A Numerical Validation of Analytical and Experimental Estimation to Comprehend the Behavior of RC Long Beams in Flexure

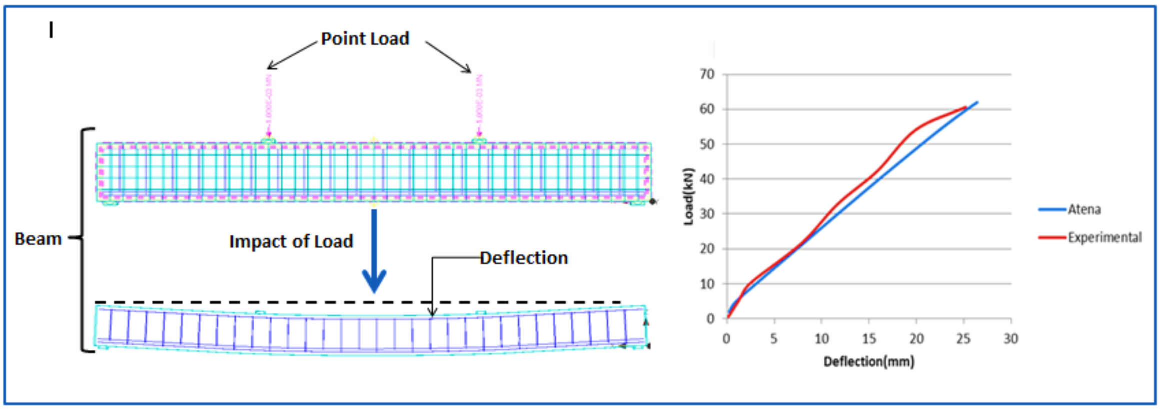
Ravpreet Kaur[1,2*] and Harvinder Singh[3]

[1] *Research Scholar, Department of Civil Engineering, I.K Gujral Punjab Technical University, Jalandhar-Kapurthala-144603, Punjab, India.*

[2] *Assistant Professor, Department of Civil Engineering, Faculty of Engineering & Technology, Shree Guru Gobind Singh Tricentenary University, Gurugram-122505, Haryana, India.*

[3] *Professor, Department of Civil Engineering, Guru Nanak Dev Engineering College, Ludhiana- 141006, Punjab, India.*

Graphical Abstract



ABSTRACT

In prior research publications, it was discovered that long/slender beams have not been commonly used in Reinforced Cement Concrete Structures. These thin slender RCC beams have a different response in flexure than a normal Standard sized RCC beam. The purpose of this study is to quantitatively validate the theoretical equations provided in earlier long beam studies for predicting the behavior of exceedingly thin and moderately slender RC beams. Non-linear finite element (FE) analysis was used to investigate the response of these thin long beams in flexure due to slenderness.

In ATENA (FEA) software, a total of 8 RCC rectangular long beams were modeled with different cross-sectional areas, support conditions, and reinforcement ratios, referring to the experimental study performed and then analyzed by applying progressive loading pattern. Furthermore, the output from ATENA software was used to plot the Load Deflection curves for each corresponding test beam, which were observed to be in good accordance with the experimental data. Furthermore, it indicated a comparable way of collapse for moderately and excessively narrow beams, as shown in prior papers. Finally, in line with the practical laboratory tests, the mathematical equations provided in the given works were numerically confirmed using ATENA software.

Keywords: RC Long Beams, Flexure, Slenderness Ratio, Slender Beam, ATENA (FEA) Software.

1. Introduction

RCC long/slender beams are uncommon in concrete cement (CC) constructions. The structural elements (beams or columns) are considered 'slender' in the sense if they show more susceptibility to the development of instability (buckling) in transverse direction. Whenever these elements are subjected to "peak" stresses, they buckle (compression in the axial zone, flexure with torsion, twisting). Such a rapid and fragile style of failing is undesirable from a design position; hence, from the core emphasis of design, the major one is to ensure that within this phase, there is still an adequate endurance towards failure. When it pertains to instability in lateral direction, thin long beams, on either hand, haven't gained the credit they deserve. Worldwide, substantial investigation on the behavior of thin columns has already been done, and pertinent requirements have been adopted in practice guidelines with respect to the design among these columns derived from the results of the research. When constructing steel structures, the reaction of the beam due to changes in slenderness ratio is well ascertained, but not so much when developing RCC structures. The IS codes presently do not include any specifications for RC narrow beams. The maximum load handled by these long concrete beams must be greater than the flexural strength equal to the breaking load at which the material collapses to avoid failure owing to abrupt destabilization (since in case of RCC beam, it collapses owing to the combination of flexure and tensile stresses). It is generally presumed that a quick failure due to destabilization will occur. This does not happen in case of these beams until they fail in flexure and fulfils the slenderness requirements. Furthermore, when it comes to these slenderness standards, there is a lot of variation in the design laws.

Given the assertion that Standards in Indian Building codes [1–5] states that the slenderness in RCC beams must be determined by beam size i.e. the geometrical attribute be considered, however researches reveal that there are a number of factors influencing it. Thin slender columns have become the subject of vast research and analysis all around the world, resulting in numerous revisions and alterations to existing national codes for design practices [6,7]. Marshall, however performed the first research on the his subject i.e. the lateral stabilization in RCC beams in 1948, as further discussed in detail by Hansell & Winter [8]. Predicated on their own experimental studies, Hansell & Winter et al. determined that the length (L) to width (b) as stipulated in the ACI code isn't really a reasonable criterion of slenderness, as well as even farther attempted to propose that (Ld/b^2), where d is the effective height of the beam, is a good predictor of slenderness, so there was hardly any considerable alteration noticed during collapsing in both the under-reinforced and over-reinforced beams with such a method. Furthermore, it has been hypothesized that the reinforcing ratio has the greatest impact on slenderness. Slenderness in beams is an important feature to explore since it can have a negative impact on RC beam behavior by causing an unanticipated destabilization collapsing or a considerable loss in strength in flexure. In a suggested design, Siev et al. investigated the impact of reinforcement ratio on the reaction of RCC thin beams. Sant & Bletzacker studied RCC beams and found that the height/width proportion has an influence on the response of narrow RC beams [10]. The influence of reinforcing bars, transverse reinforcement, and grade of concrete on the torsion robustness of the section was considered by Massey et al [11]. Massey and Walter [12] then used the proposed concept of Massey to the RCC members supported simply under the application of concentrated load a mid-span.

Slender reinforced cement concrete (RCC) beams, according to study by Revathi and Menon, and the previous researches, affirmed that these beams respond differently than regular sized beams. When opposed to somewhat moderately thin beams, which collapse in flexure, but the excessively thin or long beams are more prone to sudden failure owing to instantaneous destabilisation. Revathi and Menon et al. [13, 14] studied the behavior of moderately and extremely thin RC beams and established equations to compute the predicted crucial bending moment (M_{cr}) for such rectangular RCC long beams as follows:

$$Mcr = \frac{C_1 C_3\, E_c \sqrt{\alpha\beta}}{C_2 6\sqrt{2\left(1+\upsilon_c\right)}} \frac{b^3 d}{L}$$

Where C_1 is attributed to the loading condition, C_2 is governed by the type of supports on which the beam is placed, & it's equal to 1 if the beam is supported simply and 0.5 if the ends are restrained in all directions. The factor C_3 is measured by the location of load application corresponding to the equilibrium of the section of beam, and it ranges from 0.9 to 1.1, and is equal to 1 when he load is applied at the centerline of the portion. E_c is the elastic modulus of concrete, α and β are the coefficients for bending and torsion resistance, and υ_c is the concrete's Poisson's ratio [14]. As it has already been discovered, how diverse configurations of designing components provide a wide range of slenderness limits, and thus a maximum measure of slenderness ratio was postulated.

$$\frac{Ld}{b^2} \le \frac{C_1}{10C_2} . \frac{E_c}{R} . \sqrt{\alpha\beta}$$

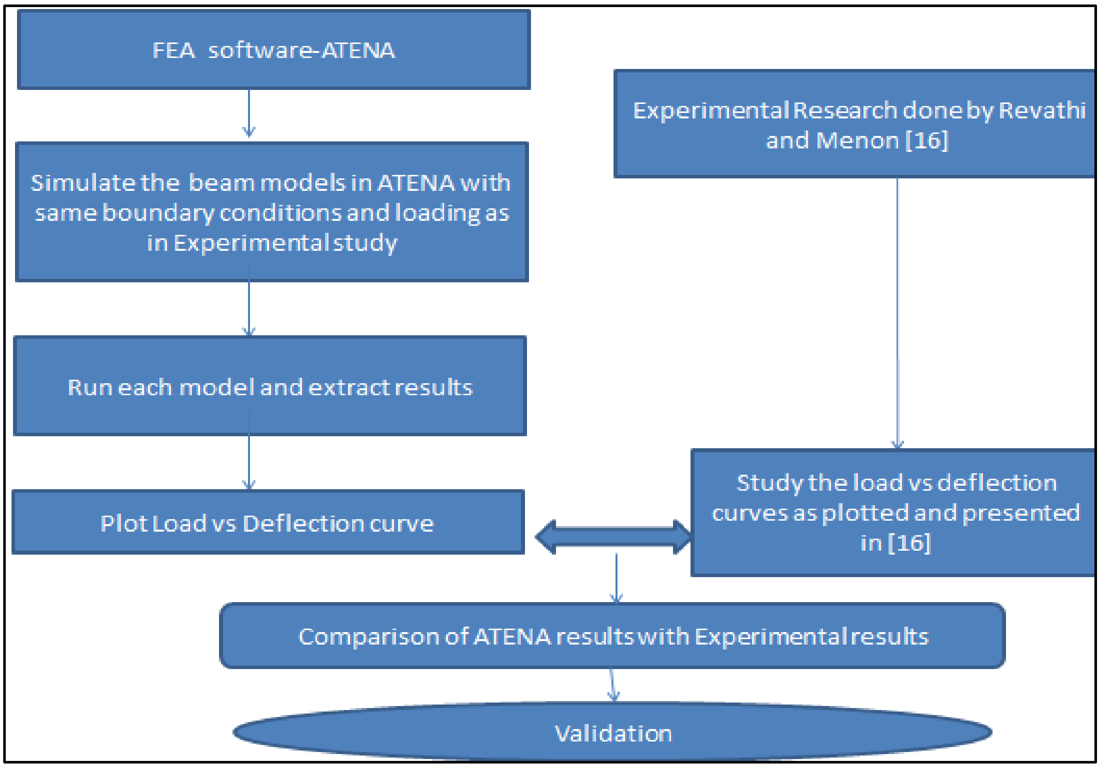
The maximum value of slenderness (Ld/b^2) for a rectangular section of RCC beam under the application of any sort of load as well as supports may be found with appropriate value of C_1 and C_2. A total of seven test beams designed by researchers Revathi and Menon [13], 3 separate beams developed by Sant & Bletzacker [10], and another set of eleven beams tested by Massey [11] were also employed to much farther confirm the provided formulation for critical buckling moment. Because Revathi and Menon's laboratory experimental findings were in strong accord with Hansell & Winter, as well as Massey's and moreover were corroborated by the contextual approach presented by them in the formulation [16]. Hence this paper further intends to understand the response of RCC long beams in flexure as predicted by proposed mathematical formulation in agreement with experimental results and hence further reinforced by the numerical affirmation using Finite element analysis in this study. Revathi and Menon [16] presented detailed investigational findings as well as conceptual formulation to anticipate the behavior of long RC beams. The beam samples in [16] were further simulated using finite element analysis tools in ATENA (FEA software) to compare the geometrical assessments for determining the valuable involvement of beam dimensions towards the load carrying capacity.

In engineering, FE (finite element) analysis approach has been used and holds significance. Finite Element analysis on reinforced concrete structures is conducted using the variety of concrete model types; a very prevalent however is the smeared cracking approach. The method was used to assess the behavior of RC members [19–24]. Dagher and Kulendran [25] simulated a computational model for corrosion degradation in steel using the smeared crack technique. , which offered a stronger insight of collapse propagation, warping, and debonding techniques. Coronelli and Gambarova [26] used non-linear FE analysis to evaluate the integrity of the structure of rusted RCC beams undergoing failure in flexure.

The present numerical study makes use of a widely viable FE approach using ATENA.

2. Research Significance

FEA (finite element analysis) is considered as one of the highly dependable and realistic approaches for analyzing intricate design engineering issues like reinforced cement concrete because it gives a complete and adaptable approach for both the precise behavior of RCC components. The main objective of this work is to conduct a computational assessment using FE analysis for the influence of slenderness in reinforced cement concrete long beams, correlating it to the laboratory investigation conducted by Revathi and Menon [16]. The load deflection curve and mechanism of failure have been studied and found to be in good agreement with experimental test results and suggested equations. Structural engineers can utilize the simulation tools to measure the impact of geometric variation of RCC beams.



3. Methodology

The following is the approach used in the numerical analysis provided in this study:

1. To begin, the data collected from earlier investigations on RCC long beams are gathered and analyzed. The study which covered both excessively long and moderately thin beams showing both destabilization and bending failure was chosen for the numerical analysis as well as the focus was kept to include the one which had considered and tested the beams with variation in sizes.
2. Of all the published literature on RCC long beams, the study by Revathi and Menon [16] was found to be accounting to all the considerations.
3. FEM based software ATENA was used to model and evaluate the beams for numerical validation.
4. The Load displacement graphs generated from the readings recorded during experimental study were analyzed and contrasted with LD curves generated from the ATENA analysis.
5. The failure of the beams during numerical analysis was seen and compared with the one noted during the Experimental investigation.

4. Validation

The research technique outlined in [16] was used, which selected eight beams from the experimentally tested total of 15 beams in that research, depending upon the selection criterion highlighted in methodology of this study presented in the previous section.

In ATENA, a load - displacement graph was produced automatically, that the ultimate load was recorded from the observation, as well as the manner of collapse. The ATENA programme was used to obtain the peak load at collapse and load displacement profile of the beams analyzed is shown in Table 1.

Table 1: Preliminary Details of Beams with dimensions of each beam.

S. No.	Beam Tag	*Size of Beams* *Width(b) in (m) ×Depth(D)in(m) × Span(L) (m)*	Length to width ratio (L/b)	Depth to width ratio (d/b)	Ld/b^2	Remarks
1	$B_{550,5.0}$	0.1 × 0.55 × 5	50	5.2	260	Highly slender
2	$B_{450,6.0}$	0.1 × 0. 45 × 6	60	4.2	252	Highly slender
3	$B_{550,6.0}$	0.1 × 0.55 × 6	60	5.2	312	Highly slender
4	*$B_{300,6.0}$	0.08 × 0. 3 × 6	75	3.3	247	Highly slender
5	$B_{300,6.0}$	0.1 × 0.3× 6	60	2.7	162	Moderately slender
6	$B_{300,5.5}$	0.1 ×0.3 × 5.5	55	2.7	149	Moderately slender
7	$B_{400,5.0}$	0.1 × 0.4 × 5	50	3.7	185	Moderately slender
8	$B_{450,4.0}$	0.1 ×0.45 × 4	40	4.2	168	Moderately slender

The goal of this study is to learn about the flexural behavior of RCC long and moderately slender beams using FEM analysis. The beams chosen were modeled in ATENA 3D to perform the analysis. In the ATENA, materials are defined in material definition section as follows:

1. Concrete -3D Non-Linear Cementitious 2
2. Rebars - Reinforcement
3. Stirrups-Reinforcement
4. Steel plates (for the application of load and supports)-3D Elastic-isotropic

The RC beams were modeled in ATENA 3Dv5 according to the specifications in [16], with the end-support conditions and loaded in the identical fashion as in Revathi and Menon's work [16], and a four-point flexural test was conducted. According to the laboratory program [13,14], 8 rectangular RC thin beams with varying dimensions such as width, depth and length were simulated in ATENA having the identical input parameters. To recreate the identical end circumstances as in the laboratory, the beam's one end was constrained in the X and Z planes, while the other end was restricted in the Y and Z planes. Two steel plates were employed to apply concentrated structural load at the central 3rd span locations, as in a flexure test, as indicated in the diagram beneath (Fig. 1).

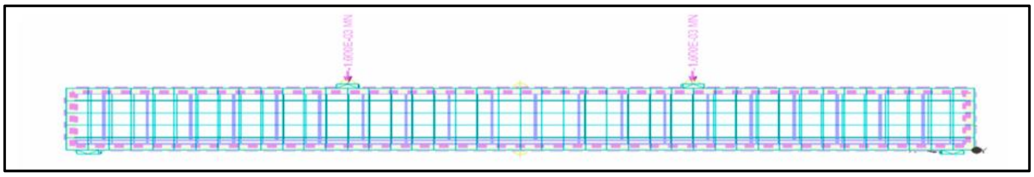


Fig 1. shows the beam model simulated as in ATENA.

Table 2 illustrates the findings of laboratory, mathematical, and computational research, therefore it is be stated that the laboratory experimental and mathematical findings have no substantial difference. In addition, the computational analysis [Fig 2-9] reveals the identical pattern of load - deformation graphs as the findings from experimental programme, and the collapse mechanism is the same in both studies. The force deformation curves for all beams reviewed using the Finite-element method approach (ATENA) are presented underneath and compared to the Load-deformation curve generated from laboratory investigation.

Table 2: Laboratory, mathematical, and computational outcomes are presented.

The outcomes from the laboratory investigation and the computational analyses are examined. The following (Fig. 2-9) shows the outcome of the contrast.

S.No	BeamTag	Computed flexural collapse load W_{uf} (kN) IS 456 (2000)	Computed Buckling collapse load W_{cr} (kN) [16]	Collapse load from laboratory investigation W_{test}(kN)	Recorded Collapse Load from ATENA W_{num}(kN)	Failure mode as observed (expt.)	Recorded Failure mode (ATENA)
t	$B_{550,5.0}$	155.3	119.5	115.6	96	Sudden instability	Sudden instability
2	$B_{450,6.0}$	91.00	72.28	69.04	62	Sudden instability	Sudden instability
3	$B_{550,6.0}$	131.0	86.74	85.90	64.96	Sudden instability	Sudden instability
4	*$B_{300,6.0}$	27.67	24.79	23.12	26	Sudden instability	Sudden instability
5	$B_{300,6.0}$	25.51	36.98	22.09	24.08	Failure with warning	Failure with Warning
6	$B_{300,5.5}$	27.70	42.65	24.07	25.14	Failure with warning	Failure with Warning
7	$B_{400,5.0}$	54.07	70.30	49.96	43.52	Failure with Warning	Failure with Warning
8	$B_{450,4.0}$	97.52	132.3	87.28	96	Failure with Warning	Failure with Warning

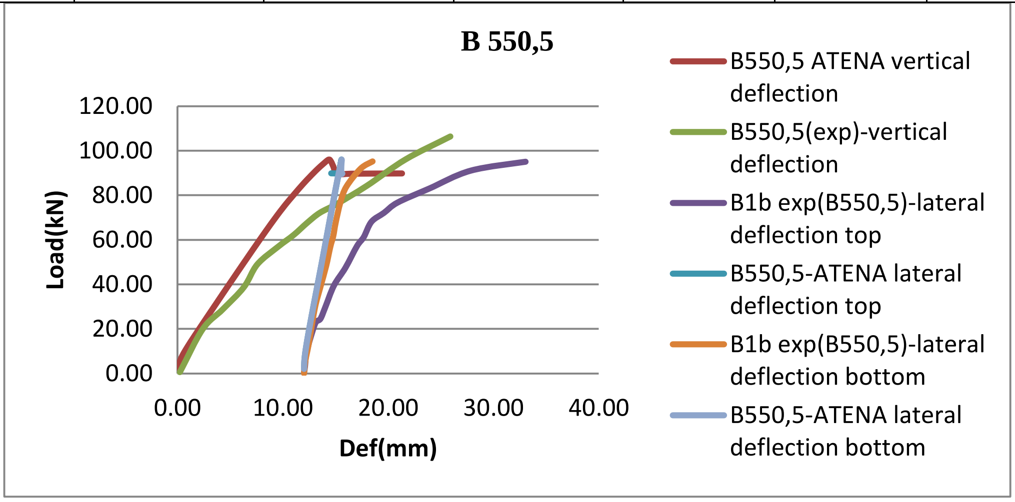


Fig. 2: Load-deflection curve for $B_{550,5}$

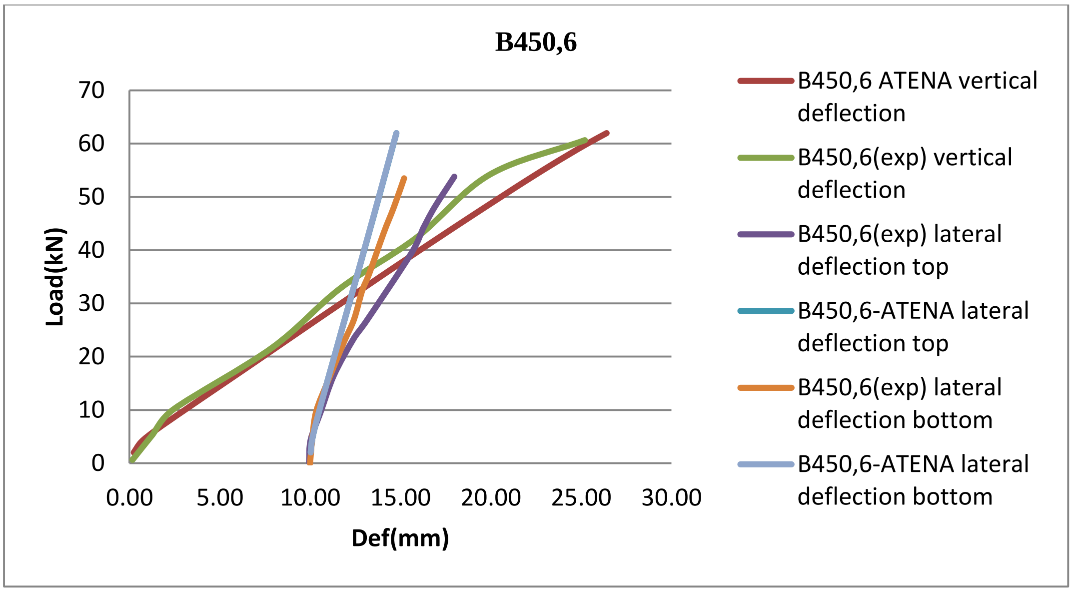


Fig. 3: Load-deflection curve for $B_{450,6}$

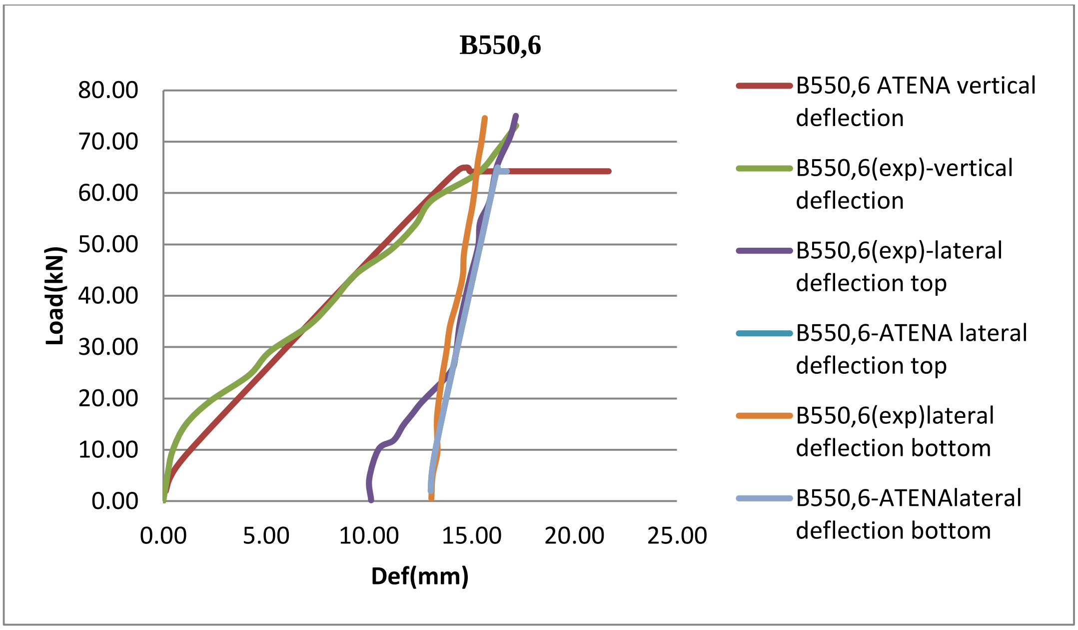


Fig. 4: Load-deflection curve for $B_{550,6}$

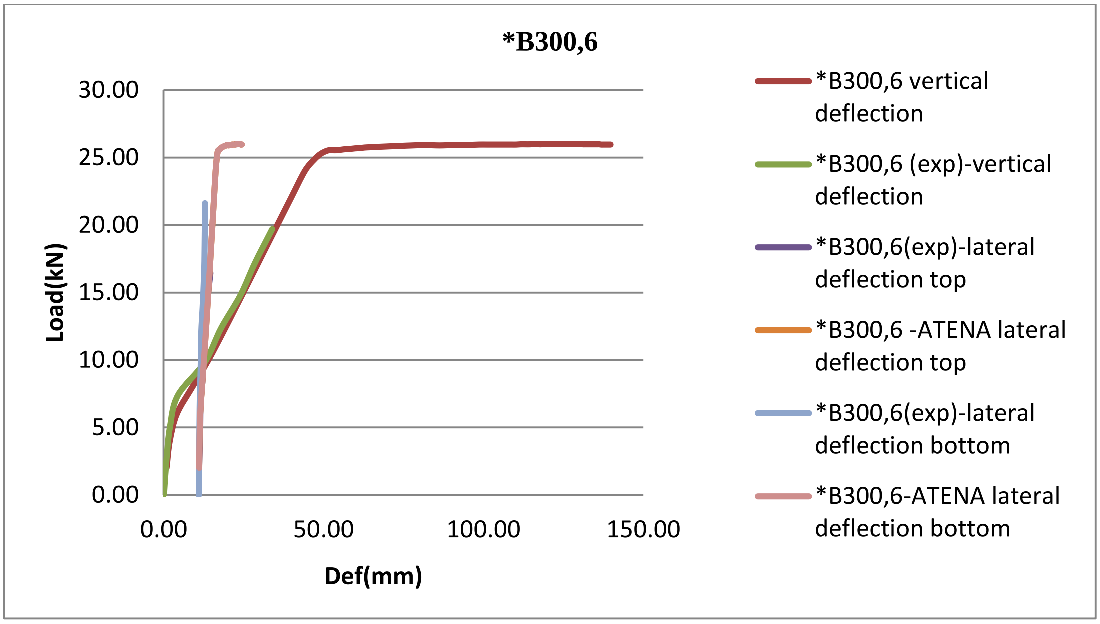


Fig. 5: Load-deflection curve for* $B_{300,6}$

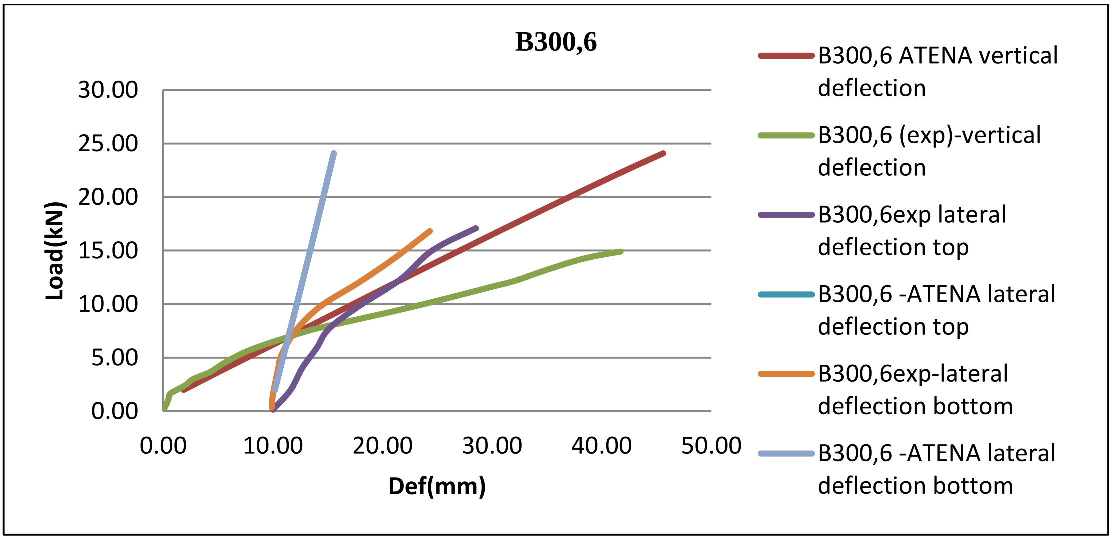


Fig. 6: Load-deflection curve for $B_{300,6}$

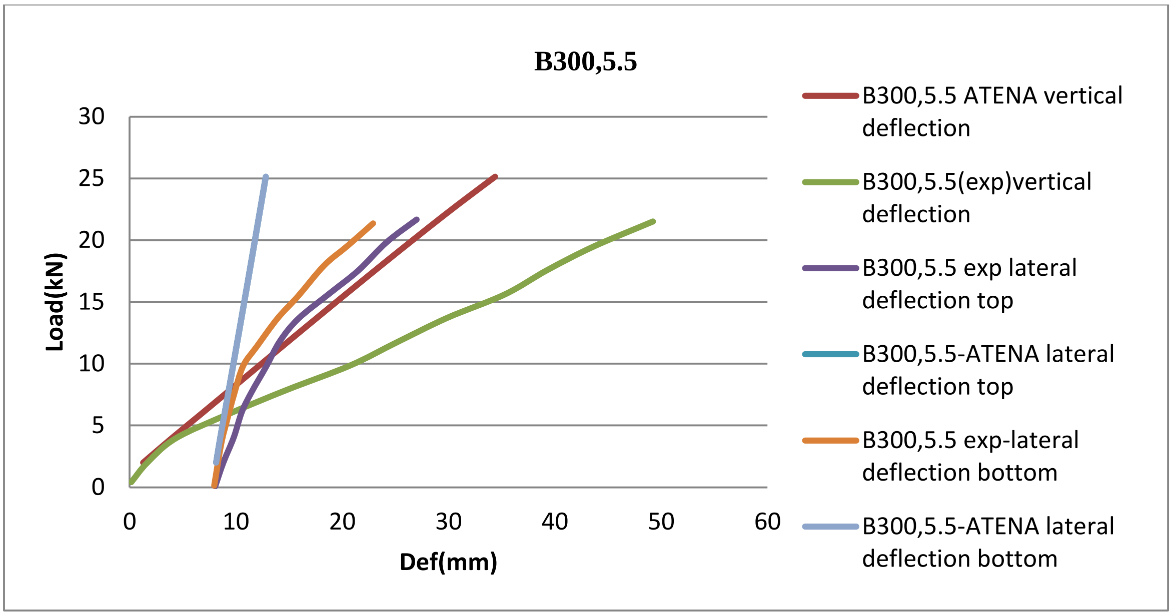


Fig. 7: Load-deflection curve for B$_{300,5.5}$

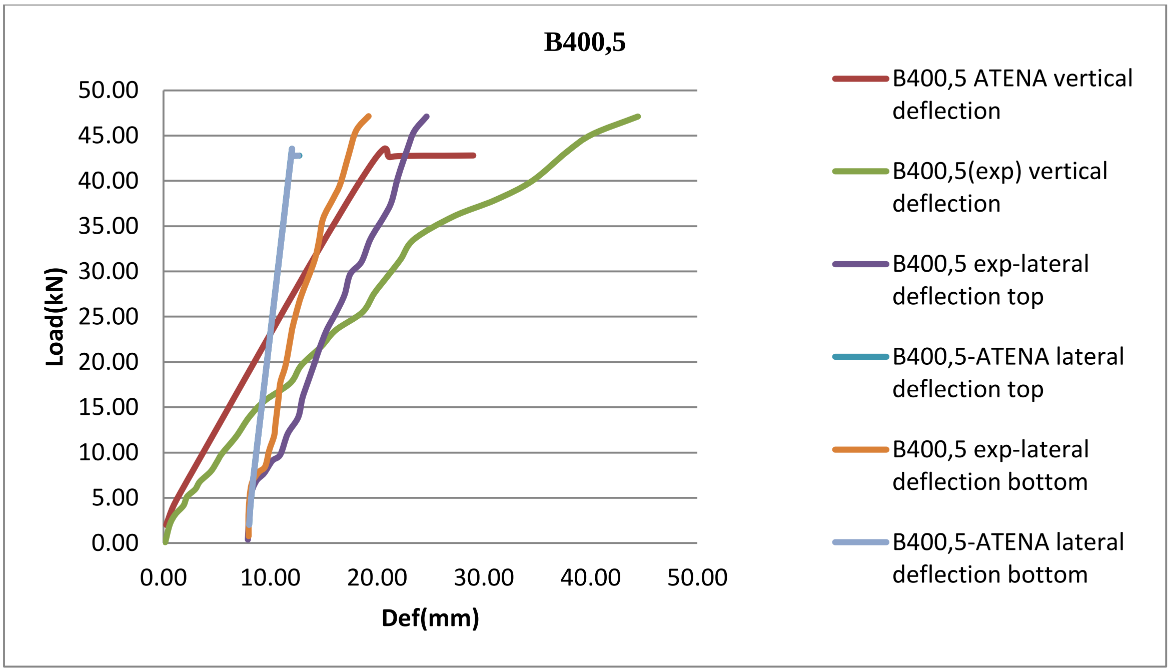


Fig. 8: Load-deflection curve for B$_{400,5}$

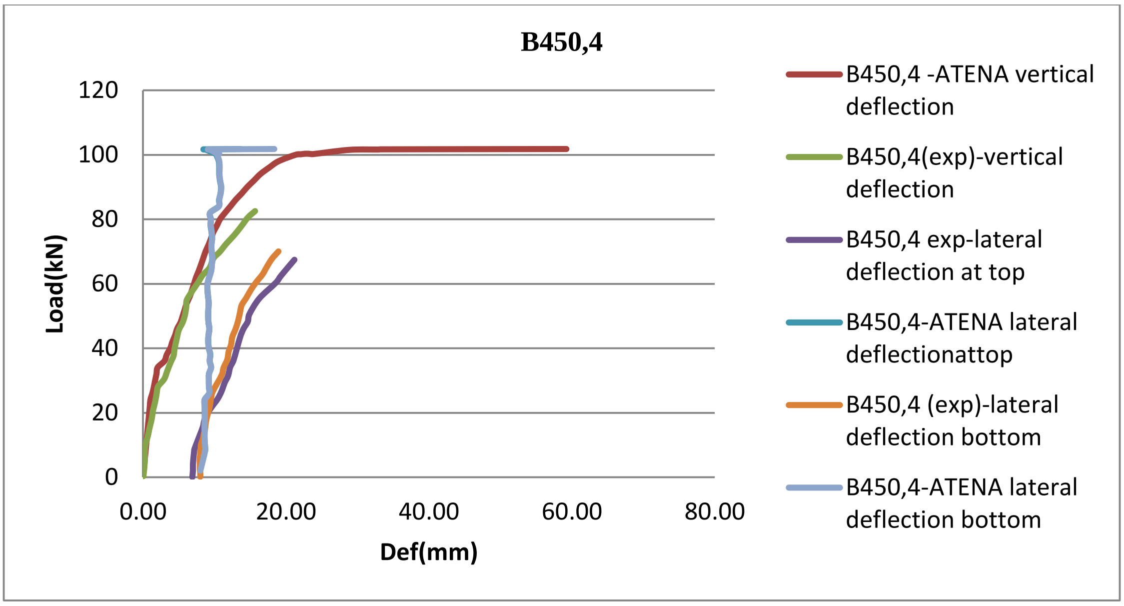


Fig. 9: Load-deflection curve for $B_{450,4}$

According to IS456:2000 [3], slenderness limits for RC beams are prescribed as L< $(250b^2)/d$ or 60b, whichever is less, where L is the span of beam, b is width and d is the depth of beam. From the numerical investigation taken up the set of beams in Table 1, it has been realized that the beams $B_{550,5}$, $B_{450,6}$ $B_{550,6}$ *$B_{300,6}$ exceeding the slenderness limits ($Ld/b^2>250$), as prescribed by IS 456:2000[3], fall in highly slender category of RC Beams and thus exhibit sudden instability failure unlike the expected flexural failure as predicted by the existing theories, reference in [16]. The mode of failure for all beams analyzed was the same as predicted the formulae proposed by Revathi and Menon [16], since $W_{cr} < W_{uf}$ in the highly slender beams($B_{550,5}$, $B_{450,6}$ $B_{550,6}$ *$B_{300,6}$) and failed by sudden instability .And the moderately slender beams ($B_{300,6}$,$B_{300,5.5}$,$B_{400,5}$ and $B_{450,4}$) failed by flexural tension as expected ,as the calculated critical buckling load is more than the calculated flexural failure load (from IS 456), which is more than observed failure load as presented in the table 2. The cross section was found to be twisted as the difference in the lateral deflection at top and at bottom was seen in the highly slender beams ($B_{550,5}$, $B_{450,6}$ $B_{550,6}$ *$B_{300,6}$) and sufficient warning was seen in Load deflection curve of moderately slender beams($B_{300,6}$,$B_{300,5.5}$,$B_{400,5}$ and $B_{450,4}$) as shown in Fig 2-9.

The Load vs Deflection plot of $B_{300,6}$ and *$B_{300,6}$ furthermore reveals that as the range of slenderness is surpassed, the failure mechanism shifts from warning before collapse to sudden destabilisation. Figure 10 illustrates the cracked deflected beam.

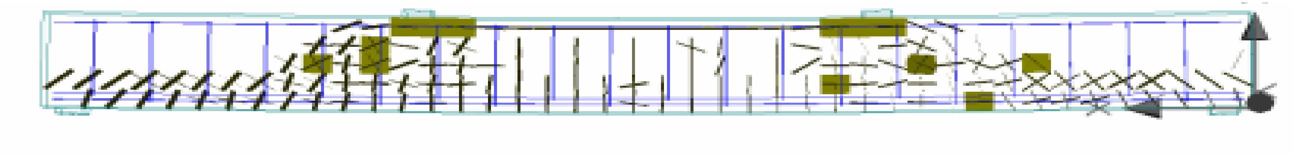


Fig. 10: Cracked deflected beam

The introspective analyses furthermore suggests that the simulated maximum load in flexural bending for routine (non-slender) beams from pre - existent mathematical algorithms wasn't really accomplished during laboratory experiment on relatively slender beams, referring to the deficit of strength in bending which is identified in only a few beams, as confirmed by the finite element based software investigation performed throughout the current research.

5. Conclusions

1. A critical analysis done on particularly thin slender reinforced concrete beams indicated that excessively slender beams tumble suddenly and unexpectedly, whereas fairly slender beams fail gradually.
2. The study also indicates that the simulation model yields pretty much comparable results to laboratory tests performed, implying that applying the Finite Element Approach to examine RCC frameworks is a realistic alternative.
3. It is indeed worth mentioning that the beam, $B_{550,5.0}$, fulfills the prevailing ACI: 318 (2005) [1] slenderness standards, indicating that destabilization failure is unlikely.
4. The collapse of this particular beam due to unforeseeable destabilization exposes flaws in the standards of design code's

slenderness regulations.

5. On the basis of the results recorded and conclusions presented in the study performed by Revathi and Menon in [16], a simulation investigation using FEM was conducted and thus, revealed that the laboratory results as well as the mathematical model presented in [16] confirm the same.
6. It is important to realize that the beam, $B_{550,5.0}$, meets the current ACI: 318 (2005) [1] slenderness guidelines, suggesting that destabilization breakdown is highly improbable. The failure of this beam due to unanticipated imbalances reveals imperfections in the prescribed slenderness range in Indian Standards.
7. Revathi and Menon in [16], displayed mathematical framework and then experimentally validated and hence it was further numerically validated with the results obtained b FEM based computational software as shown in the load deflection plots as shown in Fig. 2-9.
8. According to recognised concrete engineering philosophies, the beams, $B_{550,5.0}$, $B_{450,6.0}$, $B_{550,6.0}$, $*B_{300,6.0}$ cease by sudden disturbances leading to destabilizations rather than flexural tension failure [8,10,11].

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