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Capacity Evaluation of Unequal-Leg Single-Angle Steel Compression Members using Indian and American Code Provisions

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Abstract

Objectives: This study aims to compare the design strength of eccentrically loaded unequal leg single angles under compression according to IS 800:1984, IS 800:2007, IS 800:2007 (Amendment 2), and AISC 360-22 Specifications for structural steel buildings. **Methods:** Spreadsheets were developed to evaluate the compression capacities of unequal single-angle sections using all these codes. The analysis focused on unequal leg single angle connected by either longer or shorter legs, under eccentric loading conditions. **Findings:** IS 800:2007 (Amendment 2) significantly enhances the compression strength of unequal leg single angles compared to IS 800:2007, with increases of up to 40% for angles fastened through the longer leg and up to 87% for those fastened through the shorter leg. Compared to the AISC 360-22 LRFD method, IS 800:2007 (Amendment 2) provides up to 184% more strength for angles fastened through the longer leg and up to 179% more for angles fastened through the shorter leg, While IS 800:2007 provides up to 112% more strength for angles connected by the longer leg and up to 68% more for those connected by the shorter leg. IS 800:1984 also shows increased strength over the AISC 360-22 ASD method, with up to 67% more strength for angles connected by the longer leg and 27% more for those attached by the shorter leg. Additionally, IS 800:2007 (Amendment 2) reveals that unequal leg single angles connected by the shorter leg provide up to 56% more compression strength than those connected by the longer leg. **Novelty:** This research compares the capacity predicted by the latest amendment of the Indian standard code for steel design with its previous versions and the American code, focusing on the design of unequal-legged single-angle compression members. It offers valuable insights into the capacity prediction and overall structural safety, and thereby the resulting economy in the choice of steel sections. An important insight from the study is that unequal leg single angles connected by the shorter leg exhibit greater compression strength than those connected by the longer leg.

Keywords: Unequal legs; Eccentrically loaded; Single angles; Steel sections; Indian codes; American codes

1 Introduction

Single-angle steel sections are widely used in structural applications such as transmission towers, substation equipment support structures, trusses, connection elements, and bracing frames due to their high strength-to-weight ratio, simplicity, and ease of connection through bolted or welded joints. Despite their structural advantages, the design of single-angle members under compression remains complex due to their asymmetric geometry and eccentric load application. When loaded in compression, single-angle sections are prone to flexural-torsional buckling, primarily because the load transfer through a single leg introduces additional moments due to the offset between the shear center (SC) and the centroid (C) (Figure 1). This complexity leads to significant challenges in accurately predicting the strength and stability of single-angle members under compression.

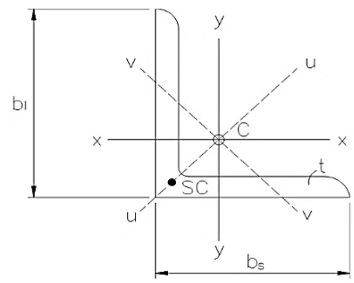

Fig 1. Unequal-leg single-angle section

Several studies have explored the behavior and design of single-angle members under compression. Sai Babu and Vivek (2021)[1] highlighted that flexural-torsional buckling governs the failure of unequal leg single angles and noted a substantial reduction in design strength compared to flexural buckling, especially for intermediate slenderness ratios and larger leg size differences.

Sai Kota Vivek, Mohammad Adil Dar, and Narayanan Subramanian (2024)[2] studied the compression strength of eccentrically loaded equal leg single equal angles according to IS 800:2007 and IS 800:2007 Amendment -2. The findings indicated that the latest design provisions generally produced significantly higher design strengths than the earlier ones, with a maximum increase of 104.84%.

Reddy and Chandra (2024)[3] compared the Indian and Canadian design standards, finding that the Indian approach produced more optimal results for single angles. However, they noted that both codes overlooked torsional effects in double-angle replacements. Kettler et al. (2019)[4] presented detailed experimental and FEM results on bolted single angles under varying end conditions, confirming that boundary conditions significantly affect buckling capacity.

Sardroud and Zaghian (2021)[5] proposed increasing the bearing capacity of single-angle compression members without adding weight by installing gusset plates at a 45° angle to each flange, aligning the gusset plate's gravity center with that of the single angle.

Bashar and Amanat (2021)[6] analyzed the single-angle compression members connected through one leg in lattice steel trusses using non-linear finite element simulations. Their study shows that AISC, ASCE, AASHTO, SSRC, AS, and Eurocode overestimated strength by 118% to 140%, whereas BS and IS provisions were more conservative, estimating 75% and 90% of the test results, respectively.

Despite these advancements, significant gaps remain in the understanding and designing of eccentrically loaded unequal-leg single-angle members under compression and their connection configurations. Furthermore, there is a lack of comprehensive comparative analysis of the compression capacity of unequal-leg single-angle members across different design codes.

This study aims to bridge these gaps by performing a detailed comparative analysis of eccentrically loaded unequal-leg single-angle compression members based on IS 800:1984, IS 800:2007 (original and Amendment 2), and AISC 360-22. A key insight from the study is that unequal-leg single angles attached by the shorter leg exhibit higher compression strength than those connected by the longer leg. This research demonstrates that IS 800:2007 (Amendment 2) predicts significantly higher compression strength compared to other codes, offering valuable guidance for the design of eccentrically loaded unequal-leg single-angle members under compression. An important insight from the study is that unequal leg single angles attached by the shorter leg exhibit greater compression strength than those connected by the longer leg.

2 Methodology

In the present study, Indian steel codes such as IS 800:1984, IS 800:2007, and IS 800:2007 (Amendment 2), along with the American steel code AISC 360-22, were used to analyze the compression design capacity of unequal leg single angles employing spreadsheet calculations. The brief design provisions from these codes are outlined below.

2.1 Design provision for IS 800:1984[7]

IS 800:1984 utilizes the Working Stress Method (WSM) to determine the compression design strength of structural members. The WSM approach ensures that the stresses developed under service loads do not exceed a specified fraction of the material's yield strength, providing a conservative and straightforward method for design. This method was widely used for structural design before the Limit State Method became predominant in later revisions.

As per IS800:1984[7], Clause 5.5.1:
Single-angle discontinuous members fastened with a single rivet or bolt:

1. These can be designed to carry only axial loads, as long as the compressive stress remains under 80% of the values specified in IS 800:1984 Table 5.1[7].
2. The effective length should be considered as the center-to-center distance of the intersection at each end, along with the minimum radius of gyration.
3. The slenderness ratio for single-angle members must not exceed 180 under any circumstances

Single-angle discontinuous members fastened by welds or two or more rivets/bolts in line along the angle:

1. These may also be designed to carry only axial loads, as long as the compressive stress remains under 80% of the values specified in IS 800:1984[7] Table 5.1.
2. The effective length should be considered as 85% of the center-to-center length of the member, along with the minimum radius of gyration.

Equations (1) to (4) represent the compression capacity calculations as per IS 800:1984

$$\lambda = \frac{le}{r_{\min}} \tag{1}$$

$$f_{CC} = \frac{\pi^2 E}{r_{\min}} \tag{2}$$

$$\sigma_{sc} = 0.6 \cdot \frac{f_{cc} \cdot f_y}{\left[(f_{cc})^n + (f_y)^n\right]^{\frac{1}{n}}} \tag{3}$$

$$p_d = \sigma_{sc} \cdot Ae \tag{4}$$

l_e = Effective length (mm)
r_{min} = Minimum radius of gyration (mm)
λ = Slenderness ratio
E = Modulus of elasticity of steel (2×10^5 MPa)
n = a factor taken as 1.4 (as per IS 800:1984[7], clause 5.1.1)
α_{sc} = Permissible axial compression stress (MPa)
f_y = Yield stress of steel (MPa)
f_{cc} = Elastic critical stress under compression (MPa)
A_e = Sectional area (mm^2)
p_d = Permissible axial compression load capacity, in kN

2.2 Design provision for IS 800:2007 [8]

IS 800:2007 [8] adopts the Limit State Method (LSM) as its primary design philosophy. This method is more advanced than the Working state method and ensures an optimal balance between safety and economy. The LSM approach considers both ultimate loads (strength limit state) and serviceability requirements (serviceability limit state), providing a more comprehensive framework for structural design.

IS 800:2007 [8] Clause 7.5.1.2 is used to design eccentrically loaded single angles compression members.

Equations (5) to (12) represent the compression capacity calculations as per IS 800:2007 :

$$\varepsilon=\left(\frac{250}{f_y}\right)^{0.5} \tag{5}$$

$$\lambda_{vv}=\frac{\left(\dfrac{l}{r_{vv}}\right)}{\varepsilon\sqrt{\dfrac{\pi^2 E}{250}}} \tag{6}$$

$$\lambda\varphi=\frac{\dfrac{(b_1+b_2)}{2t}}{\varepsilon\sqrt{\dfrac{\pi^2 E}{250}}} \tag{7}$$

$$\lambda_e=\sqrt{k_1+k_2\lambda_{vv}^2+k_3\lambda_{\varphi}^2} \tag{8}$$

$$\phi=0.5\left[1+\alpha(\lambda-0.2)+\lambda^2\right] \tag{9}$$

$$\mathrm{X}=\frac{1}{\left[\phi+\left(\phi^2-\lambda^2\right)^{0.5}\right]} \tag{10}$$

$$f_{cd}=\frac{\chi f_y}{\gamma_{m0}} \tag{11}$$

$$P_d=A_e f_{cd} \tag{12}$$

P_d = Design compressive strength, in kN
f_{cd} = Design compressive stress (MPa)
Ae = Effective sectional area (mm^2)
X = stress reduction factor
γ_{m0} = Partial safety factor for material strength
α = imperfection factor, Considering buckling class c
λ_e = non dimensional effective slenderness ratio
l = center to center length of supporting member
r_{vv} = radius of gyration about the minor axis
b_1, b_2 = widths of legs of single angle
t =thickness of the leg
ϵ = yield stress ratio
E = Modulus of elasticity (2×10^5 MPa)
The constants K_1, K_2, and K_3 represent the different end connection configurations, as outlined in Table 1

2.3 Design provision for IS 800:2007 (Amendment 2)[9]

IS 800:2007 (Amendment 2)[9] also adopts the Limit State Method (LSM) as its primary design philosophy. As per IS 800:2007 - Amendment 2[9], a single-angle member subjected to eccentric compression through one of its legs is designed to account for the combined effect of flexural torsional buckling and bending.

Equations (13) to (20) represent the compression capacity calculations as per IS 800:2007 (Amendment 2)

$$\varepsilon = \left(\frac{250}{f_y}\right)^{0.5} \tag{13}$$

$$\lambda_{aa} = \frac{\left(\dfrac{l_{aa}}{r_{aa}}\right)}{\varepsilon\sqrt{\dfrac{\pi^2 E}{250}}} \tag{14}$$

$$\lambda\varphi = \frac{\dfrac{(b_1+b_2)}{2}t}{\varepsilon\sqrt{\dfrac{\pi^2 E}{250}}} \tag{15}$$

$$K_f = k_1 + k_2\lambda_{aa} + k_3\lambda_\phi \tag{16}$$

$$\phi = 0.5\left[1+\alpha\left(\lambda_{aa}-0.2\right)+{\lambda_{aa}}^2\right] \tag{17}$$

$$\mathrm{X} = \frac{1}{\left[\phi+\left(\phi^2-{\lambda_{aa}}^2\right)^{0.5}\right]} \tag{18}$$

$$f_{cde} = \frac{K_f \chi f_y}{\gamma_{m0}} \tag{19}$$

$$P_d = A_e f_{cd} \tag{20}$$

P_{de} = Design compressive strength, in KN
f_{cde} = Design compressive stress (MPa)
Ae = Effective sectional area (mm^2)
X = stress reduction factor
γ_{m0} = Partial safety factor for material strength
α = imperfection factor, Considering buckling class b
K_f = Modification factor for eccentric load connections
l_{aa} = center to center length of lateral support preventing translation of member perpendicular to a-a axis
r_{aa} = radius of gyration of angle member about the a-a axis, parallel to the plane of end gusset plates.
b_1, b_2 = widths of legs of single angle
t =thickness of the leg
ϵ = yield stress ratio
E = Modulus of elasticity (2×10^5 MPa)

The constants K_1, $K_{2,}$ and K_3 represent the different end connection configurations, as outlined in Table 1. Bolted connections are categorized into two cases: single-bolt connections and two or more bolt connections. Welded connections are considered equivalent to two or more bolt connection cases.

Table 1. Constants K1 , K2 and K3 as per IS800:2007 and IS800:2007 (Amendment 2)

		IS 800-2007 (Amb 2)			IS 800-2007		
No. of bolts at each end connection	**Gusset/Connecting member fixity**	**K1**	**K2**	**K3**	**K1**	**K2**	**K3**
Fully welded or connected with two or more bolts	Fixed	0.794	0.563	-2.072	0.20	0.35	20
	Hinged	0.401	0.420	-1.040	0.70	0.60	5
Single bolt	Fixed	0.418	0.547	-1.400	0.75	0.35	20
	Hinged	0.374	0.415	-2.072	1.25	0.50	60

2.4 Design provision for AISC 360-22[10]

AISC 360-22[10] Specifications for structural steel buildings are used for the design of single angles under compression. It provides design compression strength of members by both the Allowable Strength Design (ASD) and Load and Resistance Factor Design (LRFD) methods.

In this study, we are analyzing the non-slender unequal leg single angle for flexural buckling. For single angles with a b/t greater than 20, torsional and flexural torsional buckling must be considered in the design.

The effects of eccentricity on single angle members may be neglected when analyzed as axially loaded compression members, provided that:

(1) The members are loaded in compression at the ends through the same leg.

(2) The members are connected either by welding or with a minimum of two bolts.

(3) No intermediate transverse loads are present.

Single angle members with different end conditions from those described above, a long leg to short leg width ratio greater than 1.7, or subjected transverse loading must be analyzed for combined axial load and flexure following the section H of the AISC 360-22[10] Specifications for structural steel buildings.

In this study, we are considering an unequal leg single angle which is an individual member of planar trusses, with an adjacent web member connected to the gusset plate.

Equations (21) to (28) represent the compression capacity calculations as per AISC 360-22.

For unequal angles fastened through the longer legs,

1. When L/$r_x \leq$ 80

$$\frac{KL}{r} = 72 + 0.75\frac{L}{r_x} \tag{21}$$

2. When L/r_x > 80

$$\frac{KL}{r} = 32 + 1.25\frac{L}{r_x} \leq 200 \tag{22}$$

For unequal-leg angles with a leg length ratio not greater than 1.7 and connected through the shorter leg, the $\frac{KL}{r}$ value from the above equations shall be increased by adding 4 × [(b_l / b_s)^2 - 1]. However, the KL/r of the members must be greater than 0.95L/r_z.

$$F_e = \frac{\pi^2 E}{\left(\frac{KL}{r}\right)^2} \tag{23}$$

The critical stress (Fcr) is determined using the following formulation –

3. If $\frac{KL}{r} \leq 4.71\sqrt{\frac{E}{F_y}}$ or $\frac{F_y}{F_e} \leq 2.25$

$$F_{cr} = \left[0.658^{\frac{F_y}{F_e}}\right] F_y \tag{24}$$

4. If $\frac{KL}{r} > 4.71\sqrt{\frac{E}{F_y}}$ or $\frac{F_y}{F_e} > 2.25$

$$F_{cr} = 0.877F_e \tag{25}$$

$$P_n = F_{cr}A_g \tag{26}$$

$$For\, LRFD,\, P_d = 0.9 \times P_n \tag{27}$$

$$For\, ASD,\, P_d = P_n/1.67 \tag{28}$$

L = Length of member measured between points at truss chord centerlines (mm)
b1 = Length of the unequal-leg angle's longer leg (mm)
bs = Length of unequal-leg angle's shorter leg (mm)
r_x = Radius of gyration about the geometric axis parallel to the connected leg (mm)
r_z = Radius of gyration about the minor principal axis (mm)
Pd = Design compressive strength (KN)
Pn = Nominal compressive strength (KN)
F_{cr} = Critical compressive strength (MPa)
F_e = Elastic buckling stress (MPa)

3 Results and Discussion

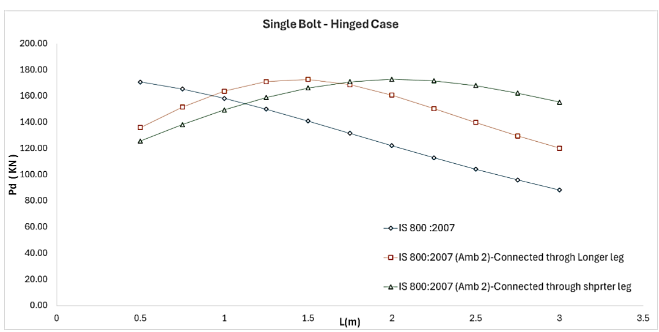

Fig 2. Design compression strength vs length of member plot for single bolt-hinged case based on IS800:2007 and IS 800:2007 (Amendment 2)

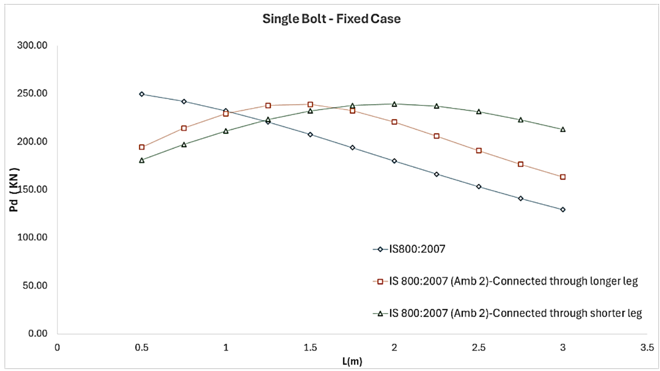

Fig 3. Design compression strength vs length of member plot for single bolt-fixed case based on IS 800:2007 and IS 800:2007 (Amendment 2)

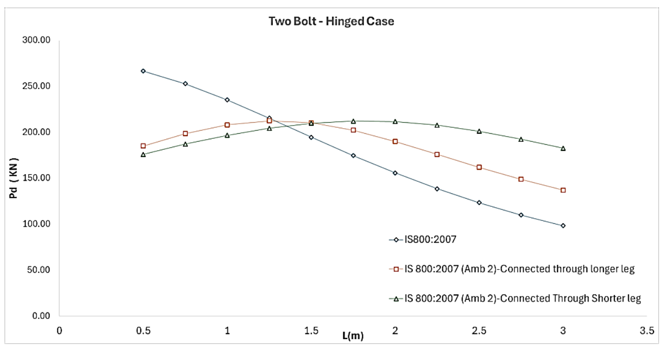

Fig 4. Design compression strength vs length of member plot for 2 bolt-hinged case based on IS 800:2007 and IS 800:2007 (Amendment2)

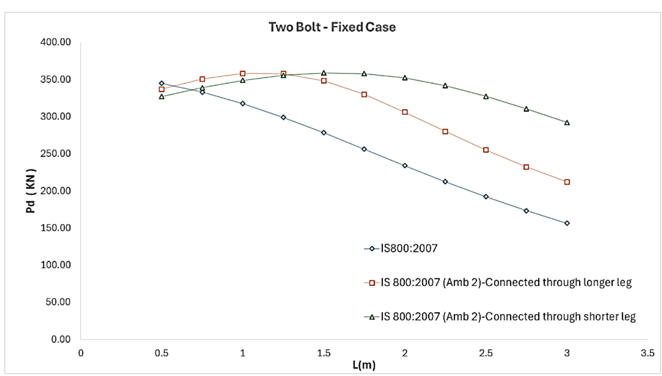

Fig 5. Design compression strength vs length of member plot for 2 bolt-fixed case based on IS 800:2007 and IS 800:2007 (Amendment2)

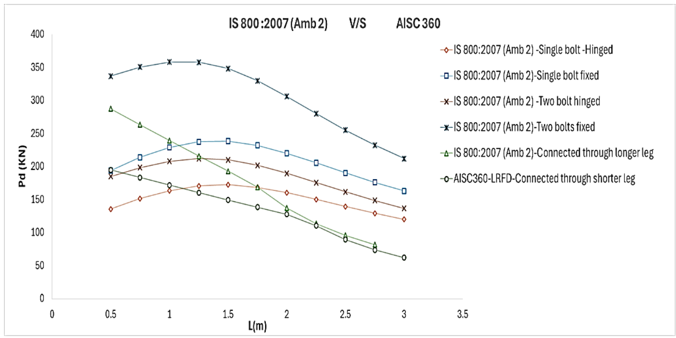

Fig 6. Design compression strength vs length of member plot based on IS 800:2007 (Amendment 2) and AISC360-22

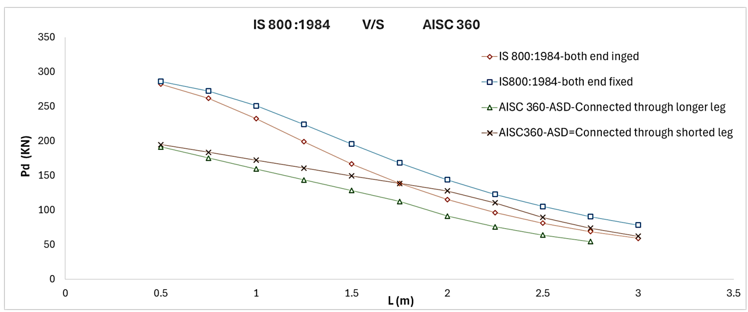

Fig 7. Design compression strength vs length of member plot based on IS 800:1984 and AISC 360-22

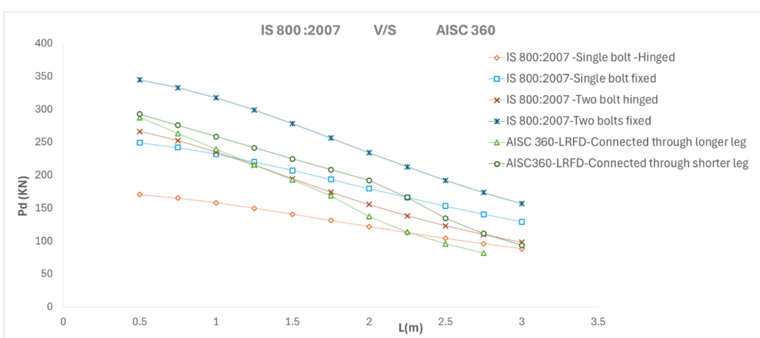

Fig 8. Design compression strength vs length of member plot based on IS 800:2007 and AISC 360-22

1. IS 800:2007 (Amendment 2) offers enhanced compression strength for unequal leg single angles compared to IS 800:2007, with increases of up to **40%** for angles connected by the longer leg and up to **87%** for those connected by the shorter leg. A study conducted by Vivek K.S., Dar M., and Subramanian N.[(2)] on eccentrically loaded equal leg single-angle sections reported that the latest provisions provide up to **104.84%** greater compression strength compared to the earlier code.
2. IS 800:2007 (Amendment 2) provides increased compression strength for unequal leg single angles as compared to the AISC 360-22 LRFD method, with up to **184%** more strength for angles attached by the longer leg and up to **179%** more for angles attached by the shorter leg.
3. IS 800:2007 provides increased compression strength for unequal leg single angles as compared to the AISC 360-22 LRFD method, with up to **112%** more strength for angles attached by the longer leg and **68%** more for angles attached by the shorter leg.
4. IS 800:1984 provides increased compression strength for unequal leg single angles as compared to the AISC 360-22 ASD method, with up to **67%** more strength for angles fastened by the longer leg and **27%** more for angles fastened by the shorter leg.
5. for IS 800:2007 (Amendment 2), unequal-leg single angles connected by the shorter leg provide up to **56%** more compression strength compared to unequal-leg single-angle attached with the longer leg.

Table 2. Compression Capacity of various angles of 2 m length as per IS800:2007 and IS800:2007 (Amendment 2)

Section Sizes	IS 800-2007				IS 800-2007 (Amb 2)				IS 800-2007 (Amb 2)			
					Angle connected by the Longer leg				Angle connected by the Shorter leg			
	Pd(kN)				Pd(kN)				Pd(kN)			
	1 bolt-Hinged	2 bolts-Hinged	1 bolt-Fixed	2 bolts-Fixed	1 bolt-Hinged	2 bolts-Hinged	1 bolt-Fixed	2 bolts-Fixed	1 bolt-Hinged	2 bolts-Hinged	1 bolt-Fixed	2 bolts-Fixed
ISA 75x50x8	42.11	62.08	47.50	75.23	55.94	76.47	64.13	99.04	78.39	108.92	94.69	153.65
					(33%)	(23%)	(35%)	(32%)	(86%)	(75%)	(99%)	(104%)
ISA 80x50x8	43.55	64.47	49.49	78.06	56.73	77.83	65.21	100.41	82.14	115.18	100.75	164.42
					(30%)	(21%)	(32%)	(29%)	(89%)	(79%)	(104%)	(111%)
ISA 90x60x8	57.30	87.11	72.30	108.85	75.36	106.30	90.53	141.46	91.24	132.59	117.58	193.21
					(32%)	(22%)	(25%)	(30%)	(59%)	(52%)	(63%)	(78%)
ISA 100x65x8	64.84	100.64	87.14	126.99	85.02	122.56	105.21	165.03	95.22	143.15	128.58	212.70
					(31%)	(22%)	(21%)	(30%)	(47%)	(42%)	(48%)	(67%)
ISA 100x75x8	72.68	114.96	105.31	147.45	95.84	141.88	123.70	196.81	97.88	149.91	134.93	222.48
					(32%)	(23%)	(17%)	(33%)	(35%)	(30%)	(28%)	(51%)
ISA 125x75x8	78.45	128.39	121.53	163.54	101.63	155.50	135.71	213.60	94.49	158.12	146.81	246.16
					(30%)	(21%)	(12%)	(31%)	(20%)	(23%)	(21%)	(51%)
ISA125 x 95x8	88.96	151.73	158.31	196.27	107.83	178.64	160.98	259.13	95.17	168.55	157.54	262.36

Note: Given percentages represent the percentage change in compression capacity with respect to IS 800:2007

4 Conclusion

1. As per the revised guidelines of IS 800:2007 (Amendment 2), the compressive strength of unequal angles appears to be greater when connected through the shorter leg, compared to when connected through the longer leg, in most of the cases considered in this study. This may lead to an apparently more economical design compared to the previous version of the code. It also highlights the need for extensive experimental investigation to gain a detailed understanding of the adequacy of the provisions in IS 800:2007 (Amendment 2).
2. IS 800-2007 (Amendment 2) provides a higher capacity of the section, thereby, for the same slenderness and loading conditions, smaller size sections can be used as compared to the previous version of IS 800-2007. This results in more economy in the design.
3. This study is limited to analytical calculations carried out through spreadsheets. A detailed study with due consideration to all parameters must be carried out experimentally and numerically to get a wholesome idea about the nature and capacity of unequal leg single-angle members under compression.
4. The study highlights the potential for more efficient and economical design of unequal leg single angles, offering valuable guidance for future design practices.

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