is to bring out the importance of consideration of ME in assuming the distribution of compression capacity. In order to study the effect of ME on compression capacity, simulation of compression capacity is carried out with and without considering ME as the random variable. The yield strength, F_y , ultimate strength, F_u , and the modulus of elasticity, E , are the material properties of CFS and used in compression capacity estimation of CFS columns as random variables. Ravindra and Galambos [59], and Hess et al. [60], suggested the lognormal distribution for F_y and E and Normal distribution for F_u for high-tensile steel plates. The Coefficient of variation (COV), as per the above studies, for F_y is 0.089, F_u is 0.091, and E is 0.038, and the same values are adopted in the present study. Simulation of 10^6 cycles are used in present investigations to estimate the statistical properties of compression capacity of a typical CFS lipped channel column (database column no. 18) as per ASCE 10-15 [8], AISI S100-16 [9], AS/NZS 4600: 2018 [10], and EN 1993-1-3:2006 [11] standard, with and without considering ME as random variable along with the other random variables. The column is selected such that it is having mean ME more than 1.15 and COV more than 0.25. The column is critical in flexure torsion mode of buckling as per the abovementioned standards. The histograms along with statistical properties of simulated compression capacity for abovementioned standards estimated with and without ME as random variable are presented in Figures 9–11.

Further, to predict statistical distributions, Chi-square goodness-of-fit test has been performed on simulated compression capacity, and the results of this test are given in Table 8.

The abovementioned results of modelling error estimation and probabilistic analysis are discussed in the following section.

7. Results and Discussions

The ME is estimated for various failure modes considered in ASCE 10-15, AISI S100-16, AS/NZS 4600: 2018, and EN 1993-1-3: 2006 standards for the database columns. The statistical details of ME and results of Chi-square goodness-of-fit test are presented in Figures 6–8 and Tables 6 and 7, respectively. The distributions of simulated compression capacity based on probabilistic analysis and corresponding results of Chi-square goodness-of-fit tests are indicated in Figures 9–11 and Table 8, respectively. Based on these results, the following observations are made.

7.1. Modelling Error

7.1.1. Mean. The mean ME for column buckling in flexure is close to 0.9 for ASCE 10-15 and AISI S100-16 & AS/NZS 4600:2018 standard, whereas the same for EN 1993-1-3:2006 standard is 0.95. In case of flexural torsional buckling, the mean ME is close to 1.2, irrespective of the design standard. For local buckling, the mean ME is 0.92 for ASCE 10-15 standard and 0.82 for AISI S100-16 & AS/NZS 4600:2018 standard. The ASCE 10-15 standard is having stringent criteria for dimensional proportions with remote chances of distortional buckling and hence does not provide any guideline for it. As per AISI S100-16 & AS/NZS 4600:2018 standard, the mean ME in distortional buckling is 1.34, which is a high value. For EN 1993-1-3:2006 standard, the combined model function is provided for the local and distortional buckling and it gives mean ME as 1.11.

In case of stub columns, the mean ME for yield failure of cross section is 1.11 for ASCE 10-15 and 1.02 for AISI S100-16 & AS/NZS 4600:2018 standard. EN 1993-1-3:2006 standard does not provide separate guidelines for yield failure of the cross section. For local buckling, the mean model error is 0.97 and 0.88, respectively, for the ASCE 10-15 and AISI S100-16 & AS/NZS 4600:2018 standard. The mean ME in distortional buckling for AISI S100-16 & AS/NZS 4600:2018 standard is 0.95. The combined mode of failure for local and distortional buckling is suggested in EN 1993-1-3:2006 standard, and the mean ME in this mode is 1.02.

It is observed that for columns, the mean MEs are within $\pm 10\%$ variation for the single mode failures viz. flexure and local buckling. In case of combined failure mode in flexure and torsion, the variation is around $+20\%$ and for distortion buckling it is $+34\%$. This indicates requirement of extensive experimental research in combined and distortion buckling modes. For stub columns, a good estimate of $\pm 10\%$ of mean ME was observed irrespective of the design standards and failure modes; except for the local buckling as per AISI

TABLE 5: Salient features of design standards.

Failure mode	Design standard		
	ASCE 10-15	AISI S100-16 and AS/NZS: 4600-2018	EN 1993-1-3: 2006
Flexure	SSRC (1966) equation is used for columns in inelastic and Euler's equation for columns in elastic range of buckling.	(i) The elastic critical buckling load for a long column is determined by the Euler's equations. (ii) For locally stable columns, the AISC LRFD specification (1993) equation is adopted for elastic and inelastic ranges of buckling.	The resistance of compressed members is based on the "European design buckling curves" (ECCS, 1978) that relate the reduction factor to the nondimensional slenderness. These (five) curves were the result of an extensive experimental and numerical research programme (ECCS, 1976), conducted on HR and welded sections, that accounted for all imperfections in real compressed members (initial out-of-straightness, eccentricity of the applied loads, residual stresses). The analytical formulation of the buckling curves was derived by Maquoi & Rondal [33], and is based on the Ayrton-Perry formula, considering an initial sinusoidal deformed configuration corresponding to an "equivalent initial deformed configuration" where the amplitude was calibrated in order to reproduce the effect of all imperfections.
Torsion	As per this code the local buckling strength is not equal to torsional buckling strength. Hence, torsional-flexural buckling strength is determined.	The torsional buckling in the elastic range is computed based on the equation provided by Winter [53] for elastic critical stress.	For members with "point-symmetric" open cross sections (e.g. Z-purlin with equal flanges), the possibility that the resistance of the member to torsional buckling might be less than its resistance on flexural buckling is considered in this code.
Torsion-Flexure	The design compressive stress for torsional-flexural buckling strength is determined using an equivalent radius of gyration.	The governing elastic flexural-torsional buckling load of a column can be found from the equation suggested by Chajes and Winter [54]; Chajes et al. [55]; Yu and LaBoube [56].	For members with mono-symmetric open cross-sections, the possibility of the resistance of the member to torsional-flexural buckling might be less than its resistance to flexural buckling is considered in this code.
Local buckling	If element slenderness ratio is not small enough to develop uniform design stress distributed over full cross section, then the post buckling strength of element which buckles prematurely is taken into account by using an effective width of an element in determining the area of the member cross section. The effective width of an element is the width, which gives the same resultant force of a uniformly distributed design stress, as the nonuniform stress develops in the entire element in the post-buckled state.	In this code, the effective width Method's approach to local buckling is adopted. It conceptualizes the member as a collection of "elements" and investigates local buckling of each element separately. The effective width method determines a plate buckling coefficient, k , for each element, then buckling stress, and finally the effective width.	An effective width approach is adopted, whereby 'ineffective' portions of a cross section are removed and section properties may be determined based on the remaining effective portions. In this standard, the local and distortional buckling modes for cross sections with edge stiffeners are considered together while estimating the resistance.

TABLE 5: Continued.

Failure mode	Design standard		
	ASCE 10-15	AISI S100-16 and AS/NZS: 4600-2018	EN 1993-1-3: 2006
Distortional buckling	Not considered	Distortional buckling is an instability that may occur in members with edge-stiffened flanges, such as lipped C and Z-sections. This buckling mode is characterized by instability of the entire flange, as the flange along with the edge stiffener rotates about the junction of the compression flange and the web. The expressions in this specification are derived by Schafer [57] and verified for complex stiffeners by Yu and Schafer [58].	EN1993-1-3 does not provide explicit provisions for distortional buckling. However, a calculation procedure is obtained from the interpretation of the rules given in the code for plane elements with edge or intermediate stiffeners in compression. The design of compression elements with either edge or intermediate stiffeners is based on the assumption that the stiffener behaves as a compression member with continuous partial restraint. This restraint has a spring stiffness that depends on the boundary conditions and the flexural stiffness of the adjacent plane elements of the cross section. The spring stiffness of the stiffener may be determined by applying a unit load per unit length to the cross section at the location of the stiffener. The rotational spring stiffness characterizes the bending stiffness of the web part of the section.
Yielding	Not indicated	Very short, compact column under an axial load may fail by yielding. Hence, the yield load determined by multiplying the gross area with yield strength.	The design resistance is computed by multiplying the gross area with increased basic yield stress for the contribution from difference of average and basic yield stress reduced by a factor based on the ratio of relative slenderness for elements.
Maximum element slenderness ratio (w/t)	(i) For elements supported on both the longitudinal edges, $w/t \leq 60$ and (ii) for elements supported on one longitudinal edge, $w/t \leq 25$ w/t = flat width to thickness ratio.	(i) For stiffened element in compression, $w/t \leq 500$, (ii) for edge stiffened element in compression $w/t \leq 90$ for $I_s \geq I_a$ and $w/t \leq 60$ for $I_s < I_a$, and (iii) for unstiffened element in compression $w/t \leq 60$ w/t = flat width to thickness ratio.	(i) For stiffened element in compression, $w/t \leq 500$, (ii) for edge stiffened element in compression a) for element $w/t \leq 60$ for stiffener $w/t \leq 50$, and (iii) for unstiffened element in compression $w/t \leq 50$ w/t = out to out width to thickness ratio.
<i>Other Considerations</i>			
Material strength	As per ASTM standards with yield strength up to 448 MPa	As per ASTM standards with yield strength up to 380 MPa	As per EN standards with basic yield strength up to 460 MPa

TABLE 5: Continued.

Failure mode	Design standard		
	ASCE 10-15	AISI S100-16 and AS/NZS: 4600-2018	EN 1993-1-3: 2006
Increase in yield strength of material due to cold-working	Not considered.	<p>At Cornell University, the influence of cold work on mechanical properties was investigated by Chajes et al. [2], Karren, [3], and Karren and Winter [4]. It was found that the changes of mechanical properties due to cold-stretching are caused mainly by strain-hardening and strain-aging, Chajes et al. [2]. Cornell research also revealed that the effects of cold work on the mechanical properties of corners usually depend on (1) the type of steel, (2) the type of stress (compression or tension), (3) the direction of stress with respect to the direction of cold work (transverse or longitudinal), (4) the F_u/F_y ratio, (5) the inside radius-to-thickness ratio (R/t), and (6) the amount of cold work.</p> <p>Investigating the influence of cold work, Karren derived the equations for the ratio of corner yield stress-to-virgin yield stress [3]. With regard to the full-section properties, the tensile yield stress of the full section approximated by using a weighted average is used in this specification.</p> <p>Good agreements between the computed and the tested stress-strain characteristics for a channel section and a joist chord section were demonstrated by Karren and Winter [4]</p>	<p>The increased yield strength due to cold forming may be taken into account if in axially loaded members in which the effective cross-sectional area equals the gross area, and in determining the effective area, the yield strength should be taken as basic yield strength.</p>

S100-16 (2016) & AS/NZS 4600:2018 (2018) standards, the variation in mean ME is 12%.

7.1.2. COV. The COV of ME for columns as per ASCE 10-15 and AISI S100-16 & AS/NZS 4600:2018 standards is close to 0.15 in flexural and local buckling modes, whereas it is 0.26 in flexural torsional buckling mode. The same is 0.28 for distortional buckling mode as per AISI S100-16 & AS/NZS 4600:2018 standard. In case of EN 1993-1-3:2006 standard, the COV is 0.27 and 0.29, respectively, for the flexural and flexural-torsional buckling modes, and in combined local and distortion buckling mode, it is 0.01.

In case of stub columns, low values of COV are observed for ASCE 10-15 and AISI S100-16 & AS/NZS 4600:2018 standards, i.e., 0.08 in yielding and 0.05 in local buckling. For distortional buckling, the COV is 0.09 for AISI S100-16 & AS/NZS 4600:2018 standards and, it is 0.01 for the combined mode of local and distortion buckling as per EN 1993-1-3: 2006 standard.

It indicates that the higher uncertainties are involved in prediction of column buckling capacities in comparison

with the stub columns. Similarly, the single-mode failures either in flexure or local buckling of columns have lower variations with respect to combined failure modes and distortion buckling. Except for the combined failure mode of local and distortional buckling for EN 1993-1-3:2006 standard, the ME is having lower COV, but only 3 database members are governing in this mode of failure. So, for getting appropriate statistical characteristics, it is recommended to have large test data.

7.1.3. Skewness. The nonzero values of skewness observed in all the buckling modes indicates a non-Gaussian distribution for ME data. Further, most of the skewness values are positive indicating positively skewed or right-skewed distribution in which maximum number of values are clustered around the left tail of the distribution while the right tail of the distribution is longer and the same is observed in Figures 6–8. For few failure modes (viz. local buckling of stub columns for ASCE 10-15 standard, yielding of stub columns for AISI S100-16 & AS/NZS 4600:2018 standard, and local and distortional buckling of columns for EN 1993-

TABLE 6: Statistical properties of modelling error of test database compression members.

Design standard	Statistical property	Compression members & failure modes						
		Columns				Stub columns		
		Flexural buckling	Flexure-torsion buckling	Local buckling	Distortion buckling	Yielding	Local buckling	Distortion buckling
ASCE 10-15	Nos [@]	14	33	10		27	10	
	Mean	0.899	1.154	0.915	Failure mode not available in this standard	1.108	0.969	Failure mode not considered in this standard
	COV	0.150	0.257	0.132		0.082	0.043	
	SK	2.018	1.934	0.962		0.476	−0.388	
	CU	8.131	5.828	2.659		2.238	2.566	
AISI S100-16 & AS/NZS 4600: 2018	Nos [@]	14	34	23	40	17	32	42
	Mean	0.870	1.198	0.821	1.338	1.017	0.884	0.951
	COV	0.149	0.262	0.164	0.279	0.081	0.049	0.091
	SK	2.331	1.864	1.036	0.155	−0.228	1.669	0.134
	CU	9.550	5.544	4.034	1.813	2.289	9.465	4.677
EN 1993-1-3: 2006	Nos [@]	39	57		3	0		74
	Mean	0.942	1.225		1.113	—		1.024
	COV	0.227	0.289		0.012	—		0.120
	SK	0.810	1.229		−1.682	—		0.147
	CU	2.325	3.661		—	—		3.584

[@]Number of Specimens from the test database critical in particular failure mode. EN 1993-1-3:2006 considers combined failure mode as local and distortion buckling.

FIGURE 6: Continued.

FIGURE 6: ME histograms for various failure modes for database member as per ASCE 10-15 Standard. (a) CF—column flexure; (b) CFT—column flexure-torsion; (c) CL—column local buckling; (d) SCY—stub column yielding; (e) SCL—stub column local buckling.

FIGURE 7: Continued.

FIGURE 7: ME histograms for various failure modes for database member as per AISI S100-16 & AS/NZS 4600: 2018 Standards. (a) CF—column flexure; (b) CFT—column flexure-torsion; (c) CL—column local buckling; (d) CD—column distortion buckling; (e) SCY—stub column yielding; (f) SCL—stub column local buckling; (g) SCD—stub column distortion buckling.

FIGURE 8: ME histograms for various failure modes for database member as per EN 1993-1-3:2006 Standard. (a) CF—column flexure; (b) CFT—column flexure-torsion; (c) CLD—column local and distortion buckling; (d) SCLD—stub column local and distortional buckling.

TABLE 7: Results of Chi-square goodness-of-fit test for modelling error of test database compression members.

Design standard	Type of compression member	Failure mode	Nos@	Assumed distribution (DOF)	Computed Chi-square value	Allowable Chi-square value	
						At $\alpha = 5\%$	At $\alpha = 1\%$
ASCE 10-15	Column	Flexural buckling	14	Normal (2)	0.556	5.99	9.21
				Lognormal (2)	0.354		
				Uniform (2)	0.722		
		Flexure-torsion buckling	33	Normal (8)	1.837	15.51	20.09
				Lognormal (8)	1.057		
				Uniform (8)	1.523		
	Stub column	Local buckling	10	Normal (1)	0.875	3.84	6.63
				Lognormal (1)	0.753		
				Uniform (1)	0.853		
		Yielding	27	Normal (6)	0.572	12.59	16.81
				Lognormal (6)	0.525		
				Uniform (6)	0.311		
		Local buckling	10	Normal (1)	0.223	3.84	6.63
				Lognormal (1)	0.242		
				Uniform (1)	0.226		

TABLE 7: Continued.

Design standard	Type of compression member	Failure mode	Nos@	Assumed distribution (DOF)	Computed Chi-square value	Allowable Chi-square value	
						At $\alpha = 5\%$	At $\alpha = 1\%$
AISI S100-16 & AS/NZS 4600: 2018	Column	Flexural buckling	14	Normal (2)	0.820	5.99	9.21
				Lognormal (2)	0.523		
				Uniform (2)	0.986		
		Flexure-torsion buckling	34	Normal (8)	1.801	15.51	20.09
				Lognormal (8)	1.116		
				Uniform (8)	1.647		
		Local buckling	23	Normal (5)	0.576	11.07	15.09
				Lognormal (5)	0.477		
				Uniform (5)	0.839		
		Distortion buckling	40	Normal (10)	0.379	18.31	23.21
				Lognormal (10)	0.442		
				Uniform (10)	0.244		
	Stub column	Yielding	17	Normal (3)	0.190	7.81	11.34
				Lognormal (3)	0.204		
				Uniform (3)	0.060		
		Local buckling	32	Normal (8)	3.455	15.51	20.09
				Lognormal (8)	1.682		
				Uniform (8)	0.902		
EN 1993-1-3: 2006	Column	Distortion buckling	42	Normal (11)	0.811	19.68	24.73
				Lognormal (11)	1.031		
				Uniform (11)	1.322		
		Flexural buckling	39	Normal (10)	1.183	18.31	23.21
				Lognormal (10)	0.978		
				Uniform (10)	1.156		
	Stub column	Flexure-torsion buckling	57	Normal (16)	0.856	26.30	32.00
				Lognormal (16)	0.473		
				Uniform (16)	0.902		
		Local and distortion buckling	3	Normal (0)	1.260	—	—
				Lognormal (0)	1.266		
				Uniform (0)	1.717		
	Stub column	Local and distortion buckling	74	Normal (22)	0.408	33.92	40.29
				Lognormal (22)	1.023		
				Uniform (22)	0.781		

@Number of Specimens from the test database critical in particular failure mode.

FIGURE 9: Compression capacity histograms for ASCE 10-15 Standard: (a) compression capacity without ME; (b) compression capacity with ME. CFT—Column flexure-torsion buckling mode, μ —Mean, σ —Std. deviation, Sk —Skewness, Kt —Kurtosis, and COV —Coefficient of variation.

FIGURE 10: Compression capacity histograms for AISI S100-16 & AS/NZS 4600: 2018 Standard: (a) compression capacity without ME; (b) compression capacity with ME. CFT—Column flexure-torsion buckling mode, μ —Mean, σ —Std. deviation, Sk —Skewness, Kt —Kurtosis, and COV —Coefficient of variation.

FIGURE 11: Compression capacity histograms for EN 1993-1-3:2006 Standard: (a) compression capacity without ME; (b) compression capacity with ME. CFT—Column flexure-torsion buckling mode, μ —Mean, σ —Std. deviation, Sk —Skewness, Kt —Kurtosis, and COV —Coefficient of variation.

1-3:2006 standard), negative skewness values are observed indicating negatively skewed or left skewed ME data. The close observation of test data of these failure modes indicates that the samples data points are less and require additional experimental investigations to get the correct statistics.

7.1.4. Kurtosis. The failure modes in flexure and flexure-torsion buckling for columns irrespective of the design standard, along with local buckling mode for column and stub columns as per AISI S100-16 & AS/NZS 4600:2018 standard and combined local and distortion buckling mode as per EN 1993-1-3:2006 standard, kurtosis values are found

to be more than three. This indicates non-Gaussian distribution for the ME data and the positive excess kurtosis in these cases indicate the data is leptokurtic having heavy tails and contains extreme values.

For other modes of failure, the kurtosis values are close to three with negative excess kurtosis which indicates that the data is platykurtic and having flat tails with small probability of extreme values. In this case, also the statistical distribution for ME data is non-Gaussian.

7.1.5. Distribution. Chi-square goodness-of-fit tests are performed to determine the nature of probability

TABLE 8: Results of Chi-square goodness-of-fit test for resistance simulation (database column no. 18—flexure-torsion mode of buckling).

Design standard	RVs	Assumed distribution (DOF)	Computed Chi-square value	Allowable Chi-square value		Null hypothesis
				At $\alpha = 5\%$	At $\alpha = 1\%$	
ASCE 10-15 (2015)	F_y , E , & ME	Normal (77)	2.460×10^{10}	98.202	108.375	Rejected
		Lognormal (77)	7.164×10^{-5}			Accepted
	F_y & E	Normal (77)	0.0024	98.202	108.375	Accepted
		Lognormal (77)	8.663×10^{-5}			Accepted
AISI S100-16 (2006) & AS/NZS 4600: 2018 (2018)	F_y , F_w , E , & ME	Normal (77)	2.032×10^7	98.202	108.375	Rejected
		Lognormal (77)	2.781×10^{-4}			Accepted
	F_y , F_w , & E	Normal (77)	0.0017	98.202	108.375	Accepted
		Lognormal (77)	0.0394			Accepted
EN 1993-1-3:2006 (2006)	F_y , F_w , E , & ME	Normal (77)	2.220×10^9	98.202	108.375	Rejected
		Lognormal (77)	8.753×10^{-5}			Accepted
	F_y , F_w , & E	Normal (77)	0.003	98.202	108.375	Accepted
		Lognormal (77)	1.347×10^{-4}			Accepted

distribution of ME. Three different hypothetical distributions, namely, Normal, Lognormal, and Uniform distributions are considered for the test. The results of these tests are presented in Table 7. From the results of Chi-square goodness-of-fit test, it is found that the hypothesis of assumed distributions considered cannot be rejected at 1% and 5% of significance level. However, a distribution with the lowest Chi-square value is considered for the particular mode of failure. In some cases, the Normal distribution is governing but considering nonzero values of skewness and kurtosis value not equal to 3.0, lognormal distribution is assumed. The assumption of lognormal distribution for ME is also justified since negative values for ME, however small they may be, do not have engineering meaning. The ME for the failure modes, for which the sample size is small, can be assumed to follow a uniform distribution.

7.2. Probabilistic Analysis of Compression Capacity. From Figures 9–11, it is observed that the distribution of compression capacities, without ME as random variable, follows normal distribution irrespective of design standard and the mean resistance value is equal to compression capacity calculated as per the respective design standards. However, the distribution of compression capacity, with ME as a random variable, seems to follow the lognormal distribution irrespective of design standard, and the COV for simulated compression capacity with ME as random variable is 0.3, which is significant compared to COV of resistance without considering the ME.

The Chi-square goodness-of-fit test results presented in Table 8 justify the use of the distributions for resistance suggested earlier based on eye judgement.

A summary of conclusions are drawn and presented in the following section, based on the above discussions.

8. Summary and Conclusions

The model functions available for different modes of failure in ASCE 10-15, AISI S100-16, AS/NZS 4600:2018, and EN 1993-1-3:2006 standards are used to predict the compression

capacity of a set of 273 CFS lipped channel compression members. The test data of compression members are obtained from the literature. Using these test results and also those of three nominally similar compression members tested at CSIR-SERC, a database is created for the first time and presented in this paper. Each test compression member has sufficient information for calculating the compression capacity using the abovementioned standards. Using the ratio of the test to predict compression capacity, ME analysis was carried out to assess the accuracy of model functions to calculate compression capacity for various failure modes available in these standards and to suggest probability distributions for the ME. The results of statistical analysis are briefly summarised as follows:

- (i) From the results presented in Tables 6 and 7, it is inferred that the ME for various failure modes (except for the cases for which the data points are less), follows a lognormal distribution at 5% significance level with means approximately equal to 1.10 and COV = 0.25. A higher value of COV is recommended to offset the effect of shield over estimation of capacity by ASCE 10-15 standard. In general, EN 1993-1-3:2006 standard seems to perform satisfactorily in the estimation of capacity of compression members. The values of coefficient of skewness and kurtosis, obtained in this investigation, also suggest the use of unsymmetrical distribution about mean (which in this paper is lognormal distribution).
- (ii) It is also noted from Tables 6 and 7 that where the data points are less, the maximum entity distribution, i.e., uniform distribution, is recommended for ME.
- (iii) As can be expected, the COV of ME associated with prediction models for combined failure modes are higher. This indicates that more number of tests to be carried out in this range for reducing statistical uncertainties.
- (iv) The probabilistic analysis of compression capacity of CFS columns has brought out the importance of

consideration of ME and in general, and it can be assumed that the compression capacity of column follows a lognormal distribution at 5% significance level.

- (v) The results presented in this paper are first of its kind, could help in carrying out the calibration studies for CFS columns, and may have potential reference to design practice.

Data Availability

The data used to support the findings of this study are included within the article as Table 4 and Figure 5.

Disclosure

This work was carried out as a part of PhD work of the first author at CSIR-SERC.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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