Shear Failure Assessment of a G+3 RC Framed Building via Nonlinear Static Pushover Analysis using SAP2000

IYTHA AVINASH [1], Mr. Gollanolla Sudhakar[2]

[1]*M.Tech Scholar, Department of Civil Engineering, Siddhartha Institute of Technology and Sciences (SITS), Hyderabad, India .*

(avinashiytha.ce@gmail.com)

[2]*Assistant Professor, Department of Civil Engineering, Siddhartha Institute of Technology and Sciences (SITS), Hyderabad, India (gsudhakar.civil@siddharatha.co.in)*

---***---

Abstract

Accurately modelling shear behaviour in reinforced concrete (RC) structures is essential for seismic evaluation, as shear failure can lead to catastrophic outcomes. Current industry practices often emphasize nonlinear flexural analysis while underestimating the critical role of shear behaviour. This study aims to develop a nonlinear force-deformation model specifically for shear in RC sections to bridge the gap in existing literature. Standards like IS-456:2000 and ACI-318:2008 provide ultimate strength estimates but may inadequately consider the contribution of concrete under seismic loads. Insights from models by Priestley et al. (1996) and Park and Pauley (1975) are integrated to improve the calculation of shear hinge properties. A comparative nonlinear static (pushover) analysis of an RC framed building, with and without shear hinges, demonstrates the impact of shear modelling. Results show that neglecting shear hinges overestimates base shear and roof displacement capacity, masking non-ductile failure modes. Incorporating shear hinges provides a more realistic assessment of structural strength and ductility, emphasizing their necessity in seismic analysis and design.

Keywords:

Shear behaviour, Reinforced concrete (RC) structures, Seismic evaluation, Shear failure, Nonlinear analysis, Force-deformation model, Shear hinge.

1.INTRODUCTION

Shear failure in reinforced concrete (RC) structures presents a critical challenge in structural engineering, especially under seismic loading. Unlike flexural failure, which is ductile and preferred in design, shear failure is brittle and catastrophic, compromising the safety and resilience of earthquake-resistant structures. Ensuring that shear failure is adequately addressed in design is paramount, particularly given concrete's lower tensile strength relative to its compressive capacity. Historical earthquake data reveal that shear failure remains a predominant cause of structural collapse in RC buildings, highlighting the disconnect between design intentions and real-world performance. This issue is especially pronounced in regions like India, where construction practices may not adequately address shear concerns.

To address these challenges, a thorough understanding of the parameters influencing shear behaviour is essential. Despite advancements in nonlinear modelling for flexure, the nonlinear behaviour of RC sections in shear remains inadequately understood and underrepresented in existing literature. Traditional industry practices often assume elastic shear behaviour, overlooking the complexities and critical contributions of nonlinear shear deformation to structural response.

This study focuses on developing a nonlinear force-deformation model specifically tailored to the shear behavior of RC rectangular sections. By integrating insights from established models and conducting nonlinear analyses, the research aims to bridge this knowledge gap. A nonlinear static (pushover) analysis is employed to evaluate the impact of shear modelling on the seismic performance of RC framed buildings. Preliminary findings indicate that neglecting shear behaviour leads to an overestimation of structural capacity and obscures non-ductile failure modes. This underscores the necessity of incorporating nonlinear shear modelling into seismic design and analysis to ensure more realistic and reliable predictions of structural performance, ultimately enhancing safety and resilience in seismic-prone regions.

1.1 Objectives

1.To develop nonlinear modelling parameters for the shear behaviour of rectangular reinforced concrete (RC) members with transverse reinforcement.

2.To perform a seismic evaluation of an RC framed building by considering nonlinear behaviour in both shear and flexure using the developed parameters.

1.2 Scope of the Study

1.The analysis is limited to rectangular RC sections, excluding other geometric shapes.

2.Spiral web reinforcement is excluded from the present study, focusing solely on sections with transverse reinforcement.

3.The stress-strain relationship for reinforcing steel is adopted as per the provisions of IS 456:2000.

2. METHODOLOGY

Shear Capacity and Displacement Models for RC Beams: A Summary

Research into shear capacity models for reinforced concrete (RC) beams has explored various equations developed through theoretical and experimental studies. Significant parameters influencing shear capacity include the shear span-to-depth ratio (a/d), reinforcement ratio (ρ), and compressive strength of concrete (fc). Shear failure modes in RC beams without web reinforcement vary with a/d and include diagonal tension, diagonal compression, and true shear failure. Design codes such as IS 456:2000, BS 8110:1997, and ACI 318:2008 provide guidelines for shear strength estimation, with differences in their approaches to reinforcement contributions.

Shear displacement, critical in nonlinear failure analysis, arises from the sliding of beam sections under shear forces. It is quantified through uncracked, yield, and ultimate displacement models. Models by Priestley et al. (1996) and Gerin and Adebar (2004) provide methods to estimate shear displacement at yield. While Priestley's model accounts for concrete and transverse reinforcement contributions, Gerin and Adebar's approach incorporates axial load effects but may underestimate displacements. Panagiotakos and Fardis (2001) offer a simplified model but tend to overestimate yield displacement.

For ultimate shear displacement, models by Park and Paulay (1975) and CEB (1985) utilize truss analogies, predicting displacement based on contributions from concrete and stirrups. Park and Pauley's model is widely used for beams, while CEB incorporates total shear force, offering broader applicability.

Case studies comparing these models reveal variability in predictions. Models like Sezen (2002) rely on regression analysis, while others like Gerin and Adebare are suited for specific conditions. Overall, refinement of shear displacement models remains critical for improved accuracy in RC design.

3. EXPERIMENTAL STUDY

This study evaluates the seismic performance of an existing three-story RC frame residential building located in Seismic Zone III, designed per IS 1893:2002 and IS 456:2000. The analysis incorporates both flexural and shear failures of frame elements, emphasizing the significance of shear modeling for accurate seismic risk assessment. A computational model is developed using SAP 2000, incorporating linear and nonlinear static and dynamic analyses.

Material properties are derived from IS 456:2000, with concrete M20 and steel Fe 415 used in the frame model. Beams and columns are modeled as 3D frame elements with rigid beam-column joints and fixed column ends at the foundation. Nonlinear behavior is captured using inelastic flexural and shear hinges at potential yield locations. Slabs are considered rigid diaphragms, with their mass contribution modeled on supporting beams.

The building, constructed in 2001, is symmetric in plan with 20.5 m × 13.2 m dimensions and a height of 18 m. Exterior and interior walls are 230 mm and 120 mm thick, respectively. Structural details, including beam and column layouts, reinforcement, and the foundation system with isolated footings, are specified. The computational model accurately represents material properties, stiffness, and geometry to facilitate detailed seismic analysis.

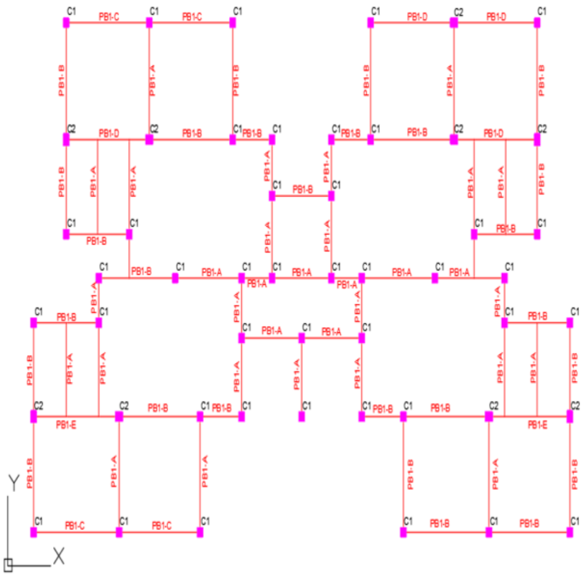

Fig.1.1 Plinth beam layout

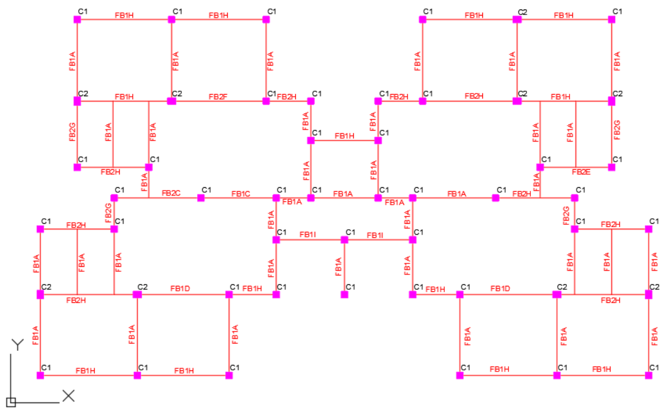

Fig.1.2 First floor layout

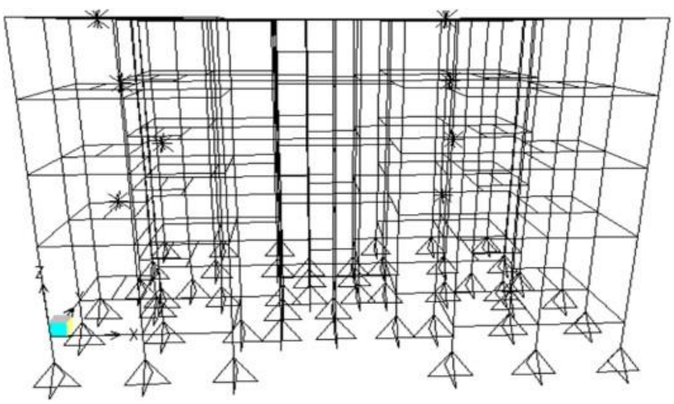

Fig.1.3 Elevation of the building – Front view

The plinth-level beams of the three-story RC frame building are detailed in Table 3.5. All beams have a uniform cross-section of 230 × 380 mm, with variations in reinforcement depending on their specific designation and structural requirements.

The top reinforcement in these beams' ranges from 2Y12 to 3Y20, while the bottom reinforcement varies between 2Y12 and 3Y16. For instance, Beam PB1 has 2Y12 bars at both the top and bottom, whereas Beam PB10 has 3Y20 bars at the top and 3Y16 at the bottom, reflecting the increasing reinforcement needed for beams with higher loading or critical positions. Transverse reinforcement, consistent across all beams, comprises 2Y8 bars spaced at 200 mm centre-to-centre, providing shear resistance.

The reinforcement detailing adheres to IS 456:2000 standards, ensuring adequate strength and ductility. The selection of 12 mm, 16 mm, and 20 mm diameter bars balances structural demands and economy. This comprehensive reinforcement design contributes to the building's capacity to withstand seismic forces while minimizing potential shear and flexural failures. Such detailed beam specifications are crucial for accurate modelling in SAP 2000 and provide the foundation for evaluating the seismic performance of the building's structural frame.

3.1 **Modelling of flexural hinges**

The study employs a nonlinear pushover analysis to model the structural behaviour under lateral loads using a point-plasticity approach. Plastic hinges are concentrated at specific points of the beams and columns, modelled as flexural (M3) hinges for beams and coupled P-M2-M3 hinges for columns, incorporating axial force and biaxial bending effects. Flexural hinge properties are derived from moment-curvature analysis, utilizing the Modified Mander model for concrete and IS 456:2000 stress-strain relations for steel.

Moment-curvature curves, generated through iterative algorithms, define the ultimate and yield behaviours of RC sections. The study also includes shear hinge modelling to capture potential shear failures in inadequately detailed structures. Shear strength and deformation properties are calculated per IS 456:2000 and other validated models.

This section details the building's geometry, reinforcement specifics, and the nonlinear modelling techniques, laying the foundation for a robust seismic performance evaluation of the selected framed building.

4. ANALYSIS AND RESULTS

The detailed description provides the procedure and results of a nonlinear pushover analysis conducted to evaluate the seismic response of a selected building using FEMA 356 guidelines. Below are summarized key points and observations:

4.1 Pushover Analysis Approach:

Gravity loads (dead load + 25% live load) are applied first using load-controlled pushover.

Lateral loads are applied monotonically, step-by-step in a displacement-controlled manner.

Lateral loads in the X-direction are based on mass and the first-mode shape amplitude at each story.

4.2 Load-Deformation Behaviour:

Stiffness degradation of structural elements is evaluated at different performance levels: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP).

The analysis considers P–Delta effects, which account for second-order effects due to lateral displacements.

4.3 Capacity Curve

The capacity curve represents the relationship between base shear force and roof displacement, which is a key indicator of nonlinear behaviour.

The analysis compares two structural models:

Structures with flexural hinges only.

Structures with both flexural and shear hinges.

Shear Hinge Properties

- Shear hinges for beams are modeled in one vertical direction (V2).
- Shear hinges for columns are modeled in two orthogonal horizontal directions (V2 and V3).
- The hinge properties include:

Yield force and displacement.

- Ultimate force and displacement.
- Residual force and plastic displacement.
- Displacement ductility.

- Beams exhibit a wide range of plastic displacements and ductility values, indicating variable deformation capacity depending on member length and section properties.
- Displacement ductility (μ) values vary, showing some sections are more ductile (higher μ) than others, which is critical for energy dissipation during seismic events.

4.4 Load Pattern

- A parabolic load pattern as per IS 1893:2002 equivalent static analysis is adopted.

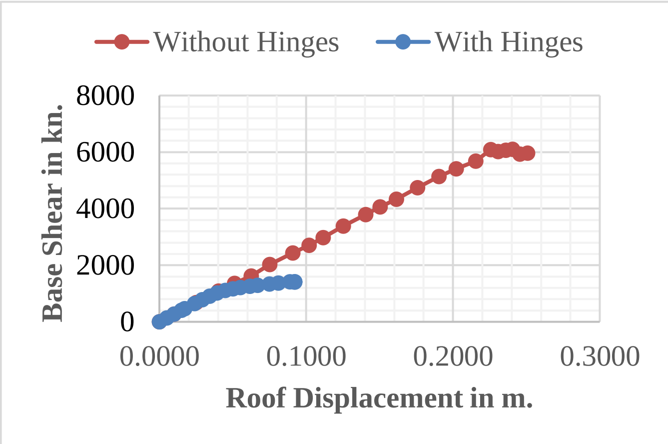

Fig.1.4 Capacity curve for Push X analysis

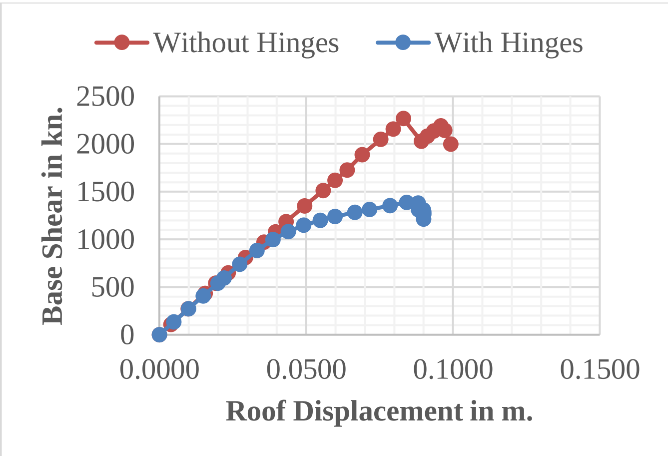

Fig.1.5 Capacity curve for Push Y analysis

Table. 1.Summary report

	Capacity(kn)	Displacement(mm)
Push -X analysis		
With shear hinge	1407.26	92.204
With no shear hinge	5966.32	250.80
Push -Y analysis		
With shear hinge	1212.29	89.952
With no shear hinge	1997.54	99.200

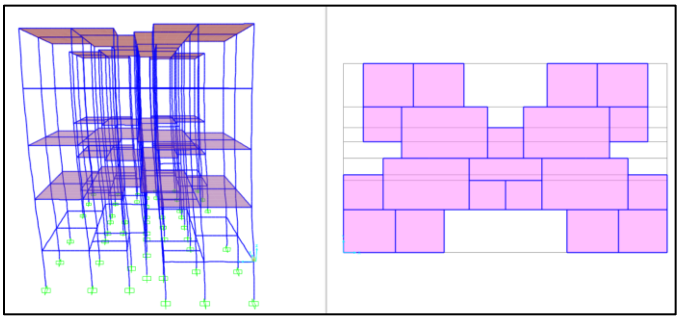

Fig.1.6 Plastic hinge mechanism

5.Conclusion

The study highlights the significance of accurately modeling shear behavior in reinforced concrete (RC) beams and columns. Current design codes such as IS 456: 2000 and ACI 318: 2008 provide ultimate shear strength contributions of web reinforcement, but inconsistencies remain in defining yield strength and shear displacement parameters. Existing models for shear displacement at yield, such as those by Sezen (2002), Panagiotakos and Fardis (2001), and Gerin and Adebar (2004), exhibit varying degrees of reliability. Among these, the Priestley et al. (1996) model is deemed the most effective for predicting shear displacement at yield, while the Park and Paulay (1975) model is most suitable for predicting ultimate shear displacement.

The case study underlines the critical role of incorporating shear hinge models in structural analysis to realistically predict strength and ductility. Neglecting shear failure mechanisms can lead to overestimated base shear and roof displacement capacities, potentially misrepresenting the structural failure mode. By incorporating shear hinges, the analysis correctly identifies non-ductile failure modes, offering better insights for designing safer structures.

5.1 Future Work

This research can be expanded by validating the developed nonlinear shear hinge properties through experimental studies, which would provide empirical support for the proposed models. Additionally, the study's focus on rectangular RC sections with rectangular web reinforcement can be extended to include circular sections with spiral reinforcement. Such an extension would address a broader range of practical applications and enhance the generalizability of the findings. Exploring the effects of varying material properties and reinforcement configurations on shear behavior also presents an opportunity for further investigation.

REFERENCES

1.A.Ghaffar, A.Javed, H.Rehman, K.Ahmed and M hyas, "Development of shear capacity equations for rectangular reinforced beams", Park J Eng. & appl.Sci.Vol.6, pp.

2.ACI 318, Building Code Requirements for Reinforced Concrete, American Concrete Institute, Detroit, Michigan, 2002.

3.Alexander Placas and Paul E. Regan and A.L.L Baker, "Shear failure of reinforced concrete beams," ACI journal, title No.68-67, pp.763-773, October 1971.

4.Applied Technology Council (ATC-40), "Seismic evaluation and retrofit of concrete buildings", Vol.1& 2, California, 1996.

5.ASCE-ACI Task Committee 426, "The Shear Strength of Reinforced Concrete Members," ASCE Journal of Structural Div., Vol. 99, pp. 1091-1187, June 1973.

6.Ali Kadhim Sallal, "Design and analysis ten storied building using ETABS software-2016" Volume 4; Issue 2; May 2018; Page No. 21-27

7.A. Kadid, D. Yahiaoui, "Seismic assessment of braced RC frames.",pg. no. 2899-2905, vol. 14, June 2011.

8.Bharat Patel, Rohan Mali, G. Mohan Ganesh, "Seismic behavior of different bracing systems in high rise RCC buildings." pg. no. 973-981, vol. 8(3), March 2017.

9.Bazant Z P and Kazemi M T, "Size effect on diagonal shear failure of beams without stirrups", ACI Structural Journal, 88(3), pp.268–276, 1991.

10.Bazant Z P and Sun H H, "Size effect in diagonal shear failure: influence of aggregate size and stirrups", ACI Materials Journal, 84(4) pp. 259–272, 1987.

11.Bazant, Z. P., Yu and Qiang, "Design Against Size Effect on Shear Strength of Reinforced Concrete Beams without Stirrups". Structural Engineering Report No.03-02/A466s, Northwestern University, Evanston, Illions, 2003.

12.BS 8110-1, Structural use of concrete, Part 1: Code of Practice for Design and Construction, British Standards Institution, London, 1997.