Behavior of Short Reinforced Concrete Columns with Varying Tie Spacing and Concrete Grades Under Compression

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ABSTRACT

The strength and stiffness of a rectangular reinforced concrete (RC) column improves owing to rectangular ties. Concrete presses lateral ties of an RC column under compression when it experiences an axial force. The resistance offered by lateral ties prohibits the expansion of the concrete core. Hairline cracks get propagated along longitudinal steel bars in column corners with the increment in the axial load. Spalling of concrete takes place as soon as the longitudinal bars undergo yielding. The column resists load even after spalling due to confinement by ties. No sooner does the axial load reach its limiting value than buckling of longitudinal bars takes place resulting in opening of the hook of ties. The response of confined concrete is a function of strength and stiffness. The increment in these parameters is due to different parameters of confinement. However, there is no direct correlation of different parameters to assess the mechanical performance of confined concrete, such as the confinement spacing of ties and the compressive strength of concrete. The short columns with dimensions 150x150x300mm are under consideration in this work. The rectangular ties are spaced at 50mm and 75mm. The response of short columns is studied in relation to concrete grade, amount of steel bars provided and equispaced rectangular ties for the evaluation of modulus of elasticity.

1. INTRODUCTION

1.1 Background

Precise estimation of modulus of elasticity of Reinforced Concrete (RC) columns is a very difficult task owing to its complex nature. The material complexity of RC columns is due to concrete which consists of cement, sand, aggregate and water mixed together in designed proportions and also provided with steel reinforcement bars. When a short RC column is subjected to axial loading, it resists the load as per the grade of concrete (f_{ck}), amount of compression reinforcement (A_{sc}) provided in columns and also the spacing of rectangular ties adopted.

The axial load carrying capacity of plain concrete columns is relatively of lower magnitude compared to an RC column on account of reinforcement provided. The analysis carried out in any finite element (FE) based software demands Modulus of Elasticity (E) of each material separately, namely concrete and steel. IS:456-2000 [1] has provided E of plain concrete as $5000\sqrt{f_{ck}}$ which is a function of characteristic compressive strength of concrete at 28 days of curing. In FE analysis, material is assumed to be homogeneous, elastic and isotropic. However, actually there are two different materials with different characteristics and material properties. In order to stick to the

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assumption of homogeneity of material, it is necessary to evaluate E of reinforced concrete material (E_{RCC}) used in columns. Various researchers [2-5] in the past have carried out detailed analytical studies on RC columns to propose empirical relations for evaluating the load carrying capacity. The authors compared the results with contemporary literature and justified individual research studies. The research work was also carried out [6] considering stress-strain non-linearity of concrete material as well as steel.

1.2 Current International Scenario

According to IS: 456-2000 [1], modulus of elasticity of plain concrete section is only considered. Numerous researchers have carried out analytical study on this issue.

For columns subjected to short-term loads, the flexural rigidity according to current ACI [7] expressions (1 and 2) is expressed as follows-

$$EI = 0.2E_cI_g + E_sI_{se}/(1+\beta_d) \tag{1}$$

$$EI = 0.4E_cI_g/(1+\beta_d) \tag{2}$$

where β_d = ratio of the maximum factored dead load, also known as sustained load, to the maximum total factored load. It is always positive, although for short-term loads, it is zero. So, simple form of this equation is according to equation (3):

$$EI = \alpha E_cI_g + E_sI_{se} \tag{3}$$

where I_g is the moment of inertia of the gross concrete section around the centroidal axis, E_s is the modulus of elasticity of steel, I_{se} is the moment of inertia of steel about the centroidal axis of the cross-section, and α is the stiffness reduction factor.

An examination of the literature reveals that numerous researchers have suggested formulations for strength and stiffness of columns as well as beams. Few investigators have proposed expressions for effective moment of inertia. The modulus of rupture should be expressed as suggested by ACI code [7]

$$f_r = 7.5\sqrt{f_c'} \tag{4}$$

where Concrete's mean compressive strength in ksi is denoted by fc'.

Eurocode [8] represents modulus of rupture (5) as

$$f_r = ma\left[f_{ctm}, \left(1.6 - \frac{h}{1000}\right), f_{ctm}\right] \tag{5}$$

f_{ctm}= concrete's average axial tensile strength.

In accordance with IS:456-2000 [1], concrete's modulus of rupture is determined by

$$f_r = 0.7\sqrt{f_{ck}} \tag{6}$$

where f_{ck} is the concrete's characteristic compressive strength, expressed in N/mm^2. Evaluation of cracking moments is done using these equations.

Internationally, following are the equations (7, 8, 9 and 10) for estimation of modulus of elasticity of concrete.

$$E_c = 4700\sqrt{f_{ck}} \text{ (ACI Code) [7]} \tag{7}$$

$$E_c = 22[(f_{cm})/10]^{0.3} \text{ (Euro Code) [8]} \tag{8}$$

$$E_c = K_0 + 0.2f_{cu} \text{ (BS Code) [9]} \tag{9}$$

$$E_c = \left(\frac{720-T}{670}\right) \times 100 \quad \text{(Australian Code) [10]} \qquad (10)$$

It is evident from equations (1) to (10) that almost all codal provisions remain silent about modulus of elasticity of RC material.

1.3 Objectives:

The prime aim was to estimate the modulus of elasticity of RC columns with varying the spacing of ties. The objectives of the study are as below:

- To study the pre and post-cracking behaviour of RC columns
- To propose an empirical equation of modulus of elasticity of RC columns dependent on percentage of steel (p_t) and grade of concrete (f_{ck})
- To study the effect of rectangular ties on the performance of RC columns under axial loading

2. *METHODOLOGY*

2.1 Selection of Reinforcement

In order to precisely estimate the modulus of elasticity of RC columns [11-13], finite element modelling of RC columns was carried out. The short columns with dimensions 150x150x300mm were under consideration in this work. The models were provided with equispaced rectangular ties spaced at 50mm and 75mm. The minimum reinforcement in a column as per IS: 456-2000 [1] ranges from 0.8% to 6% of gross area of concrete. However, in order to facilitate ease of compaction, maximum reinforcement in columns is restricted to 4% of gross area of concrete. The percentage of steel for selected cross-section is as shown in Table 1 below.

Table 1. Models in axial compression with varying percentage of steel.

Model No.	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7
Reinforcement	Plain	4-8mm Φ	4- 10mm Φ	4-10mm Φ + 2-8mm Φ	4-12mm Φ	4-12mm Φ + 2-10mm Φ	4-16mm Φ
Percentage of Steel	0.00	0.894	1.39	1.84	2.01	2.71	3.57

2.2 Finite Element Model of RC Columns

The finite element model of a RC column is a challenging task owing to complex nature of the specimen. For accurate prediction of such a model, there is no alternative however. Concrete part is modelled using SOLID65 element due to its brittle nature as shown in Figure 1 and steel bars are modelled using LINK8 elements. The element size adopted for meshing concrete was 7. This size was arrived at by trial and error which resulted in a better convergence and reliable results. It was ensured that the reinforcement bars and stirrups in the model were part of concrete material [14-16]. The nodes on reinforcement bars and concrete material were coincident and the bond between concrete and steel was formed through this. There was no violation of element shapes in the model. Non-linear characteristics of concrete material are incorporated using stress-strain values from standard literature [11-13]. For steel bars, bilinear behaviour is adopted from idealized stress-strain curve. The grades of concrete selected in the present study are M20, M25 and M30.

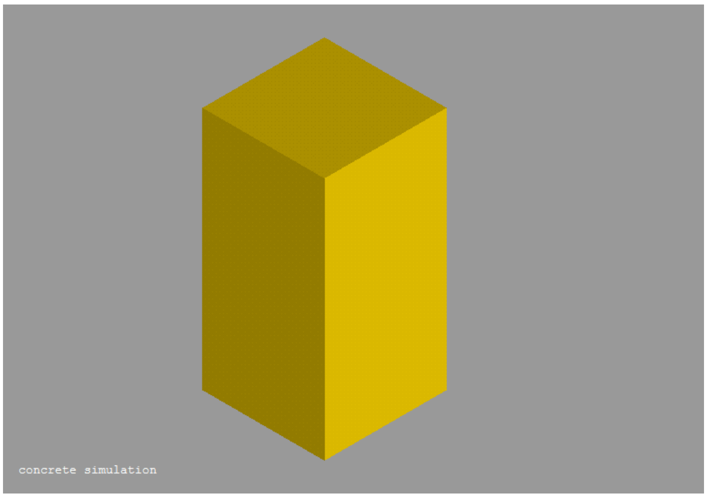

Figure 1. Finite element model of column specimen

3. *RESULTS AND DISCUSSION*

The modulus of elasticity for RC columns was evaluated for three grades of concrete namely M20, M25 and M30. The reinforcement of grade Fe 415 was selected in these models as per Table 1. Also, the spacing of rectangular ties selected was 50mm and 75mm in this study. The results for these models are discussed in subsequent sections below.

3.1 RC Column Models of M20 Concrete Grade

The response for a PCC specimen of M20 concrete grade is shown in Figure 2. First crack was induced in the specimen at a load of 355.24 kN and it failed due to crushing at 397.14 kN. The consistent deformation at first crack was 0.23mm. The first crack load and corresponding deflection was extracted from FE model of RC column. The calculation of modulus of elasticity for the specimen is shown in equation (11).

$E_{RCC} = \left(\frac{Stress}{Strain}\right)$, Stress= (First crack load/Area of Cross-section), Strain= (First crack deflection/Original length of specimen)

$$E_{RCC} = \left(\frac{15.68}{0.0007}\right) = 22402.54 N/mm^2 \tag{11}$$

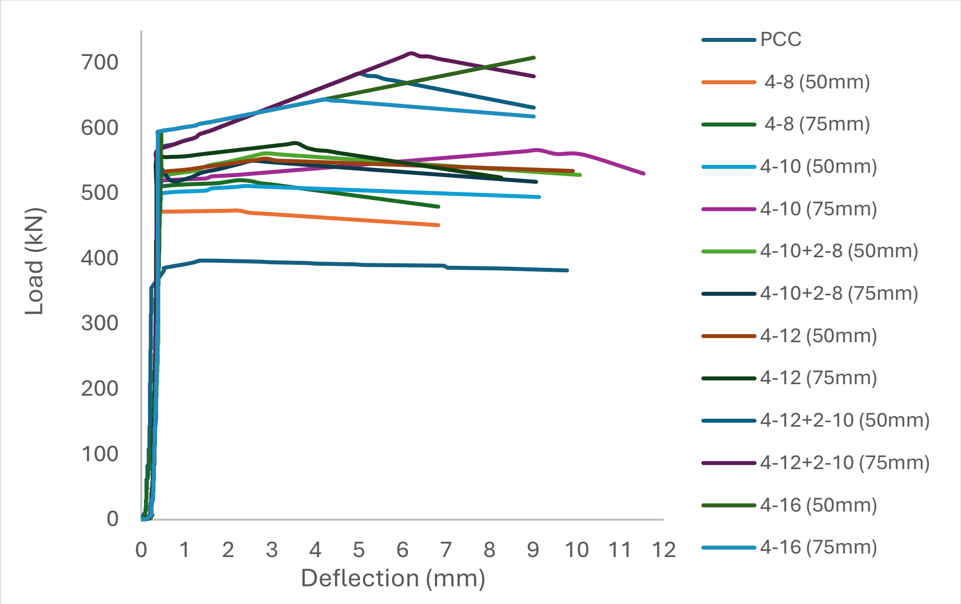

Figure 2. Response of FE Models for M20 Concrete (50mm & 75mm spacing)

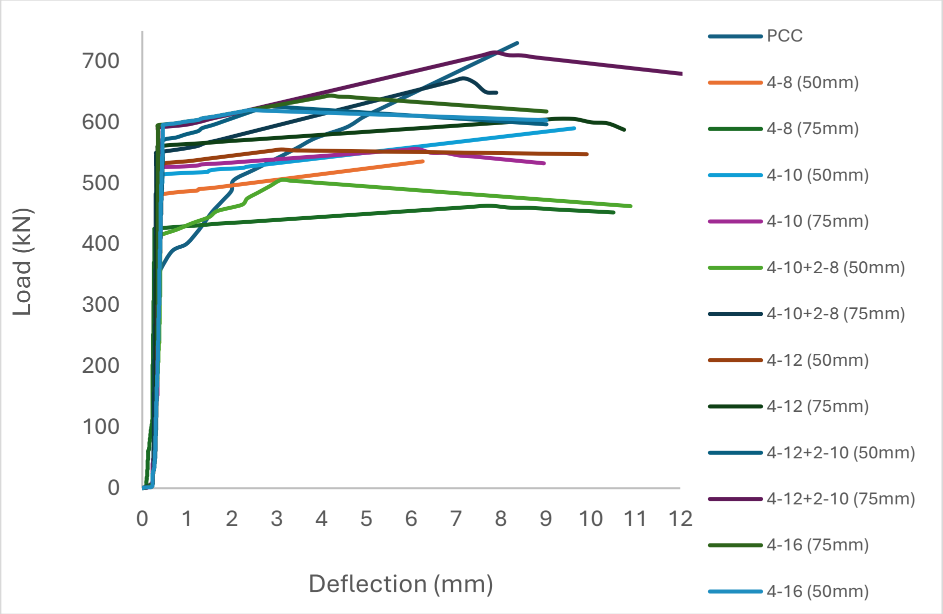

Figure 3. Response of FE Models for M25 Concrete (50mm & 75mm spacing)

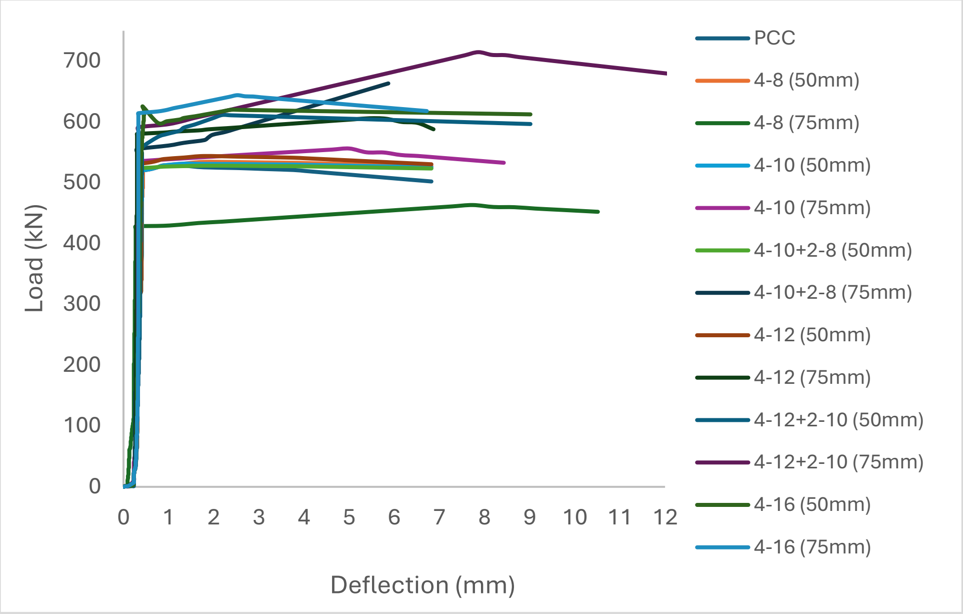

Figure 4. Response of FE Models for M30 Concrete (50mm & 75mm spacing)

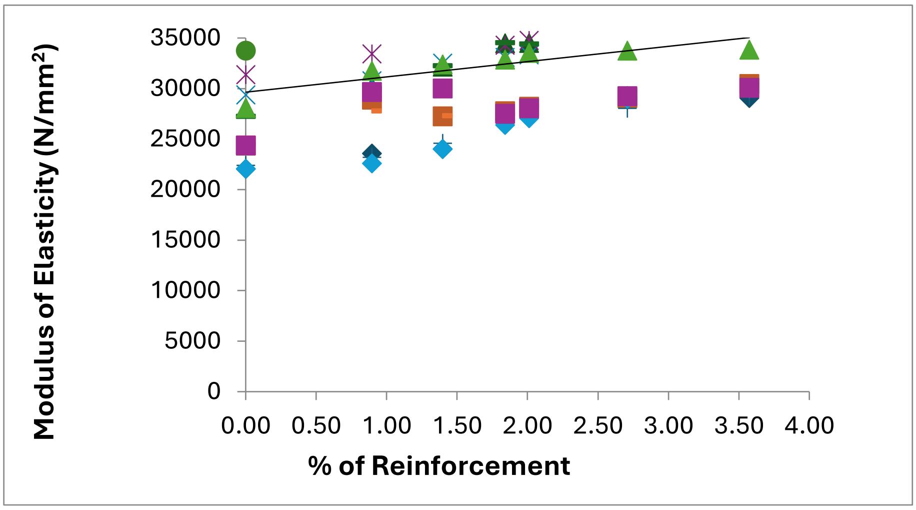

Figure 5. Elasticity Modulus for RCC Columns in All Grades

Figures 2, 3 and 4 represent load-deflection response of all the models as per Table (1). The effect of reinforcement increments and spacing of ties is clearly observed from the variation. The response of each specimen for different stages of loading i.e. first crack, yielding and failure stage is shown in Table 2 below. First crack load and corresponding deflection values from Table 2 for each model were used for evaluation of modulus of elasticity as per equation (11).

Table 2. Load and deformation for Columns at different loading stages

Model No.	Concrete Grade	Spacing of Ties (mm)	First Crack Load (kN)	Deflection (mm)	Yield Load (kN)	Deflection (mm)	Failure Load (kN)	Deflection (mm)	Modulus of Elasticity (N/mm^2)
Model 1	M20	---	355.24	0.23	392.55	1.08	397.14	1.37	22402.54
	M25	---	352.28	0.39	418.82	1.21	730.20	8.36	24552.78
	M30	---	519.88	0.43	528.00	1.34	502.16	6.82	27260.74
Model 2	M20	50	472.18	0.47	472.97	1.47	473.78	2.23	23582.02
	M25		481.82	0.43	488.33	1.23	536.10	6.26	27809.86
	M30		519.88	0.43	531.49	1.34	527.27	6.82	30016.19
	M20	75	510.35	0.39	517.94	1.98	520.21	2.23	23034.79
	M25		425.63	0.27	431.57	1.34	452.33	10.51	26952.70
	M30		428.36	0.37	43.57	1.34	452.33	10.51	31647.04
Model 3	M20	50	500.29	0.47	509.63	2.10	511.43	2.41	24019.18
	M25		514.39	0.45	518.73	1.45	590.38	9.63	27322.00
	M30		519.88	0.41	531.49	1.34	525.45	6.82	32255.87
	M20	75	519.28	0.40	526.18	1.62	566.37	9.14	24281.42
	M25		526.31	0.39	529.53	1.25	532.92	8.96	25923.95
	M30		535.34	0.34	539.58	1.22	532.92	8.43	32363.03
Model 4	M20	50	525.78	0.46	547.98	1.96	561.30	2.83	26947.54
	M25		414.33	0.40	434.59	1.11	462.65	11.89	27481.89
	M30		524.28	0.41	527.40	1.34	523.50	6.82	34564.00
	M20	75	545.31	0.36	537.02	1.76	550.07	2.55	26791.78
	M25		550.36	0.31	561.30	1.23	648.77	7.90	27022.63
	M30		555.36	0.30	565.74	1.34	648.77	6.87	32843.56
Model 5	M20	50	531.76	0.46	544.78	1.93	553.47	2.87	27727.57
	M25		531.76	0.45	538.27	1.23	547.79	9.92	28248.36
	M30		531.47	0.41	541.49	1.34	530.5	6.82	34422.67
	M20	75	553.14	0.35	562.47	1.69	577.03	3.57	27404.84

	M25		560.34	0.34	566.11	1.36	588.00	10.75	28136.60
	M30		580.35	0.30	586.13	1.66	588.00	6.87	34324.44
Model 6	M20	50	570.00	0.47	606.25	1.98	683.80	5.00	29270.99
	M25		570.00	0.46	585.57	1.24	596.88	9.02	29123.08
	M30		558.24	0.41	590.74	1.34	596.64	9.02	35370.79
	M20	75	565.27	0.36	601.08	1.78	701.77	7.21	29383.82
	M25		591.35	0.36	601.08	1.29	679.50	12.06	29146.91
	M30		591.35	0.33	606.25	1.55	679.50	12.06	33487.94
Model 7	M20	50	595.96	0.47	614.66	1.98	692.13	7.81	30497.91
	M25		595.96	0.46	603.98	1.24	603.54	9.02	30454.55
	M30		625.35	0.43	606.65	1.34	612.55	9.02	36130.43
	M20	75	594.69	0.38	611.99	1.78	641.89	4.60	29061.98
	M25		595.35	0.35	603.98	1.24	617.94	9.02	30473.08
	M30		614.39	0.33	628.02	1.47	617.94	6.72	34795.18

The finite element models of RC columns have been analyzed thoroughly which were subjected to axial loading. The columns were provided with variable reinforcement and equispaced rectangular ties as per IS: 456-2000 [1]. It is established that the variation in E_{RCC} is approximately ±5%. It is witnessed that spacing of rectangular ties is not predominant in E_{RCC} for columns. Therefore, a single equation for E_{RCC} is arrived at. The suggested relation (12) is expressed using regression analysis shown in Figure 5.

$$E_{RCC} = 2000p_t + 5000\sqrt{f_{ck}} \tag{12}$$

The comparison of present research work with similar studies in recent past studies may ensure the validity of the work and can be generalized. The research work carried out by Wang et. al [17], Sirimontree et. al. [18] and Almomani et. al. [19] has been considered for the same. The authors have considered different additives in normal RC columns like basalt fibers, steel angle sections and GFRP bars respectively. The research work was also carried out on normal RC sections as shown in table 3. The estimation of the modulus of elasticity for these sections is undertaken and compared with the present research methodology. Wang et. al [17] carried out work for M30 grade of concrete columns of size 150mm x 150mm x 550mm with 2.41% of reinforcement in the section. The stress-strain values from the curve presented in research work yield modulus of elasticity of section as 22222.22 N/mm^2 whereas this value as per equation (12) estimates as 27434.32 N/mm^2. This value underestimates the value as per the current research work which may lead to erroneous results. Sirimontree et. al. [18] studied columns of size 150mm x 150mm x 1200mm with 2.32% of reinforcement. The values estimated according to curves from this research work are in good agreement with the present research work with an error of 2.1%. The percentage of reinforcement in both the studies [18 and 19] differ for the same section owing to different concrete cover provided to the reinforcement. Almomani et. al. [19] studied response of M35 grade concrete columns of size 205mm x 306mm x 1020mm with 0.99% of reinforcement. The effect of concrete grade and percentage of reinforcement does not contribute to reach expected modulus of elasticity of the section. The column section in this research is supposed to have modulus of elasticity of 29600.77 N/mm^2 whereas the same value as per the curve in the research work amounts to 21578.77 N/mm^2 only. This enhanced value is due to additional GFRP bars used in concrete mix to enhance the load carrying capacity of the column member. It can be observed that the past researchers have lacked in a consistent approach in evaluating the modulus of elasticity of column sections to a certain extent. It justifies the experimental work undertaken to arrive at an empirical equation (12) for the same.

Table 3. Modulus of Elasticity of Columns from Past Studies

Research work & Concrete Grade fck (N/mm^2)		Cross-Section (mm x mm) & Height (mm)	Asc (mm^2) & pt (%)	Stress (N/mm^2)	Strain	Modulus of Elasticity (N/mm^2)
Wang et. al [17] & M30		150x150 & 550	4#12 & 2.41	22.2222	0.00100	22222.22
Equation (12)		-	-	-	-	27434.32
Sirimontree et. al. [18] & M23	CC1	150x150 & 1200	4#12 & 2.32	23.1111	0.00083	27733.33
	CC2	150x150 & 1200	4#12 & 2.32	24.0000	0.00092	26181.82
Equation (12)		-	-	-	-	24026.90
Almomani et. al. [19] & M35		205x306 & 1020	6#11 & 0.99	23.7366	0.00100	21578.77
Equation (12)		-	-	-	-	29600.77
Present Work & M20		150x150 & 300	4#12 & 2.01	23.5400	0.00090	27161.88

4. *CONCLUSIONS*

Suggested relation (12) for E_{RCC} in terms of f_{ck} and p_t for columns offers reasonable evaluation. In structural analysis, if E_{RCC} is incorporated instead of E_{PCC}, deformations along with bending moments observed shall be on lower side. Based on the analytical work and comparison with literature, it can be concluded that estimated modulus of elasticity is in close agreement for columns with reinforcement range mentioned with

± 1.3% error. Elastic deformations in FE models for reinforced columns were found less compared to that of plain concrete columns by about 15%. It is also to be observed that the effect of tie spacing in short columns does not play a significant role in case of variation in E_{RCC}. Economy in steel can be achieved using this approach against conventional approach. In framed structures, lateral forces in the form of earthquake and wind may exhibit reversal of bending for columns. The effect of reinforcement on long columns in this case needs to be studied for further understanding of E_{RCC} of columns.

CONFLICT OF INTEREST

The authors declare no conflicts of interest related to this research.

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