Comparison of Provisions for Nonslender Reinforced Concrete Columns: American Concrete Institution, Eurocode, Indian Standard, and Canadian Standards Association

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Abstract: The basis for the design of any concrete structural element is the concrete building code. Since the requirements for different used codes are dissimilar, a detailed comparative analysis needs to be conducted to compare multiple structural design aspects of various codes used worldwide and find out if there is any significant differences in the design procedures. The main objective of this study is to compare 4 building codes: ACI Standard: *Building Code Requirements for Structural Concrete*; the European Standard: *Eurocode 2: Design of concrete structures—Part 1-1: General Rules and Rules for Buildings*; the Indian Standard: *Plain and Reinforced Concrete—Code of Practice*; and the Canadian Standard: *CSA A23.3-19 Design of Concrete Structures* to draw conclusions on the differences in the design requirements for general characteristics, flexure, and provisions for nonslender columns. The same column cross section was used to calculate axial capacities based on all four codes and the results were presented in a comparative table. All the codes have some differences in the provisions compared. In general, regarding column axial capacities, it was seen that estimates provided by the Indian code were more conservative compared to the remaining three codes. **DOI: 10.1061/(ASCE)SC.1943-5576.0000620.** *© 2022 American Society of Civil Engineers.*

Author keywords: ACI 318-19; CSA A23.3/19; European Committee for Standardization (CEN); IS 456; Code comparison; Flexure; Column; Axial capacities; Reinforcement; Interaction charts.

Introduction

In order to regulate the design and construction of concrete structures, different countries use different building code requirements. This paper presents a comparison between the provisions included in the ACI Standard: Building Code Requirements for Structural Concrete (ACI 2019) and Commentary; the European Standard: *Eurocode 2: Design of concrete structures—Part 1-1: General Rules and Rules for Buildings* (CEN 2004); the Indian Standard: Plain and Reinforced Concrete—Code of Practice (IS 2000); and the Canadian Standard: CSA A23.3-19 Design of concrete structures (CSA 2019). Comparison tables and examples focusing on columns are presented to aid in the explanation of the provisions. The analysis will be presented according to subcategories: general characteristics, flexure, and provisions for columns.

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Literature Review

Comparison of various codes was undertaken by other researchers before. In a study performed by Tabsh (2013), the design of various reinforced concrete structure elements based on ACI 318 and BS 8110 was compared. It was concluded that for the design of flexural elements there is a minor difference. However, the difference in design strength of compression members per ACI 318 was about 10% to 25% less than the predicted strength according to BS 8110. Bakhoum et al. (2016) compared the design loads and section's design procedure of various structural elements of buildings design codes in the US (ACI 2019), Europe (CEN 2004), and Egypt (ECP 2007). The authors concluded that designed sections based on Egyptian standards resulted in more rebar per section. For the design of compressive members, ACI 318 provided larger sections among the codes that were studied. Also, using a combination of design codes resulted in unsafe sections.

The design of concrete flexural members based on ACI 318 and CEN Eurocode 2:1992 [EN 1992-1-1 (CEN 2004)] was compared by Hawileh et al. (2009). It was determined from the results that the codes have very different safety concepts. However, this does not significantly affect the computation of the design of flexural members. Also, EN 1992-1-1 provides more conservative strength designs and a higher factor of safety than the ACI 318 code for flexural members. In another study by Gupta and Collins (2001), experiments were undertaken to test and compare the shear strength of RC members designed based on AASHTO and ACI 318 and subjected to axial compression. The results of the experiments showed that although the AASHTO code is more complex than ACI 318's simple method, AASHTO's method predicts the sections' strength more accurately. Furthermore, the members designed per ACI 318's detailed procedure experienced brittle failure subjected to lower loads. However, the simple method of ACI 318 could predict the shear strength of the members conservatively.

El-Shennawy et al. (2014) compared the provisions of the ECP (2007) and EN 1992-1-1 (CEN 2004) and concluded the buildings designed by using the Egyptian code have bigger dimensions and heavier reinforcement, likely due to the live loads and reinforcements used in the Egyptian code. Labani and Guha (2014) compared the design of reinforced concrete structure based on IS 456:2000, BS8110:1985, and EN 1992-1-1 from an economical point of view. Similarly, Nwoji and Ugwu (2017) compared the structural design and analysis of concrete building using BS 8110 and EN 1992-1-1, concluding that EN 1992-1-1 is easier to use, provides more economical sections, and is technologically more advanced.

Objectives

The main purpose of this paper is to compare and contrast the various clauses in ACI 318-19, CSA A23.3/19, EN 1992-1-1, and IS 456:2000 regarding general characteristics of steel, concrete, and reduction factors. The paper also compares the clauses provided in the above four codes along with the design methodologies used for nonslender column sections. It is expected that this will assist engineers in understanding the methodologies of the four analyzed design standards better. It is also expected that this paper will help engineers understand exactly why there are differences when the same axial member is designed using different code provisions. Furthermore, it is expected that the comparative analysis of the code methods will provide insight into the aspects that govern the formulation of the code clauses studied.

General Characteristics

The compared codes use various common symbols to represent similar quantities. However, the definitions for the same symbols can vary from one code to another. For easy reference, Appendix IV: Notations, lists all the symbols used in this paper along with their descriptions according to the different codes.

Concrete Strength

All codes specify minimum and maximum concrete strength limits. These limits vary depending on the codes and, therefore, some codes can be used to design concrete structures with concrete compressive strengths not covered in other codes. However, unlike ACI 318-19, CSA A23.3-19, and EN 1992-1-1 which use cylindrical specimens to test concrete strength, IS 456:2000 makes use of cubic specimens, which tend to result in higher strength. On average, the ratio of compressive strength of 150 x 300 mm cylinders to 150 mm cubes is 0.8 (Reddy et al. 2019). Therefore, all concrete compressive strengths for IS: 456 will be given as multiplied by 0.8 for uniformity in the comparison. Table 1 shows the minimum and maximum permitted concrete strength limits for ACI 318-19, CSA A23.3-19, IS 456:2000, and EN 1992-1-1, respectively.

Table 1. Minimum and maximum compressive strength limits of concrete

	Concrete compressive strength (MPa)		
Code	Min	Max	Sample
ACI 318-19	17	—	Cylinder 150 × 300 mm
CSA A23.3-19	20	80	Cylinder 150 × 300 mm
IS 456:2000	10	80	Cubic 150 × 150 mm
	8	64	Equivalent cylinder
EN 1992-1-1	12	90	Cylinder 150 × 300 mm

Concrete Modulus of Elasticity

Codes use concrete compressive strength as a base value to calculate the modulus of elasticity of concrete. A study of the equations shows that IS 456:2000, ACI 318-19, and CSA A23.3-19 have almost similar equations. EN 1992-1-1 uses an equation that is slightly different than other codes. Table 2 shows the equations used for the calculation of modulus of elasticity for ACI 318-19, CSA A23.3-19, IS 456:2000, and EN 1992-1-1, respectively. Fig. 1 shows that for concrete with a given compressive strength, EN 1992-1-1 gives the greatest modulus of elasticity followed by ACI 318-19. CSA A23.3-19 and IS 456:2000 give approximately the same values, as can be seen by the almost overlapping curves.

Steel Strength

Unlike concrete strength limits, the codes deal with steel strength limits in a nonuniform way. Only EN 1992-1-1 provides specific minimum and maximum strength limits. IS 456:2000, ACI 318-19, and CSA A23.3-19 provide only maximum permitted steel strengths. These three codes further classify the maximum steel strength limit according to the application or type of steel used. Table 3 lists the maximum (and minimum, in the case of EN 1992-1-1) permitted steel strengths for ACI 318-19, CSA A23.3-19, IS 456:2000, and EN 1992-1-1, respectively, along with the application and type of classification.

Steel Modulus of Elasticity

All four codes provide 200 GPa as the value for the modulus of elasticity of steel.

Table 2. Equations used to calculate modulus of elasticity for concrete

Code	Equations for modulus of elasticity
ACI 318-19	$E_c = 4{,}700\sqrt{f_c'}$
CSA A23.3-19	$E_c = 4{,}500\sqrt{f_c'}$
EN 1992-1-1	$E_{cm} = 22\left(\frac{f_{cm}}{10}\right)^{0.3}$
IS 456:2000	$E_c = 5{,}000\sqrt{f_{ck}}$

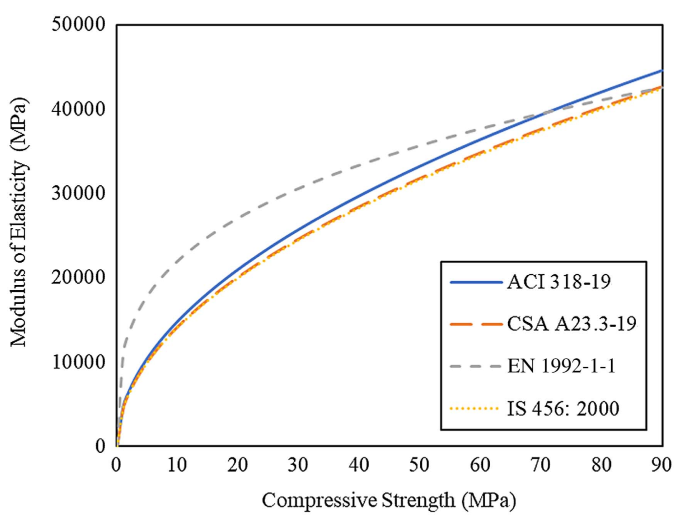

Fig. 1. Variations in modulus of elasticity for different concrete compressive strengths.

Table 3. Maximum and minimum permitted strengths of steel

Codes	Application	Min	Max f_y or f_{yt} permitted (psi)
ACI 318-19	Application type: Special moment frames	—	80,000 (~550 MPa)
	Special structural walls	—	100,000 (~670 MPa)
	Other	—	100,000 (~670 MPa)
CSA A23.3-19	Application type:		Max f_y or f_{yt} permitted (MPa)
	Tension	—	500
	Compression	—	400
IS 456:2000	Application type: Type of steel	f_y (MPa)	Max permitted ($fy/\Upsilon s$) (MPa)
	Fe250	250	217
	Fe 415	415	361
	Fe 500	500	434.8
EN 1992-1-1	—	Min f_{yk} (Mpa)	Max f_{yk} (MPa)
	—	400	600

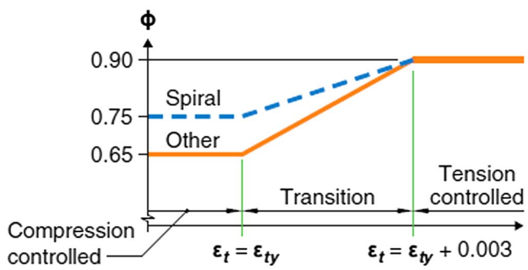

Fig. 2. Variation of ϕ (strength reduction factor) with net tensile strain in extreme tension reinforcement. (Adapted from ACI 2019.)

Strength Reduction Factors

Comparing the strength reduction factors shows that the reduction factors of ACI 318-19 differs fundamentally from the other three codes. ACI 318-19 considers strength reduction factors for design moment and axial force strengths, whereas the other three codes use strength reduction factors to reduce the material strengths (for concrete and reinforcing steel). Furthermore, ACI 318-19 is the only code which considers a variable strength reduction factor (ϕ), with the variation depending on the net tensile strain in extreme tension reinforcement (Fig. 2). The summary of the general characteristics from this section are available in Appendix I: General Characterstics.

Flexure

Maximum Concrete Strain

The assumptions of flexural design presented in the codes are very similar. Among the four codes being compared, only ACI 318-19 considers a maximum concrete strain value of 0.003. CSA A23.3-19, IS 456:2000, and EN 1992-1-1 all consider a maximum concrete strain value of 0.0035. For concrete with a compressive strength greater than 50 MPa, EN 1992-1-1 provides a specific equation to calculate the maximum concrete strain.

Stress Block

ACI 318-19 and CSA A23.3-19 consider rectangular stress blocks in the compressed area of the structural elements. EN 1992-1-1 offers two alternatives for the design of cross sections, the parabola-rectangle and bilinear diagrams (Narayanan and Beeby 2005). It also permits a rectangular stress block to be used for section design. The height of the rectangular stress block is determined by multiplying the depth of the neutral axis with an appropriate factor, while the width of the rectangular stress block is a function of the concrete strength. Fig. 3 shows the stress blocks as given in ACI 318-19, CSA A23.3-19, EN 1992-1-1, and IS 456:2000, respectively. IS 456:2000 considers a rectangular-parabolic shape for the stress block with both the area of the stress block and its depth calculated by the provided equations. Fig. 4 shows the depth of stress blocks for different concrete compressive strengths (assuming a neutral axis at 10 cm). Similarly, Fig. 5 shows the maximum compression stresses for different concrete compression strengths for the four design standards. Detailed information related to this section is presented in Appendix II: Flexure.

Provisions for Columns

Axial Capacities

When a symmetrical column is subjected to concentric axial load, longitudinal strains develop uniformly across the section.

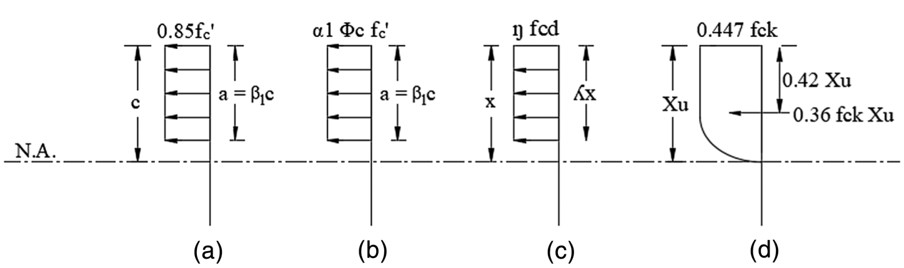

Fig. 3. (a) Stress blocks for ACI 318-19 (adapted from Wight 2016); (b) CSA A23.3-19 (adapted from CSA 2019); (c) EN 1992-1-1 (adapted from CEN 2004); and (d) IS 456:2000 (adapted from IS 2000).

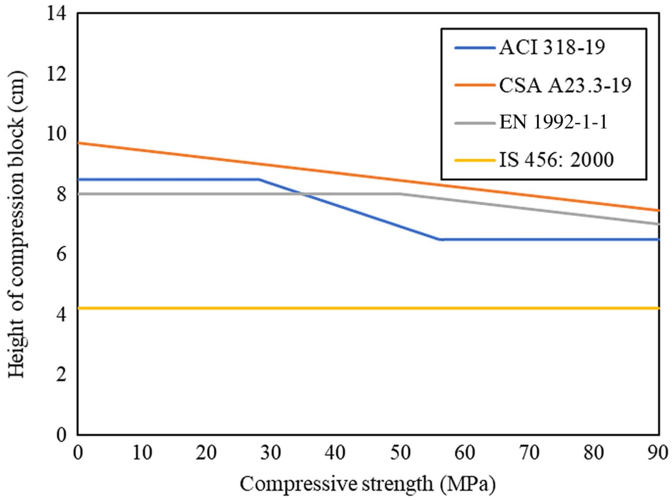

Fig. 4. Depth of stress distribution block for different concrete compressive strengths (assuming neutral axis at 10 cm).

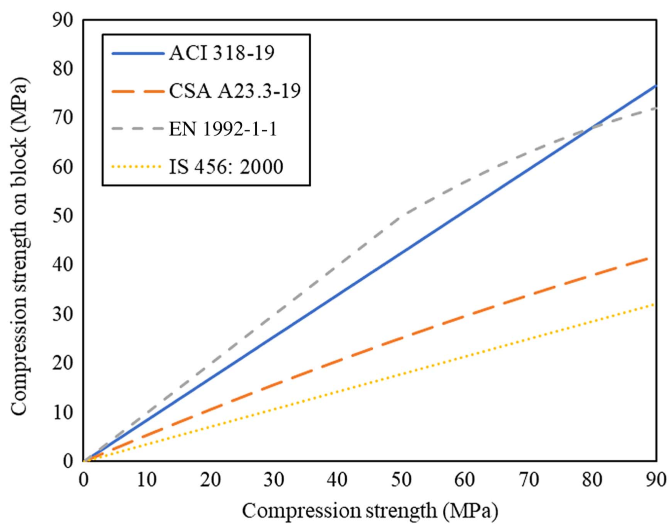

Fig. 5. Maximum compression stresses for different concrete compressive strengths.

Stresses in both concrete and steel can then be computed using stress-strain curves for the two materials. The corresponding forces in concrete and steel are equal to the stresses multiplied by the respective areas (Wight 2016). All of the codes use this method to calculate the theoretical nominal resistance for a column under axial loading. However, the nominal axial capacity cannot normally be attained because there are always unbalanced moments and moments present due to misalignments. The codes, therefore, further reduce this capacity to arrive at the maximum compressive strength for the column. Also, in all of the codes, the final maximum allowable axial capacity of a column is further influenced by the type of lateral confinement, tied or spiral, and reduction factors used.

For ACI 318-19:

Nominal axial capacity:

$$P_o = 0.85 f'_c (A_g - A_{st}) + f_y A_{st} \tag{1}$$

Maximum compressive strength:

$$P_{\max} = \phi(0.85 f'_c (A_g - A_{st}) + f_y A_{st}) \tag{2}$$

Maximum allowable axial capacity:
For columns with tied lateral confinement:

$$P_{\max\_allow} = 0.8 \times \phi(0.85 f'_c (A_g - A_{st}) + f_y A_{st}) \tag{3}$$

For columns with spiral lateral confinement:

$$P_{\max\_allow} = 0.85 \times 0.85 \phi f'_c (A_g - A_{st}) + f_y A_{st} \tag{4}$$

For CSA A23.3-19:

1. Nominal axial capacity:

$$P_o = 0.85 \times 0.85 \phi f'_c (A_g - A_{st}) + f_y A_{st} \tag{5}$$

Maximum compressive strength:

$$P_{\max} = \alpha_1 \phi_c f'_c (A_g - A_{st}) + \Phi_s f_y A_s \tag{6}$$

Maximum allowable axial capacity:
For columns with tied confinement:

$$P_{\max\_allow} = ((0.2 + 0.002h) \le 0.8) \times \alpha_1 \phi_c f'_c (A_g - A_{st}) + \phi_s f_y A_{st} \tag{7}$$

For columns with spiral lateral confinement:

$$P_{\max\_allow} = 0.9 \times \alpha_1 \phi_c f'_c (A_g - A_{st}) + \phi_s f_y A_{st} \tag{8}$$

For EN 1992-1-1:

2. Nominal axial capacity:

$$P_o = \alpha_{cc} f_{ck} (A_g - A_{st}) + f_{yk} A_{st} \tag{9}$$

Maximum allowable axial capacity:

$$P_{\max\_allow} = \frac{\alpha_{cc} f_{ck} (A_g - A_{st})}{\Upsilon_c} + \frac{f_{yk} A_{st}}{\Upsilon_s} \tag{10}$$

For IS 456:2000:

For design, the value of maximum compressive stress of concrete is generally taken as 0.85 times the cylinder strength; however, because IS 456:2000 makes use of cubic specimens, which tend to result in higher strength, multiplying the value again by 0.8 (Reddy et al. 2019) gives 0.68, which is approximately 0.67, the code adopted factor to be multiplied with the characteristic cube strength, f_{ck}.

3. Nominal axial capacity:

$$P_o = 0.67 f_{ck} A_g + (f_{sc} - 0.67 f_{ck}) A_{sc} \tag{11}$$

4. Maximum compressive strength:

$$P_{\max} = 0.447 f_{ck} A_g + (f_{sc} - 0.447 f_{ck}) A_{sc} \tag{12}$$

Table 4. Maximum and minimum permitted compression reinforcements

Code	Min compression reinforcement	Max compression reinforcement
ACI 318-19	$0.01\,A_g$	$0.08\,A_g$
CSA A23.3-19	$0.01\,A_g$	$0.08\,A_g$
EN 1992-1-1	Greater of: $\frac{0.1N_{Ed}}{f_{yd}}$ or $0.002\,A_c$	$0.04\,A_c$ outside lap locations $0.08\,A_c$ at lap locations
IS 456	$0.008\,A_g$	$0.06\,A_g$

5. Maximum allowable axial capacity:
   For columns with tied confinement

$$P_{\max\_allow} = 0.4 f_{ck} A_c + 0.67 f_y A_{sc} \tag{13}$$

   For columns with spiral lateral confinement:

$$P_{\max\_allow} = 1.05(0.4 f_{ck} A_c + 0.67 f_y A_{sc}) \tag{14}$$

The maximum allowable axial capacity of a section under axial loading is a useful property and gives one of the limiting points in the axial behavior of the column. A comparative analysis of axial capacities calculated for an example cross section in the current study is provided for comparison.

Reinforcement Percentage (ρ)

All codes provide the minimum and maximum percentages for compression reinforcements for a column section as shown in Table 4. It is assumed that 1% to 2% is an economical choice.

Estimation of Column Size

It is possible to substitute the values of ρ and the axial load to be resisted by the column in the equations for maximum allowable axial capacity to arrive at the estimation for column size. Assuming that $\rho = A_{st}/A_g$ and P_u = axial load on the column, the values of A_g obtained from the equations in the "Axial Capacities" section can then be used to estimate the dimensions (b or h for rectangular and d for circular) of the required columns. However, if there are moments present, the above equations tend to underestimate the size required. Rounding off to a value 10% to 15% higher than the calculated A_g helps take into account any moments.

Number of Longitudinal Reinforcement Bars

Only ACI 318-19, IS 456:2000, and EN 1992-1-1 provide clauses that govern the number of bars. CSA A23.3-19 does not provide such clauses. In Table 5, the minimum number of bars per different code is provided.

Table 5. Minimum number of reinforcement bars

Code	Min number of bars
ACI 318-19	3 within triangular ties 4 within rectangular or circular ties 6 enclosed by spirals
CSA A23.3-19	No clause in code
EN 1992-1-1	Rectangular ≥ 4 Circular ≥ 6
IS 456	Circular ≥ 4

Table 6. Minimum permissible diameter of reinforcement bars

Code	Min diameter of bars
ACI 318-19	No clause in code
CSA A23.3-19	No clause in code
EN 1992-1-1	$\varphi \geq 8$ mm
IS 456	$\varphi \geq 8$ mm

Minimum Diameter of Bars (Longitudinal Reinforcement)

Table 6 compares the required minimum size of the bars for different codes. Only IS 456:2000 and EN 1992-1-1 provide clauses that govern the minimum diameter of bars. ACI 318-19 and CSA A23.3-19 do not provide such clauses.

Spacing of Longitudinal Bars

All four codes provide specifications for minimum spacing of longitudinal reinforcement as shown in Table 7. After designing a column using the above steps, usually interaction charts can be used to verify that it meets the load requirements. All the information for reinforcement are also summarized in Appendix III: Compression Reinforcement.

Interaction Charts

Column capacity is influenced by several factors such as arrangement of reinforcement, cover to the bars, lateral reinforcement type used, etc. Furthermore, the axial capacity of a column section varies with the moment acting on the section. To avoid the use of complicated equations resulting from taking into account all of the influencing properties, a family of interaction charts for commonly used sections and reinforcement patterns have been derived for each of the codes, ACI 318-19, CSA A23.3-19, IS 456:2000, and EN 1992-1-1, and agreed upon by engineers. These published interaction charts are independent of column dimensions and can be referred to as nondimensional interaction diagrams. These are often used as a practical way to design large groups of sections that fit certain limitations.

Selection of Interaction Chart to Use

Interaction charts based on ACI 318-19, CSA A23.3-19, IS 456:2000, and EN 1992-1-1 all require that common variables be determined before utilizing a chart for design. The variables required by the design chart to choose the columns are as follows:

1. Column shape
   Published chart families are for circular and rectangular columns.
2. Reinforcement pattern
   Selection of reinforcement pattern is more relevant for rectangular columns. Charts can be selected based on the decision of

Table 7. Criteria governing spacing of longitudinal bars

Code	Spacing of bars
ACI 318-19	Greatest of 2.54 cm, $1.5\,d_b$, or $\frac{4}{3}d_{agg}$
CSA A23.3-19	Greatest of $1.4\,d_b$, 1.4 times size of max aggregate, or 30 mm
EN 1992-1-1	Should not be less than the maximum of $k1$ × bar diameter; ($dg + k2$ mm); or 20 mm
IS 456	Greatest of 1.5 cm; 2/3 of maximum size of aggregate; or maximum bar diameter

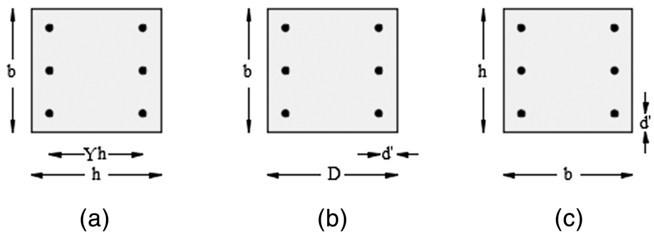

Fig. 6. Relation of effective cover with chart selection for (a) ACI 318-19 and CSA A23.3-19 (adapted from Wight 2016; CAC 2004); (b) BIS (1980) (adapted from BIS 1980); and (c) EN 1992-1-1 (adapted from CEN 2004).

Table 8. Nondimensional quantities in the horizontal and vertical axes for ACI 318-19, CSA A23.3-19, IS 456:2000 and EN 1992-1-1

Code	Horizontal axis	Vertical axis
ACI 318-19	$\frac{\Phi P_n}{bh}$	$\frac{\Phi M_n}{bh^2}$
CSA A23.3-19	$\frac{P_r}{A_g}$	$\frac{M_r}{A_g h}$
IS 456:2000	$\frac{P_u}{f_{ck} bD}$	$\frac{M_u}{f_{ck} bD^2}$
EN 1992-1-1	$\frac{N}{bhf_{ck}}$	$\frac{M}{bh^2 f_{ck}}$

providing reinforcement on 2 opposite column faces or all 4 column faces.

3. Cover to reinforcement

Charts based on ACI 318-19 and CSA A23.3-19 make use of the effective cover to reinforcement bars by using a factor Υ to select the charts.

Charts based on IS 456:2000 and EN 1992-1-1 make use of the d'/D ratio for chart selection, where d' = effective cover to the reinforcement and D/h = overall height of the section.

Fig. 6 shows the parameters of cover to reinforcement used in the interaction chart selection based on all four codes.

4. Design strength of concrete

Charts based on ACI 318-19 and CSA A23.3-19 require the design strength of concrete for chart selection. However, for charts based on IS 456:2000 and EN 1992-1-1, the design strength of concrete is an integral part of the nondimensional values calculated in either axis (Table 8). Therefore, the design strength of concrete does not influence chart selection.

5. Yield strength of steel

Charts based on ACI 318-19, CSA A23.3-19, and IS 456:2000 require the yield strength of reinforcement used as a primary variable for chart selection. However, for charts based on EN 1992-1-1, the design yield strength of steel has also been included in the chart and, therefore, does not influence chart selection.

Calculation of Nondimensional Axial Values

The calculation of nondimensional axial values requires column dimensions b and h (or D) or A_g (gross area of column section)

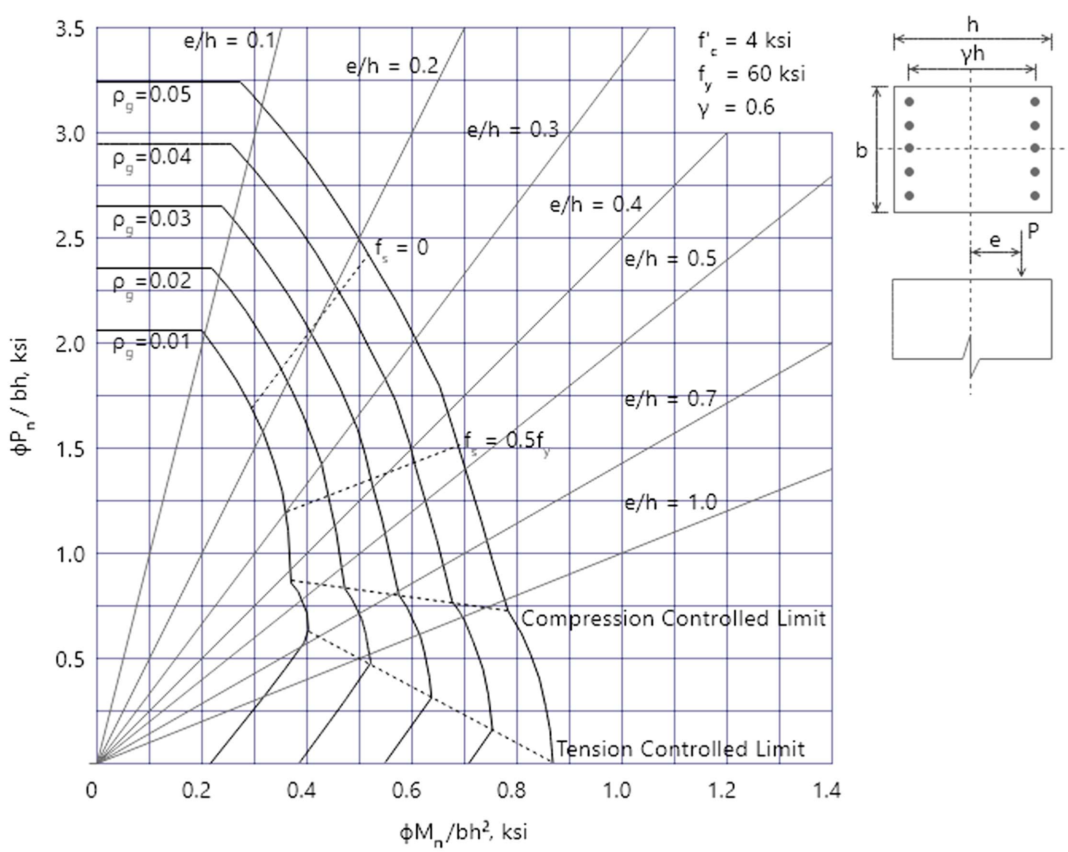

Fig. 7. Sample nondimensional interaction chart, ACI 318-19 for rectangular tied column with bars in two faces: $f_c' = 27.57$ N/mm^2 (4,000 psi), $f_y = 60$ Ksi, and $\Upsilon = 0.6$. (Adapted from Wight 2016.)

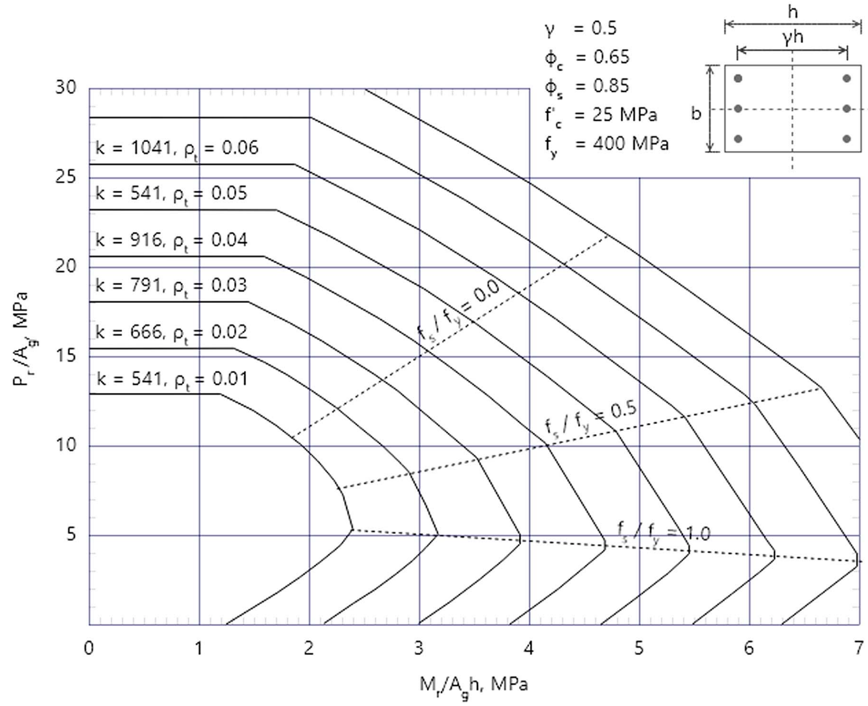

Fig. 8. Sample nondimensional interaction chart, CSA A23.3-19 for rectangular tied column with bars in two faces: $f_c' = 25\ \mathrm{N/mm^2}$, $f_y =$ 400 MPa, and $\Upsilon = 0.5$. (Adapted from CAC 2004.)

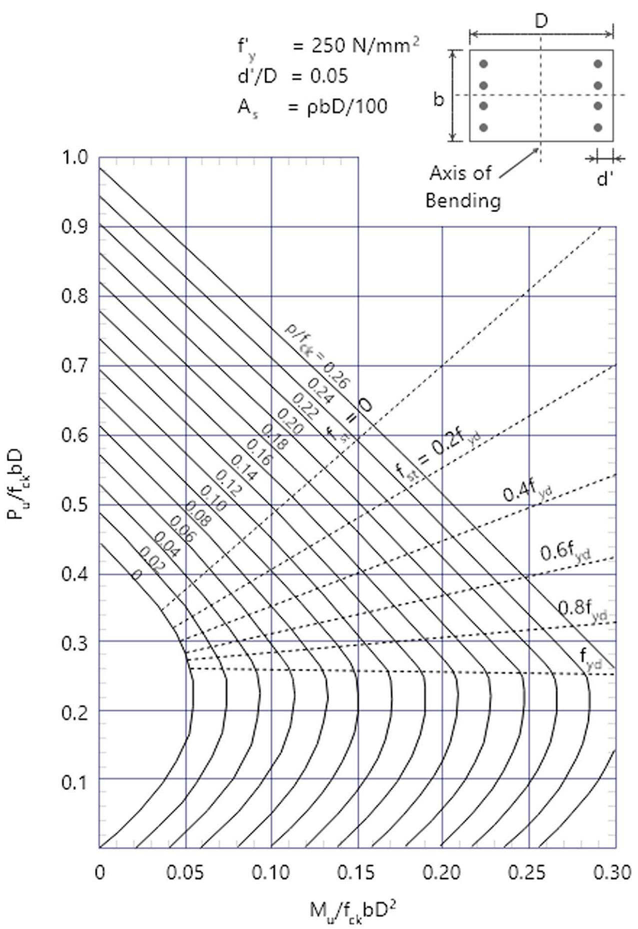

Fig. 9. Sample nondimensional interaction chart, IS 456:2000 for rectangular tied column with bars in two faces: $f_y = 250\ \mathrm{N/mm^2}$ and $d'/D = 0.05$. (Adapted from BIS 1980.)

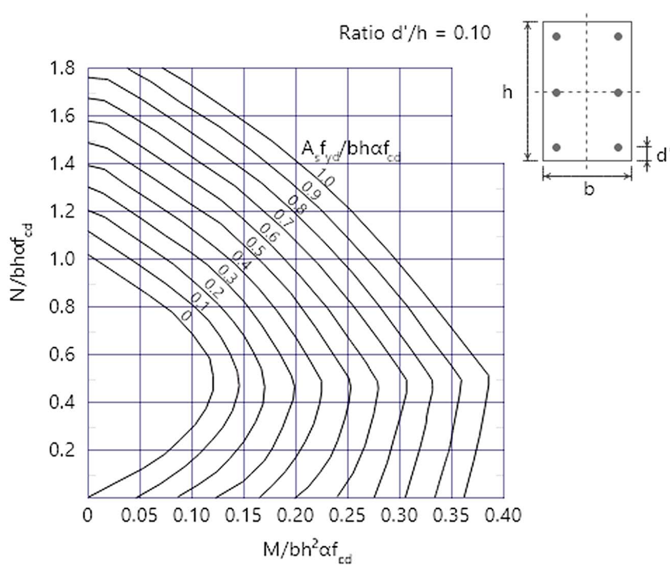

Fig. 10. Sample nondimensional interaction chart, EN 1992-1-1 for rectangular tied column with bars in two faces: $f_y = 250\ \mathrm{N/mm^2}$ and $d'/D = 0.05$. (Adapted from Narayanan and Beeby 2005.)

for charts based on all four codes under consideration. When the dimensions are available and only reinforcement has to be estimated, the calculation of the axis values is easy to perform. The nondimensional values on the axes can be obtained based on the variables gathered previously. The nondimensional quantities in the horizontal and vertical axes for the codes being compared are listed in Table 8. Figs. 7–10 show a sample nondimensional interaction chart based on ACI 318-19, CSA A23.3-19, EN 1992-1-1, and IS 456:2000, respectively.

Table 9. Comparision of axial capacities for tied columns

Axial capacities	ACI 318-19	CSA A23.3-19	EN 1992-1-1	IS 456
Nominal axial capacity	$P_o = 3{,}883.16$ kN	$P_o = 3{,}883.16$ kN	$P_o = 3{,}883.16$ kN	$P_o = 2{,}718.42$ kN
Maximum compressive strength	$P_{\max} = 2{,}524.06$ kN	$P_{\max} = 2{,}787.09$ kN	—	$P_{\max} = 2{,}258.57$ kN
Maximum allowable axial capacity	$P_{\max\_allow} = 2{,}019.25$ kN	$P_{\max\_allow} = 2{,}229.67$ kN	$P_{\max\_allow} = 2{,}932.108$ kN	$P_{\max\_allow} = 1{,}958.59$ kN

Comparison of Axial Capacities for Tied Columns

Data:

$A_g = 90{,}000$ mm^2

8, #8 bars;

$A_{st} = 8 \times 509.68 = 4{,}077.44$ mm^2

Concrete strength (f'_c or f_{ck}) = 30 N/mm^2 (~24 for IS 456)

Steel strength (f'_y) = 415 N/mm^2

$\phi_{compression} = 0.65\phi_c = 0.65\phi_s = 0.85$

$\Upsilon_c = 1.5\Upsilon_s = 1.15$

For CSA19 $\alpha_1 = (0.85 - 0.0015f'_c) \geq 0.68 = 0.805(0.2 + 0.002 \text{ x } h) \leq 0.8 = 0.80$

For EN 1992-1-1 $\alpha_{cc} = 0.85$

For IS-456 $f_{sc}(415) = 0.79 \text{ x } f_y = 327.85$ N/mm^2

Confinement = Tied

Table 9 lists the comparison of axial capacities calculated for the example section given in Fig. 11 using ACI 318-19, CSA A23.3-19, EN 1992-1-1, and IS 456:2000.

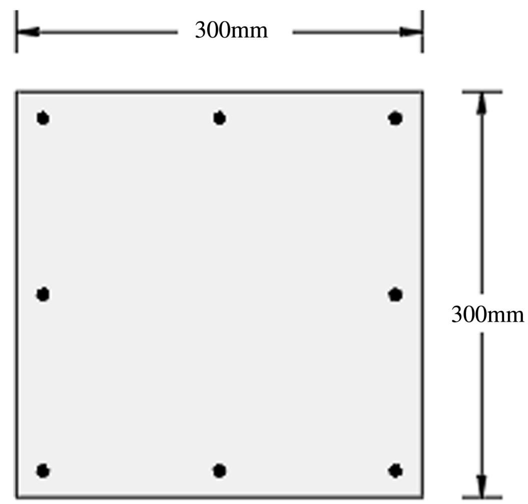

Fig. 11. Section for sample calculation.

Conclusion

Regarding concrete, while all other codes use a 150 × 300 mm cylinder for measuring concrete compressive strength, IS 456:2000 makes use of cubic specimens, which tend to result in higher strength values. EN 1992-1-1 permits the use of 90 MPa concrete, which is the highest among the codes compared. EN 1992-1-1 also estimates a greater value for the modulus of elasticity while IS 456:2000 estimates the least.

Although all four codes provide 200 GPa as the value for the modulus of elasticity of steel, ACI 318-19 and CSA A23.3-19 list out the maximum permitted steel strength based on application. IS 456:2000 does the same based on steel types. EN 1992-1-1 simply states the minimum and maximum permissible steel strengths that can be used. While the other three codes consider reduction factors for material strength, ACI 318-19 is the only code which considers a variable strength reduction factor (ϕ) for design moment and axial strength, with the variation depending on the net tensile strain in extreme tension reinforcement.

All four codes provide clauses for estimating column axial capacities. It can be seen from the comparison of axial capacities that the nominal axial capacities per ACI 318-19, CSA A23.3-19, and EN 1992-1-1 are the same, whereas for IS 456:2000, it is considerably lower. CSA A23.3-19 gives the maximum compressive strength, and IS 456:2000 gives the lowest value for this parameter. EN 1992-1-1 gives the highest maximum allowable axial capacity, which is about 31% more than the next closest one, CSA A23.3-19. In terms of maximum allowable axial capacity, IS 456:2000 gives the most conservative value.

None of the codes give information about column dimensioning. Therefore, column sizes are often estimated by selecting reinforcement percentages within the specified range and using estimated loads and axial capacity equations to calculate required concrete areas. Finally, although not explicitly mentioned in the codes, the use of nondimensional interaction charts is common for iterative column designs.

Appendix I. General Characterstics

Specification	Standard	Clause
Concrete unit wt/density	ACI 318-19	No clause in code
	CSA A23.3-19	No clause in code
	EN 1992-1-1	Plain concrete 24 kN/m^3 (EN 1991-1-1)
		Reinforced concrete 25 kN/m^3 (Table A.1)
	IS 456	Plain concrete 24 kN/m^3
		Reinforced concrete 25 kN/m^3 (Section 19.2)
Limits for the compressive strength of concrete	ACI 318-19	Minimum: 17 MPa; Maximum: (Tables 19.2.1.1)
	CSA A23.3-19	Minimum: 20 MPa; Maximum: 80 MPa (Section 8.6.1.1)
	EN 1992-1-1	Minimum: 12 MPa; Maximum: 90 MPa (Table 3.1)
	IS 456	Minimum: 10 MPa; Maximum: 80 MPa (Table 2)

Appendix I. (*Continued.*)

Specification	Standard	Clause
Modulus of elasticity-concrete	ACI 318-19	$E_c = 4{,}700\sqrt{f'_c}$ (MPa) (Section 19.2.2.1.b)
	CSA A23.3-19	For compressive strength between 20 and 40 MPa $E_c = 4{,}500\sqrt{f'_c}$ (Section 8.6.2.3) For $1{,}500 \leq \gamma_c \leq 2{,}500$ kg/m^3 $E_c = \left(3{,}300\sqrt{f'_c} + 6{,}900\right)\left(\frac{\gamma_c}{2{,}300}\right)^{1.5}$ (Section 8.6.2.2)
	EN 1992-1-1	$E_{cm} = 22\left[\frac{(f_{ck}+8)}{10}\right]^{0.3}$ (GPa) (Table 3.1)
	IS 456	$E_c = 5{,}000\sqrt{f_{ck}}$ (Section 6.2.3.1)
Modulus of elasticity reinforcement-steel	ACI 318-19	200,000 MPa (Section 20.2.2.2)
	CSA A23.3-19	200,000 MPa (Section 8.5.4.1)
	EN 1992-1-1	200,000 MPa (Section 3.2.7)
	IS 456	200,000 MPa (Section 5.6.3)
Strength reduction factor-concrete	ACI 318-19	None
	CSA A23.3-19	$\phi_c = 0.65$ (Section 8.4.2)= 0.70 for elements produced in manufacturing plants(Section 16.1.3)
	EN 1992-1-1	$\Upsilon_c = 1.5$ (Table 2.1N)
	IS 456	$\Upsilon_c = 1.5$ (Section 36.4.2.1)
Strength reduction factor-reinforcing steel	ACI 318-19	None
	CSA A23.3-19	$\phi_s = 0.9$ (Section 8.4.3)
	EN 1992-1-1	$\Upsilon_s = 1.15$ (Table 2.1N)
	IS 456	$\Upsilon_s = 1.15$ (Section 36.4.2.1)

Appendix II. Flexure

Specification	Standard	Clause
Maximum strain at the extreme concrete compression fiber	ACI 318-19	0.0030 (Section 22.2.2.1)
	CSA A23.3-19	0.0035 (Section 10.1.3)
	EN 1992-1-1	0.0035 for $f_{ck} \leq 50$ MPa $2.6 + 35\left[\frac{(90 - f_{ck})}{100}\right]^4\%$ for $f_{ck} > 50$ MPa (Table 3.1)
	IS 456	0.0035 (Section 38.1b)
Concrete stress distribution	ACI 318-19	$0.85f'_c$ (Section 22.2.2.4.1)
	CSA A23.3-19	$\alpha_1 \Phi_c f'_c$ where: $\alpha_c = 0.85 - 0.0015f'_c$ but not less than 0.67 (Section 10.1.7(c))
	EN 1992-1-1	ηf_{cd} where: $\eta = 1.0$ for $f_{ck} \leq 50$ MPa $\eta = 1.0 - \frac{(f_{ck} - 50)}{200}$ for $50\ MPa < f_{ck} \leq 90\ MPa$ (Section 3.1.7)
	IS 456	Area of stress block: $0.36 f_{ck} x_u$ (Section 38.1c)
Height of concrete stress distribution	ACI 318-19	$a = \beta_1 c$ where: $\beta_1 = 0.85$ for $17.23\text{ MPa} \leq f'_c \leq 27.58\ MPa$ $\beta_1 = 0.85 - \frac{0.05(f'_c - 28)}{7}$ for $27.58\text{ MPa} < f'_c < 55.16$ MPa $\beta_1 = 0.65$ for $f'_c \geq 55.16$ MPa (Tables 22.2.2.4.3)
	CSA A23.3-19	$a = \beta_1 c$ where: $\beta_1 = 0.97 - 0.0025f'_c$ but not less than 0.67 [Section 10.1.7(c)]

Appendix II. (*Continued.*)

Specification	Standard	Clause
	EN 1992-1-1	$y = \lambda x$ where: $\lambda = 0.8$ for $f_{ck} \leq 50$ MPa $\lambda = 0.8 - (f_{ck} - 50)/400$ for 50 MPa < $f_{ck} \leq 90$ MPa (Section 3.1.7)
	IS 456	Area of stress block: $0.36 f_{ck} x_u$ (Section 38.1c)

Appendix III. Compression Reinforcement

Specification	Standard	Clause
Minimum compression reinforcement	ACI 318-19	$0.01\,Ag$ (Section 10.6.1.1)
	CSA A23.3-19	$0.01\,Ag$ (Section 10.9.1)
	EN 1992-1-1	Greater of: $\frac{0.1N_{Ed}}{f_{yd}}$ or $0.002\,A_c$Section 9.5.2(2)
	IS 456	$0.008\,A_g$ (Section 26.5.3.1)
Maximum compression reinforcement	ACI 318-19	$0.08\,A_g$ (Section 10.6.1.1)
	CSA A23.3-19	$0.08\,A_g$ (Section 10.9.2)
	EN 1992-1-1	$0.04\,A_c$ Outside lap locations $0.08\,A_c$ at lap locations (Section 9.5.2(2))
	IS 456	$0.06\,A_g$ (26.5.3.1)
Number of reinforcement bars	ACI 318-19	No clause in code
	CSA A23.3-19	No clause in code
	EN 1992-1-1	Rectangular ≥ 4 Circular ≥ 6 (Section 26.5.3.1)
	IS 456	
Minimum diameter of reinforcement bars	ACI 318-19	No clause in code
	CSA A23.3-19	No clause in code
	EN 1992-1-1	
	IS 456	$\varphi \geq 8$ mm
Clear spacing between bars	ACI 318-19	Greatest of • 2.54 cm • $1.5\,d_b$ • $\frac{4}{3}\,d_{agg}$ Section 25.2.3
	CSA A23.3-19	Greatest of • $1.4\,d_b$ • 1.4 times size of max aggregate • 30 mm (Section 6.6.5.2 Annex A)
	EN 1992-1-1	Should not be less than the maximum of: • $k_1 \times$ bar diameter • ($d_g + k_2$ mm) or • 20 mm Recommended values of k_1 and k_2 are 1 and 5 mm, respectively [Section 8.2 (2)]
	IS 456	Greatest of • 1.5 cm • 2/3 of maximum size of aggregate; • Maximum bar diameter (Section 26.3.2)

Appendix IV. Notations and Definitions by Standard

Symbol	Standard	Description
a	ACI 318-19 CSA A23.3-19	Depth of equivalent rectangular stress block

Appendix IV. (*Continued.*)

Symbol	Standard	Description
A_g	ACI 318-19	Gross area of concrete section
	CSA A23.3-19	Gross area of section
	IS 456	
	EN 1992-1-1	
A_c	IS 456	Area of concrete
	EN 1992-1-1	Cross-sectional area of concrete
A_{st}	ACI 318-19	Total area of non-prestressed longitudinal reinforcement including bars or steel shapes, and excluding prestressing reinforcement
	CSA A23.3-19	Total area of longitudinal reinforcement
	EN 1992-1-1	Area of longitudinal reinforcement for columns
A_{sc}	IS 456	Area of longitudinal reinforcement for columns
b	ACI 318-19	Width of compression face of member
	IS 456	Breadth of beam or shorter dimension of rectangular column
	EN 1992-1-1	Overall width of a cross section, or actual flange width in a T or L beam
c	ACI 318-19	Distance from extreme compression fiber to neutral axis
	CSA A23.3-19	
D	IS 456	Overall depth of beam or slab or diameter of column; dimension of a rectangular column in the direction under consideration
d_{agg}	ACI 318-19	Nominal maximum size of coarse aggregate
d_g	EN 1992-1-1	Maximum size of aggregate
d_b	ACI 318-19	Nominal diameter of bar, wire, or prestressing strand
	CSA A23.3-19	Diameter of bar, wire, or prestressing strand
E_c	ACI 318-19	Modulus of elasticity of concrete
	CSA A23.3-19	
	IS 456	
E_{cm}	EN 1992-1-1	Secant modulus of elasticity of concrete
f'_c	ACI 318-19	Specified compressive strength of concrete
	CSA A23.3-19	
f_{ck}	IS 456	Characteristic cube compressive strength of concrete
	EN 1992-1-1	Character compressive cylinder strength of concrete at 28 days
f_{cm}	EN 1992-1-1	Mean value of concrete cylinder compressive strength
f_{sc}	IS 456	Compressive stress in steel corresponding to a strain of 0.002 (BIS 1980)
f_y	ACI 318-19	Specified yield strength for non-prestressed reinforcement
	CSA A23.3-19	Specified yield strength of non-prestressed reinforcement or anchor steel
	IS 456	Characteristic strength of steel
	EN 1992-1-1	Yield strength of reinforcement
f_{yt}	ACI 318-19	Specified yield strength of transverse reinforcement
	CSA A23.3-19	
f_{yd}	EN 1992-1-1	Design yield strength of reinforcement
f_{yk}	EN 1992-1-1	Characteristic yield strength of reinforcement
h	ACI 318-19	Overall thickness, height, or depth of member
	CSA A23.3-19	Overall thickness or height of member (mm)
	EN 1992-1-1	Height
k_1	EN 1992-1-1	Coefficient; factor
k_2	EN 1992-1-1	Coefficient; factor
M_n	ACI 318-19	Nominal flexural strength at section
M_r	CSA A23.3-19	Factored moment resistance
M_u	IS 456	Moment on the member
M	EN 1992-1-1	Bending moment
N	EN 1992-1-1	Axial force
N_{Ed}	EN 1992-1-1	Design value of the applied axial force (tension or compression)
ϕ	ACI 318-19	Strength reduction factor
ϕ_c	CSA A23.3-19	Resistance factor for concrete
ϕ_s	CSA A23.3-19	Resistance factor for non-prestressed reinforcing bars
P_n	ACI 318-19	Nominal axial compressive strength of member
P_o	ACI 318-19	Nominal axial strength at zero eccentricity
	CSA A23.3-19	Nominal axial resistance at zero eccentricity
P_u	ACI 318-19	Factored axial force; to be taken as positive for compression and negative for tension
	IS 456	Axial load on compression member
P_r	CSA A23.3-19	Factored axial load resistance of wall
x_u	IS 456	Depth of neutral axis
x	EN 1992-1-1	Neutral axis depth
α_1	CSA A23.3-19	Ratio of average stress in rectangular compression block to the specified concrete strength
α_{cc}	EN 1992-1-1	Coefficient taking account of long term effects on the tensile strength and of unfavorable effects, resulting from the way load is applied

Appendix IV. (*Continued.*)

Symbol	Standard	Description
β_1	ACI 318-19	Factor relating depth of equivalent rectangular compressive stress block to depth of neutral axis
	CSA A23.3-19	Ratio of depth of rectangular compression block to depth to the neutral axis
Υ_c	EN 1992-1-1	Partial factor for concrete
Υ_s	IS 456	Partial safety factor for steel
	EN 1992-1-1	Partial factor for steel
ρ	ACI 318-19	Ratio of As to bd
	CSA A23.3-19	Ratio of non-prestressed tension reinforcement, equal to As/bd
	IS 456	Reinforcement ratio
η	EN 1992-1-1	Factor defining the effective strength of the compression zone
λ	EN 1992-1-1	Factor defining the effective height of compression zone
ρ_t	CSA A23.3-19	Ratio of total area of reinforcing steel to gross concrete section

Data Availability Statement

The data used in the analysis will be available upon request from the authors.

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