Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 45 No. 1 (2024)

Studies on Deflections of Reinforced Concrete Beams

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Abstract

In engineering structures that are susceptible to service loads, deflection is an essential design parameter. Many studies were conducted to compute the effects of short-term and long-term deflection in reinforced concrete beams with different parameters. Many of the researchers recommended the procedures and control of the deflection in various methods. From those approaches, here the present study was conducted with different methods which are proposed by Branson (1965), Bischoff and Scanlon (2007), and ACI 318, IS 456 different codes also given the expressions to compute the effective moment of inertia for compare the deflection estimates from those methods and to calculate the deflection values of reinforced concrete beams.
Furthermore, the study was conducted with two different type conditions i.e., change in depth and depth in constant by designed and practical assumption cases with three different conditions of reinforcement have been investigated in each of the three different beam dimensions. One-third of the beam had only tensile steel i.e., No compression steel, one-third had tensile plus and the same amount of compressive steel i.e., Half compression steel, and one-third had tensile steel plus one-half as much compressive steel i.e., Full compression steel. A comparative analysis was carried out for analytical and numerical studies.

Keywords: Reinforced concrete beams, Deflection, Depth, Effective moment of inertia, Finite element analysis, Compressive reinforcement.

1. Introduction

Infrastructure development initiatives benefited greatly from the use of reinforced concrete structures. Structures made of reinforced concrete are vulnerable to a variety of functional and structural challenges due to different factors i.e., overloading, deformation, exposure to environmental changes and cracking, corrosion of steel reinforcement, and long-term effects (Parikshit Hurukadli et al., 2023). Often, poorly maintained buildings will experience distress in a shorter span, which reduces the building's economic period. Developing nations have seen functionally abandoned failed structures and reasonable functioning structures throughout time. When compared to rich nations, the economic lifeline of reinforced concrete structures in developing nations is significantly lower.

Independent of the constructing material most of the structures experience deflections due to various loading conditions. Deflections in reinforced concrete members will rise over some time as a result of this it impacts concrete creep and shrinkage. A member may experience structural collapse as a result of excessive deflections. The probability of damage to adjacent structural members and elements with apparent deflections that are not aesthetically pleasing to the occupants and building owners are the most frequent difficulties (Al-Tarafany et al., 2022). While designing a member the designer's objective is to minimize deflections to avoid these kinds of serviceability challenges.

Deflection in beams is the representation of the deformation of the structure from its original unloaded position. In many different types of engineering structures beams are widely used. Therefore, it is important to know how to predict the deflection in beams with different types of load combinations and the loads applied to them (Mohamed et al., 2008). It is very important to limit the deflection in beams it may cause damage to other parts of the structures with too much deflection. If the beam is allowed to deflect excessively, it will not meet the requirements for serviceability. Despite the minimal and safe stresses acting within the beam, the structure will not fulfill the intended purpose of construction.

A serviceability limit describes the point at which certain service requirements arising from the intended use are no longer satisfied, and it specifies the performance standard for serviceability (Patel et al., 2015). When it comes to limit state design, a structure is considered to be unserviceable if the conditions of the limit state of serviceability are not fulfilled with the necessary dependability and over the designated service life (Anusha Gullapalli et al., 2009).

2. Methods and materials

The deflections of reinforced concrete beams were calculated as the sum of the short-term and long-term deflection. The short-term deflections, which occur instantly when a load is applied to a structure, may be calculated by usual methods for elastic deflections using the short-term modulus of elasticity of concrete (E_c) and effective moment of inertia (Ie).

The time-dependent effects of concrete creep and shrinkage are the cause of the long-term deflection of reinforced concrete members under sustained stresses (A. Fuzail Hashmi et al., 2020). The inherent material properties of creep and shrinkage are heavily impacted by the design of the concrete mix as well as the surrounding environmental factors. These long-term deflections are computed by applying a multiplier to short-term deflection using empirical methods by ACI 318-19, IS 456:2000, CSA A23.3-14, proposed by Branson 1965 and other researchers. Thus, it is necessary to reevaluate the existing provisions and recommendations for calculating the short-term deflections. Branson’s (1965), Bischoff and Scanlon (2007) methods are strongly dependent on short-term deflection.

The present study was conducted on short-term deflection by using the existing methods available in the literature and codes. When a simply supported beam is subjected to a uniformly distributed load of intensity w per unit run, the short-term deflection of the beam in the elastic condition is given by,

$$\Delta = \frac{5}{384}\frac{wl^4}{E_c I_{eff}} \qquad \text{------------------------1}$$

The value of the effective moment of inertia recommended by the codes and the other researchers is explained in the following section.

2.1 Effective Moment of Inertia

The effective moment of inertia is a concept used to account for the non-uniform distribution of material in a cross-section. When a load is applied to a concrete member it experiences the crack pattern on increasing the load (Akmal Uddin et al., 2011). The concrete under the cracked portion of a tension zone will lose its resistance capacity even though the reinforcement section can resist the moments and forces. Thus, an effective moment of inertia helps in accurately predicting the short-term deflection of cracked flexural members.

a. IS:456 2000 Code Recommendation:

The Indian Standard (IS) 456 Code recommends the usual method of elastic deflections using the short-term modulus of elasticity of concrete (E_c) and an effective moment of inertia (I_{eff}) given by the following equation.

$$I_{eff} = \frac{I_r}{1.2 - \frac{M_r}{M}\frac{z}{d}\left(1-\frac{x}{d}\right)\frac{b_w}{b}} \qquad \text{------------------------2}$$

Where $I_r \le I_{eff} \le I_{gr}$

$$M_r = \frac{f_{cr} I_{gr}}{y_t} \qquad \text{--------------------------3}$$

Where M_r = cracked moment and M = maximum moment under service load

Whereas all other parameters are taken as per the code recommendations.

b. ACI 318-19 Recommendation:

As per ACI 318-19 the effective moment of inertia (I_{eff}), shall be calculated under Table 24.2.3.5 given below based on the service bending moment (M_a).

$$If, M_a \leq \frac{2}{3} M_{cr}, I_{eff} = I_g$$

$$If, M_a \rangle \frac{2}{3} M_{cr}, I_{eff} = \frac{I_{cr}}{1 - \left(\frac{(2/3) M_{cr}}{M_a} \right)^2 \left(1 - \frac{I_{cr}}{I_g} \right)} \qquad \text{------------------------4}$$

Where M_{cr} = cracked moment and M_a = maximum moment under service load and all other parameters are taken as per the recommendation of the code ACI 318-19.

c. Branson's (1965) Equation:

Branson's expression for effective moment of inertia which averages the fully-cracked and uncracked moments of inertia of concrete beams is followed by ACI 318-14, 19 (ACI 2019), CSA A23. 3-14, AS 3600, TS 500 in the short-term deflection calculation. Based on the test results for simply supported rectangular reinforced concrete beams with reinforcement ratios ranging from 1% to 2%, this formula was empirically developed. The effective moment of inertia recommended by Branson (1965) is given below.

$$I_{eff} = \left(\frac{M_{cr}}{M_a} \right)^3 I_g + \left[1 - \left(\frac{M_{cr}}{M_a} \right)^3 \right] I_{cr} \qquad \text{----------------------------5}$$

d. Bischoff and Scanlon(2007) Equation:

Bischoff (2005) developed the following effective moment of inertia equation and provides a more appropriate application of the approach to the in-plane bending behavior of reinforced concrete beams. Bischoff and Scanlon (2007) explained the value of *m* = 2 assures that the tension-stiffening contribution in the model is only dependent on the applied load level.

$$I_{eff} = \frac{I_{cr}}{\left[1 - \left(\frac{M_{cr}}{M_a} \right)^m \left(1 - \frac{I_{cr}}{I_g} \right) \right]} \qquad \text{-----------------------------6}$$

Where $m = 2$,

All the parameters are taken in line with the other methods explained above.

As it is found in the literature the IS 456 and other international codes have adopted the modified version of the equation recommended for the effective moment of inertia. And for computing deflections of reinforced concrete beams are strongly dependent on the short-term deflection as per Branson's (1965), Bischoff and Scanlon (2007) methods (Ilker Kalkan et al., 2013). Hence the main focus of the study is confined to calculating the short-term deflections of the RC beams as per the equations explained above.

2.2. Design of Reinforced Concrete Beams

From the study, it is decided to analyze the beams with three different conditions of steel reinforcement in each of the different beam sizes. One-third of the beam had only tensile steel i.e., No compression steel, one-third had tensile plus and an equal amount of compressive steel i.e., Half compression steel, and one-third had tensile steel plus one-half as much compressive steel i.e., Full compression steel (Washa et al., 1952).

a. CASE I: Singly reinforced beam

- To design a singly reinforced beam, The length of the beam was assumed as 6m. M30 grade concrete and Fe415 steel are adopted. The sectional area of the beam is estimated from IS 456 as D= 500mm, d= 450mm with an effective cover(d') = 50mm, and the breadth of the beams as 200mm. And effective span is also calculated by keeping the given provisions as 6m.
- The loads on the beam are also determined by taking the imposed load as 16KN/m and the total load(w) is calculated as 18.5KN/m. The design load(w_u) on the beam is 27.75KN/m along with factored moment (M_u) due to loads is 124.875KN-m.

b. CASE II: Doubly reinforced beam with Half Compression Steel

Here in this case also, assuming the parameters for the design of a beam i.e., Doubly reinforced beam.

With Case I, the same geometric properties but by changing depth the doubly reinforced beam design is as follows,

- The length of the beam is assumed as 6m. M30 grade concrete and Fe415 steel are adopted. The cross-section of the beam is estimated from IS 456 as D= 300mm, effective depth (d)= 275mm with an effective cover(d') = 25mm, and breadth of the beams as 200mm. And effective span is also calculated by keeping the given provisions as 6m.
- The loads on the beam are also determined by taking the imposed load as 16KN/m and the total load(w) is calculated as 17.5KN/m. The design load(w_u) on the beam is 26.25 KN/m along with the factored moment (M_u) due to loads being 118.125 KN-m.

c. CASE III: Doubly reinforced beam with Full Compression Steel

Similar to Case II with the same properties but changing in depth the beam is designed as follows,

- The length of the beam is assumed as 6m. M30 grade concrete and Fe415 steel are adopted. The cross-section of the beam is estimated from IS 456 as D= 180mm, effective depth (d)= 155mm with an effective cover(d') = 25mm, and breadth of the beams as 200mm. And effective span is also calculated by keeping the given provisions as 6m.
- The loads on the beam are also determined by taking the imposed load as 16KN/m and the total load(w) is calculated as 16.9KN/m. The design load(w_u) on the beam is 25.35 KN/m along with factored moment (M_u) due to loads is 114.075KN-m.

d. Designed geometric properties of beams

Below Table 1 shows the designed geometrical properties of beams for the three different cases in TYPE-I. Changing the depth for which the obtained area of reinforcement is along with the diameter of steel and the number of bars required.

Table 1. Changing the depth

TYPE-I (Beams)	b (mm)	D (mm)	d (mm)	d'(mm)	No, & Dia of bar	A_{st}(mm^2)	No, & Dia of bar	A_{sc}(mm^2)
No Comp steel	200	500	457	43	3-20mm	942	0	0
Half Comp steel	200	300	275	25	5-20mm	1570	3-18mm	763
Full Comp steel	200	180	155	25	4-28mm	2463	4-28mm	2463

e. Practical assumptions in beams

For the analysis, here practically assuming the geometrical parameter for TYPE II. Depth is kept constant for three different cases by observing the above designed properties with the same loading conditions according to that only these practical cases were further analyzed. The practical assumptions are shown below in Table 2,

Table 2. Depth is constant.

TYPE-II (Beams)	b (mm)	D (mm)	d (mm)	d'(mm)	No & Dia of bar	A_{st}(mm^2)	No & Dia of bar	A_{sc}(mm^2)
No Comp steel	200	500	457	43	3-20mm	942	0	0
Half Comp steel	200	500	457	43	3-20mm	942	2-18mm	508
Full Comp steel	200	500	457	43	3-20mm	942	3-20mm	942

3. Modelling and analysis

For the designed and practical assumptions beam cases are further analyzed using the different effective moment of inertia expressions the deflections in the beams were determined by IS 456: 2000. The finite element analysis is done through ABAQUS software (Patel et al., 2015). Comparisons are made between the results of these numerical analyses and practical analyses.

The following are the steps taken while analyzing using FEM in ABAQUS,

1. Reinforced concrete designations for finite element analysis: The IS 456 is followed in the design of the RCC Beams.

2. RC beam modeling: The RC beam is modeled by the given dimensions.
3. The finite element method of analysis: It entails a step-by-step process that begins with modeling in ABAQUS and continues with assigning material and section properties, defining the type of interaction, meshing the model part by part, and applying loads.
4. Configuring the analysis and getting the outcomes: The beams' maximum deflection can be determined through the software.
5. Analysis of the results in comparison to the theoretical and validation: The software's maximum beam deflection is compared to the theoretical results.

The beams are modeled according to the following data in Fig 1 to Fig 6,

A rectangular reinforced concrete beam is simply supported with the required cross-section and all the beams of an effective span of 6m are reinforced with a diameter on tension and also with compression steel in required cases by effective cover and subjected to an imposed load and including self-weight of beams.

The deflection outcomes of RCC beams from ABAQUS software of Type-I. Changing the depth was presented below with three different cases as follows:

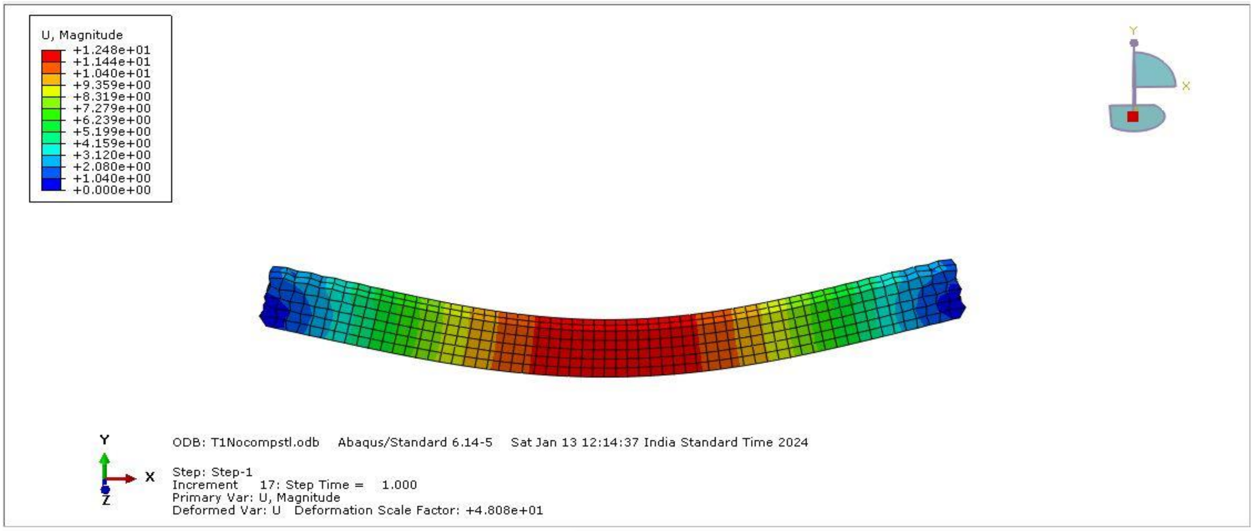

Fig 1. RCC beam model with no compression steel in change in depth

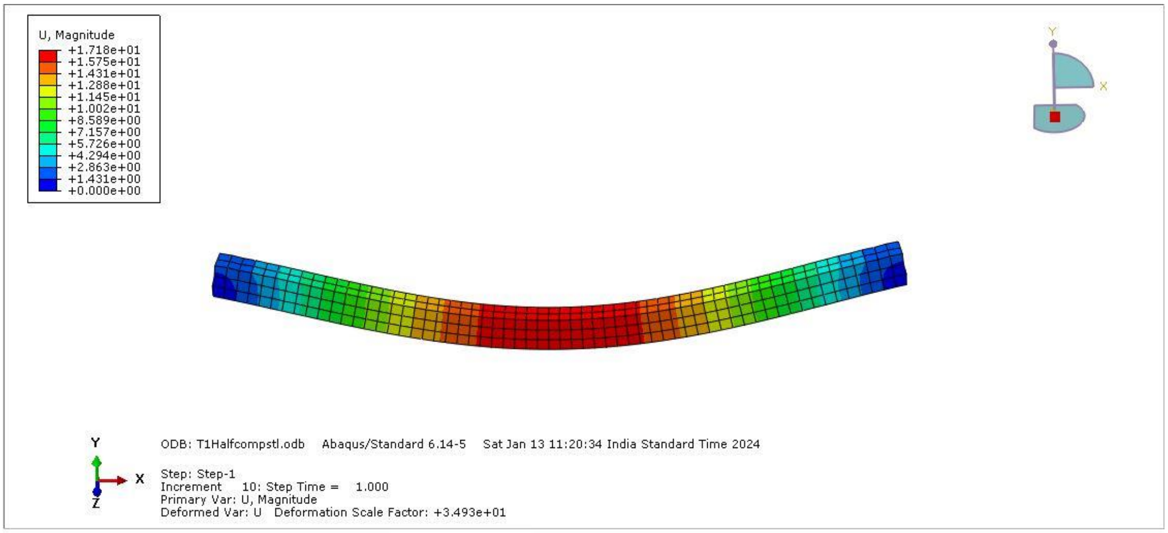

Fig 2. RCC beam model with half compression steel in change in depth

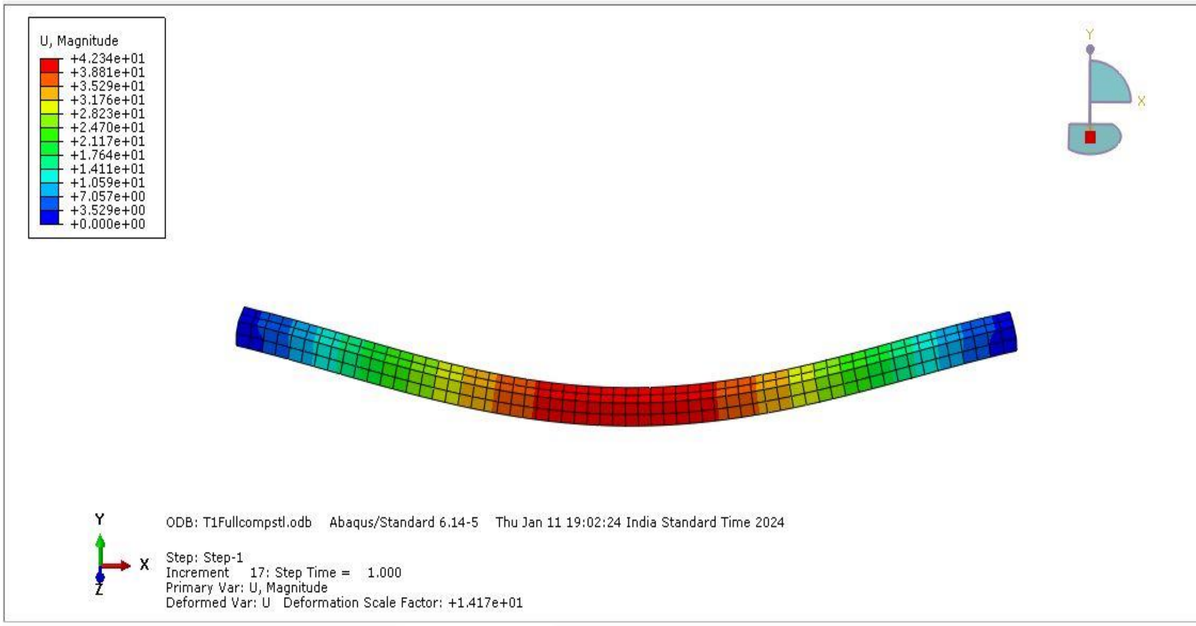

Fig 3. RCC beam model with full compression steel in change in depth

These are the deflection outcomes of RCC beams of Type-II. Depth is constant were shown below with the three different cases as follows:

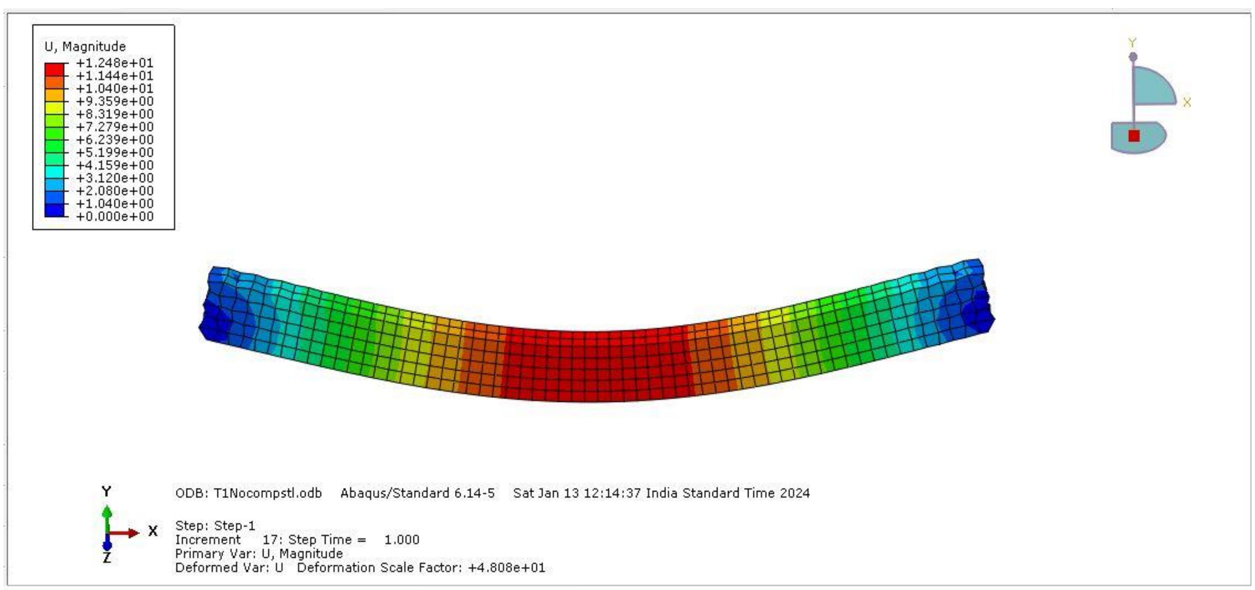

Fig 4. RCC beam model with no compression steel in depth is constant.

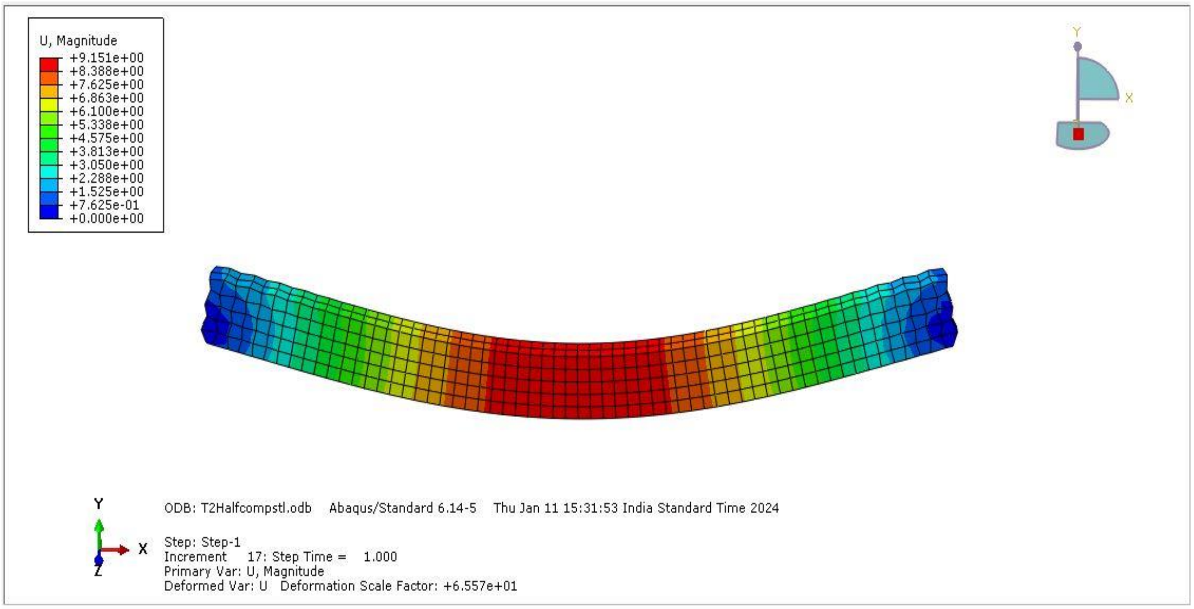

Fig 5. RCC beam model with half compression steel in depth is constant.

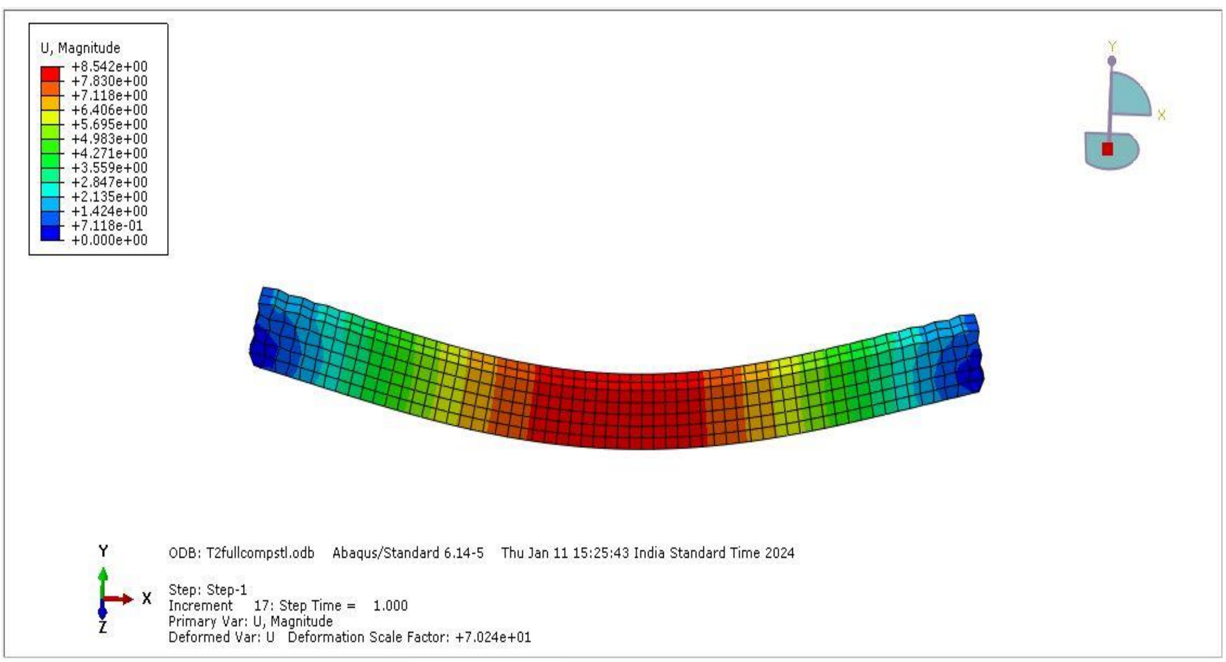

Fig 6. RCC beam model with full compression steel in depth is constant.

3.1 Numerical analysis deflection values from ABAQUS software

By using the modeling steps, the deflection values from the software and along with analytical by a different effective moment of inertia expressions for three cases are tabulated below,

Table 3. Numerical and analytical deflection values for changing the depth.

TYPE-I (Beams)	D(mm)	Δ=IS456(mm)	Δ=ACI(mm)	Δ=Bran's(mm)	Δ=Biss(mm)	Δ=Numerical (mm)
No Comp. steel	500	13.2	11.5	12.5	12.8	12.48
Half Comp. steel	300	21.9	19.8	19.39	19.39	17.18
Full Comp. steel	180	48.1	43.5	41.05	41.05	42.34

Table 4. Numerical and analytical deflection values for depth are constant.

TYPE-II (Beams)	D(mm)	Δ=IS456(mm)	Δ=ACI(mm)	Δ=Bran's(mm)	Δ=Biss(mm)	Δ=Numerical (mm)
No Comp. steel	500	13.2	11.5	12.5	12.8	12.48
Half Comp. steel	500	10.2	9.16	9.86	10	9.15
Full Comp. steel	500	9.7	8.7	9.48	9.5	8.54

The numerical and analytical calculations from IS 456 and ACI 318 codes, Branson's, and Bischoff's results i.e., deflections in RCC beams were compared and listed in Tables 3 and 4.

4. Results and discussions

The results obtained by the analytical and numerical analysis for three different conditions were compared with other parameters are graphically shown below,

Case (i): By Changing in depth

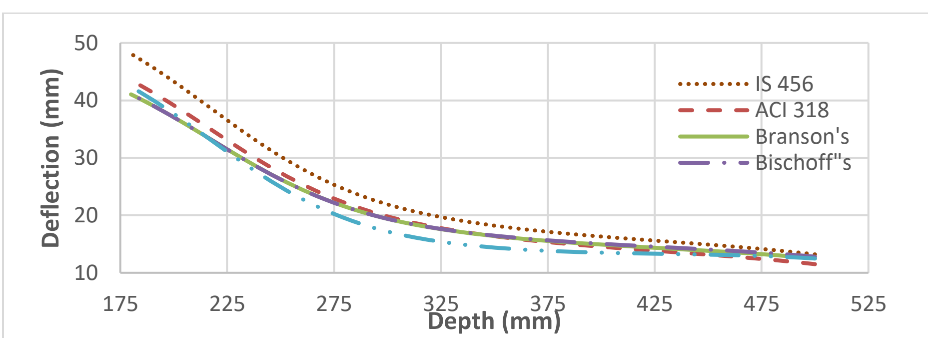

Fig 7. Change in deflection vs depth

Fig 7 shows the deflection trend with change in the depth of beams, as changes in the depth of the beam from higher to lower the flexural strength and moment of resistance in the beams were reduced due to which deflection in RC beams is increased.

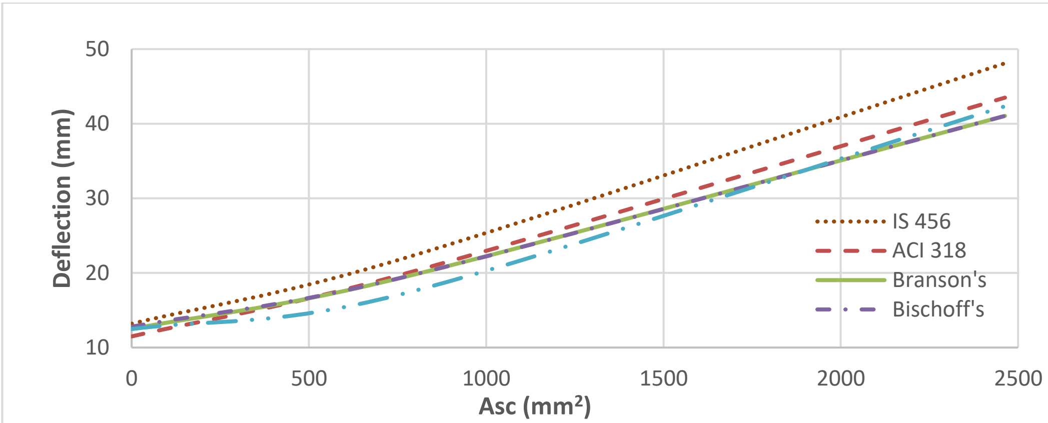

Fig 8. Change in deflection vs A_{sc}

Fig 8 shows the deflection trend with change in the area of compression steel (Asc), as the change in the depth of the beam increases in the area of compression steel the deflection also increases.

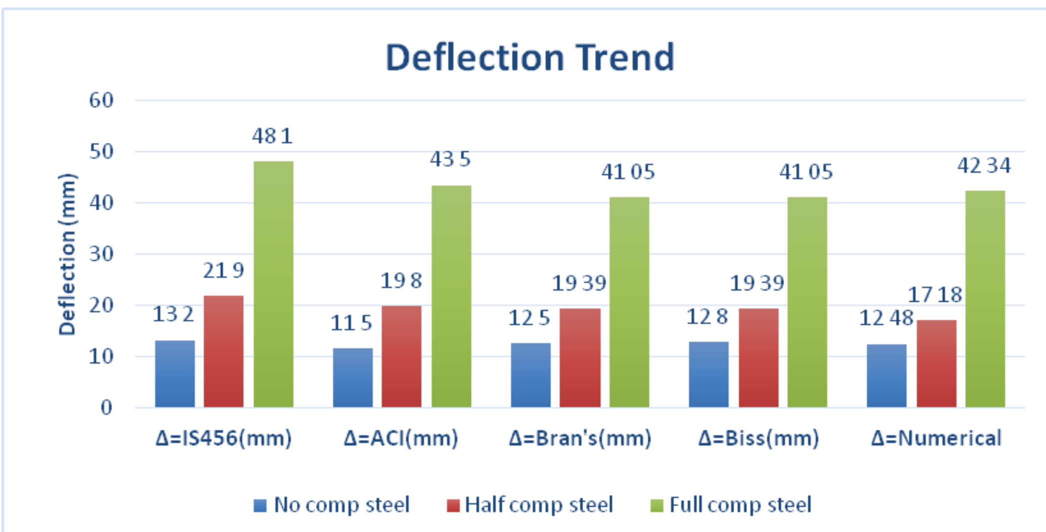

Fig 9. Deflection trend with change in compression steel in TYPE-I

Fig 9 shows the variation in deflection concerning the change in the compression steel to the different cross-sections of the beams. As the position of the compression steel and placement in the beams are changed the deflections are increased.

Case (ii): By depth is constant.

The deflection trend with depth is constant for all beam cases, providing the depth of the beams as constant the moment of resistance in the beams was increased due to which deflection in RC beams is reduced.

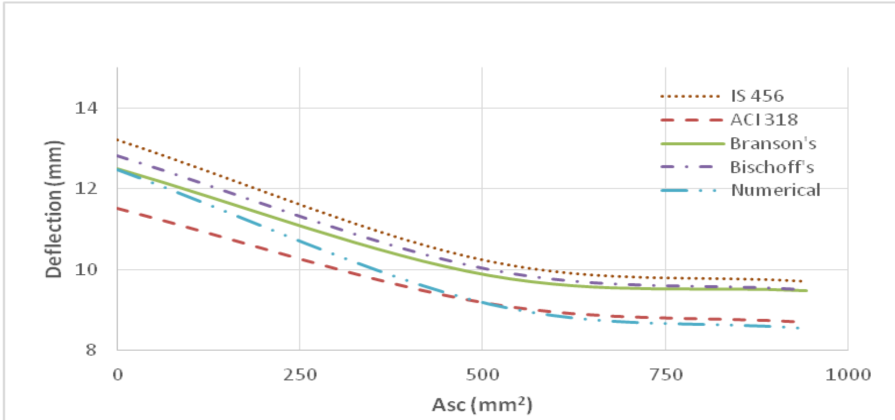

Fig 10. change in A_{sc} vs deflection

Fig 10 shows the deflection trend with change in the area of compression steel (Asc), as the depth of the beams was kept constant and by increasing the area of the compression steel due to which deflection is reduced.

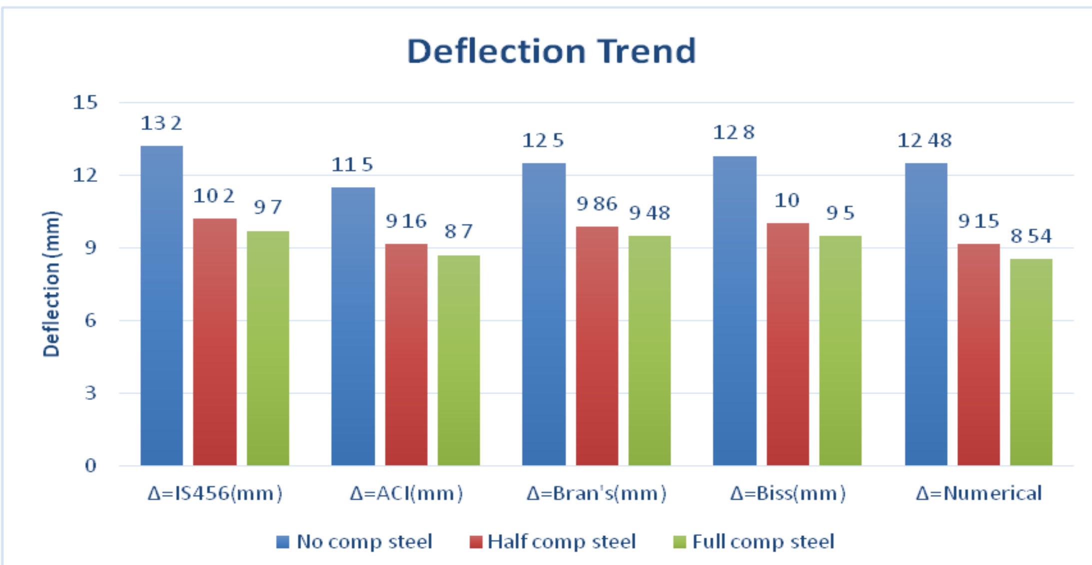

Fig 11. Deflection trend with change in compression steel in TYPE- II

Fig 11 shows the variation in deflection concerning the change in the compression steel and depth is kept constant for all beams. As the position of the compression steel and placement in the beams are changed the deflections are reduced in this case.

5. Conclusions

This study, on the effect of compression reinforcement in the deflection of reinforced concrete beams by different effective moment of inertia expressions with the theoretical and analytical results gives the conclusion on how compressive steel plays an important role in the control of deflection in RC beams leads to the formulation of the subsequent conclusions based on the comparisons of analytical and numerical outcomes of the work.

TYPE-I: Change in depth

- The results by all the effective moment of inertia methods showed similar kinds of results were observed.
- As the depth of the beam is reduced the deflections are increased in the beams.
- As the area of compression steel is increased, the depth of beams is reduced, consequently, the flexural strength of the beam is reduced and due to this, the deflection is increased.

TYPE-II: With depth as constant

- In this case, all the methods show almost the same trend of deflection.
- In addition to some amount of compression steel, the deflections are reduced. It is found that the depth of the beam as well as an area of compression reinforcement are the major parameters that influence the deflections.
- However, the depth of the beam is influenced much more in comparison to the area of compressive steel.
- Therefore, both parameters need to be considered in the design of the beam for reducing the deflections in reinforced concrete beams.

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