

Strength Enhancement and Seismic Assessment of Existing Structures

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Abstract— Structural strengthening is an essential technique used to enhance the load carrying capacity, durability, and seismic performance of existing structures. Many buildings and infrastructure systems deteriorate over time due to aging, environmental effects, increased loading, design deficiencies, or changes in functional requirements. Structural strengthening methods are therefore implemented to improve the safety, stability, and service life of such structures without complete demolition and reconstruction. Various strengthening techniques such as reinforced concrete jacketing, steel plate bonding, fiber reinforced polymer (FRP) wrapping, external prestressing, and the addition of shear walls or bracing systems are widely used in structural engineering practice. The present study focuses on evaluating the nonlinear seismic behaviour of the structure using pushover analysis for target displacements of 50 mm, 100 mm and 150 mm. The study examines base shear, lateral displacement and storey drift in the Global X and Y directions to understand the structural response under increasing lateral deformation. The results provide an assessment of the force displacement behaviour and distribution of seismic deformation in the structure. Analytical tools such as pushover analysis and nonlinear structural evaluation are often used to assess the performance of structures before and after strengthening.

Index Terms— Structural strengthening, Retrofitting, Push Over Analysis.

I. INTRODUCTION

The effects of earthquakes on structures can be devastating and sometimes catastrophic. Structures need to be built to withstand seismic activity to mitigate the impacts of such events. The underlying cause of structures collapsing due to earthquakes often has to do with design, construction, and maintenance.

In this article, we discuss the main causes of structural collapse during an earthquake and provide insights for civil engineers on how to design and construct structures that are resilient to seismic activity. One of the main causes of structural collapse during earthquakes is poor design. For instance, buildings that are not designed to withstand the lateral forces exerted by an earthquake can easily collapse. In addition, buildings that are not properly reinforced are also susceptible to collapse. In many cases, the use of sub-standard materials and construction methods can also contribute to the collapse of a structure during an earthquake.

Another cause of the collapse is poor construction. This can happen when buildings are not constructed according to their designed plans. For example, if the foundation of a building is not properly dug or if the building is not properly reinforced, it is more likely to collapse during an earthquake. Retrofitting is the method of treatment of a structure to increase its usable life. The retrofitting may include a number of procedures depending upon the structure, degree of damage, purpose of retrofit, etc. Before moving ahead let us understand why structures fail. Structures are sometimes subjected to loads for which they were originally not designed. These loads may occur due to earthquakes (seismic load), changes in loading patterns, etc. Hence, the structure experiences extraordinary stress and fails under it.

II. CORRESPONDING LITERATURE

A. Strength Enhancement of Existing Structure.

Ahmed Abdi Hassan and Ahmed Adan Yasin: Pushover analysis effectively evaluates seismic

performance through capacity curves, performance points, and plastic hinge formation. Amol Vansing Rathod and Mohammed Ishtiyaque^[1] studied building configuration, masonry infill, and soft-storey conditions significantly influence seismic response, including stiffness, displacement, and drift. Besan Talahmeh et al.^[2] presented Retrofitting techniques such as concrete jacketing and CFRP improve the strength, stiffness, and ductility of existing RC buildings Griffith and Pinto^[3] evaluates masonry infill increases initial stiffness but may crack at higher drift, leading to increased deformation and reduced stiffness. Lakshmanan D et al.^[4] Retrofitting improves structural capacity, stiffness, and ductility, but its effectiveness depends on existing design and construction quality. Abhijit Mukherjee and Amit R. Kalyani^[5] studied fiber-reinforced composites improve structural strength, stiffness, and ductility while providing a lightweight and durable retrofitting solution.

However, Shailesh Agrawal and Ajay Chourasia^[6] presented Pushover analysis demonstrates that retrofitting can improve base shear capacity, deformation capacity, ductility, and energy dissipation. Martellotta et al.^[7] examined X-bracing and V-bracing increase lateral stiffness and strength while reducing displacement and storey drift. Chetankumar Bhailalbhair Patel^[8] presented different retrofitting techniques can improve seismic safety, with selection depending on structural deficiencies and performance requirements. Dr. Durgesh C. Rai^[9] studied seismic evaluation and strengthening using techniques such as shear walls, bracing, jacketing, and FRP can improve structural performance. S. T. Dyavanal and S. A. Vasanwala^[10] presented Pushover analysis helps evaluate seismic performance, identify critical components, and develop suitable retrofitting strategies. H. Krawinkler and G. D. P. K. Seneviratna^[11] examined nonlinear static analysis provides useful information on seismic demand, displacement capacity, plastic hinges, and energy dissipation.

Further, M. N. Fardis^[12] presented retrofitting using jacketing, steel plates, FRP, shear walls, and bracing can improve strength, ductility, and energy dissipation. T. Paulay and M. J. N. Priestley^[13] presented Ductile design, proper reinforcement detailing, and the strong-column weak-beam concept are essential for seismic safety. ATC-40^[14] shows performance-based evaluation using the capacity

spectrum method and pushover analysis helps assess structural performance and strengthening requirements. FEMA-356^[15] gives performance-based seismic evaluation and nonlinear analysis provide a systematic approach for identifying weaknesses and improving structural capacity. Eurocode-8 Committee^[16] focuses on adequate strength, stiffness, ductility, regular configuration, and proper detailing are essential for earthquake-resistant structures. Agarwal and Shrikhande^[17]. Presented appropriate seismic analysis, structural dynamics, and proper detailing are essential for minimizing earthquake damage. S. K. Duggal^[18] gives earthquake resistant design requires adequate strength, ductility, stability, proper configuration, and quality construction practices.

III. OBJECTIVES OF THE STUDY

The main objective of the study is to evaluate the nonlinear seismic behaviour and overall performance of the structure under increasing lateral loads using pushover analysis. The study aims to determine the load carrying and displacement capacity, identify the sequence of plastic hinge formation, and determine the performance point corresponding to seismic demand. It also focuses on identifying weak or critical structural members and possible failure mechanisms, assessing the ductility and deformation capacity, and evaluating the seismic vulnerability of the structure. Furthermore, the study examines force redistribution after members enter the nonlinear range and verifies whether the desired strong column weak beam mechanism is achieved, thereby helping to determine the need for strengthening or retrofitting.

IV. METHOD OF ANALYSIS

1. Modelling and Initial Design: Apply all the static loads in respective load patterns. Also define equivalent static loads for earthquake. Run the analysis and design the structure.
2. Define Hinge Property: At this point I assume you successfully designed (preliminary) your structure. Now unlock the model. We will now assign hinge property to the frames. Remember by assigning hinges at a particular location, we are saying the software that this is the location where hinge can form (because software is a machine, will do

something only if told so) but depending on the load, hinge may or may not form at that location.

3. Define Non-Linear Load Cases: For the sake of simplicity, choose initial conditions as zero initial conditions. In actual project, there will be dead and live load already which you can choose if you want. But you have to create a new nonlinear load case with dead and specified live load and only then you can select that here.
4. Run the Analysis and Interpret the Results: As we go through the steps, we will see some colored dots at location of hinges defined in step 2 denoting acceptance criteria. Acceptance criteria were automatically defined by ETABS when defining hinges. This represents level of damage we could allow in the structures. There are generally three acceptance criteria, namely immediate occupancy, life safety and collapse prevention
5. Obtain the Performance Points: In the same deformed shape, ETABS shows color coding for the extent of inelastic deformation at 4th step (which is corresponding to earthquake I have defined). In my case color shown is green dot. This means beyond immediate occupancy but within the life safety level.

V. STRUCTURAL MODELLING

1. Create the Structural Model
2. Define Load Cases
3. Define Nonlinear Properties
4. Apply Gravity Loads
5. Apply Lateral Loads Incrementally
6. Monitor Roof Displacement.
7. Generate the Capacity Curve
8. Check Plastic Hinge Formation
9. Examine the location and sequence of plastic hinges
10. Identify members approaching or exceeding their performance limits.
11. Check whether the intended ductile failure mechanism is achieved.

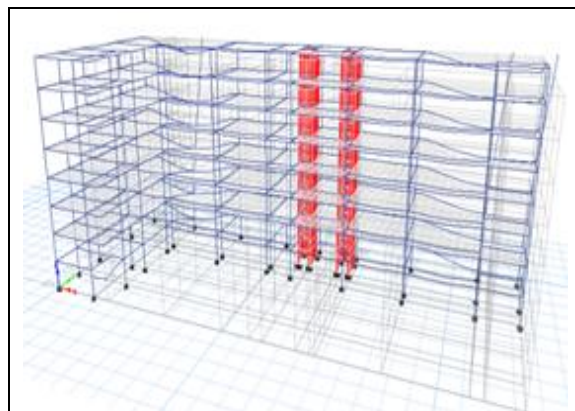


Fig. 1: Structural Model

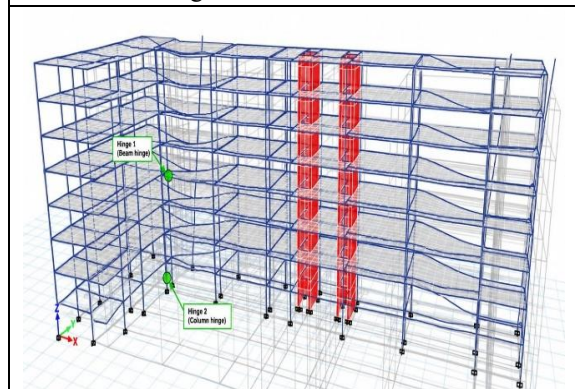


Fig 02: Displacement at 50mm.

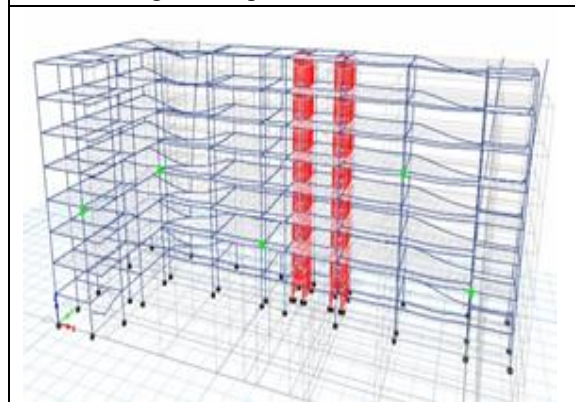


Fig 03: Displacement at 100mm.

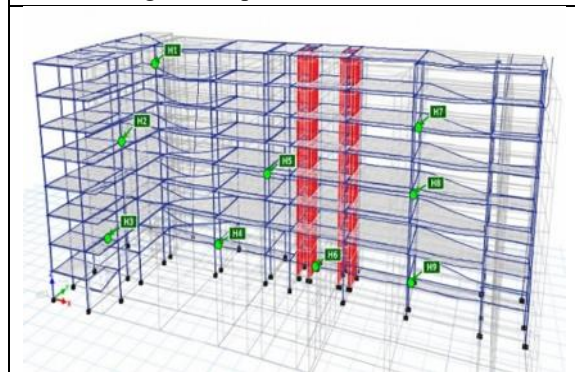


Fig 04: Displacement at 150mm.

VI. PUSHOVER ANALYSIS.

Hinge 1: Beam Hinge

1. The upper green marker is a beam plastic hinge. It occurs near the end of a beam, typically close to the beam-column joint.
2. As lateral earthquake load increases, the beam moment increases. When the moment reaches the beam's yield capacity, the beam starts to yield.
3. Further displacement produces rotation without a large increase in moment.
4. This concentrated inelastic rotation is represented by a plastic hinge.

Hinge 2: Column Hinge

1. The lower green marker is a column plastic hinge. It forms near the base or end of a column when the column reaches its nonlinear capacity. The column undergoes significant buckling and rotation.
3. Column hinging is generally more critical than beam hinging because excessive column yielding can reduce the vertical-load-carrying capacity of the structure.

Interpretation of each hinge

Hinge	Member type	Interpretation
H1	Beam	Plastic rotation has developed in an upper-level beam
H2	Beam	Beam has entered nonlinear/inelastic behavior
H3	Beam	Beam hinge at a lower/intermediate floor
H4	Beam	Beam hinge near the central frame
H5	Beam	Beam hinge at an intermediate floor
H6	Column	Column hinge near the lower part of the frame
H7	Beam	Beam hinge on the right side of the building
H8	Beam	Beam hinge at an intermediate level
H9	Column	Column hinge near the lower level

VII. GGRAPHICAL REPRESENTATION (A).



Fig 5: Graphical representation of story vs drift at displacement of 50 mm.

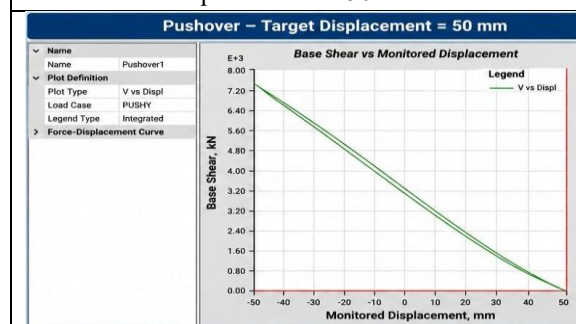


Fig 6: Graphical representation of story vs drift at displacement of 100 mm.



Fig 7: Graphical representation of story vs drift at displacement of 150 mm.



Fig 8: Graphical representation of story vs drift at displacement of 100 mm.

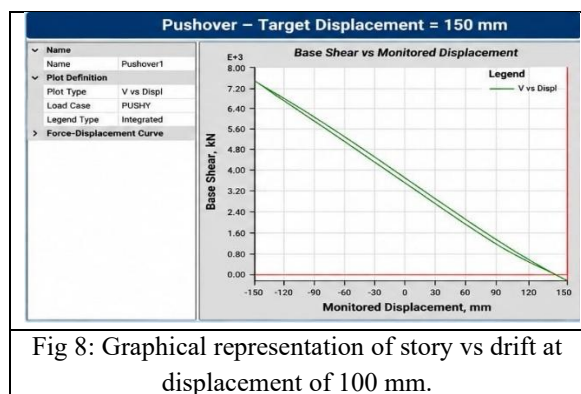


Fig 8: Graphical representation of story vs drift at displacement of 100 mm.

Above Graphical Representation states that Blue curve- Global X direction: The blue curve represents the maximum story drift in the X direction. The important observation is that the X-direction drift is much larger than the Y-direction drift.

Red curve- Global Y direction: The red curve represents maximum story drift in the Y direction. It remains very close to zero compared with the blue curve. This means that, for this particular pushover case, the structure is undergoing much more lateral deformation in X than in Y.

Target displacement	Approx. maximum X-direction drift	Equivalent drift
50 mm	0.0047	0.47%
100 mm	0.0093	0.93%
150 mm	0.0143	1.43%

1. The three graphs demonstrate a consistent increase in lateral deformation with increasing pushover target displacement.
2. At a target displacement of 50 mm, the maximum X-direction story drift is approximately 0.47%. When the target displacement is increased to 100 mm, the maximum drift increases to approximately 0.93%, and at 150 mm it reaches approximately 1.43%.
3. The Y-direction drift remains comparatively small throughout. The upper stories experience the larger X-direction story drifts in the results shown.

Target displacement	Displacement range shown	Approx. maximum plotted base shear
50 mm	-50 to +50 mm	~7200 kN
100 mm	-100 to +100 mm	~7200 kN
150 mm	-150 to +150 mm	~7200 kN

1. The base shear versus monitored displacement plots were obtained for target displacements of 50 mm, 100 mm, 150 mm, and 1000 mm.
2. The results show a similar maximum base-shear scale of approximately 7.2×10^3 kN for the different target displacement cases, while the monitored displacement range increases progressively.
3. The plotted response exhibits a decreasing trend in the selected force-displacement sign convention.
4. Therefore, the sign convention and actual nonlinear force-displacement data should be considered before interpreting the descending curve as structural strength degradation.
5. The corresponding story-drift results indicate increasing lateral deformation as the target displacement increases.

VIII CONCLUSION

From the present studies following broad conclusions are drawn:

- Lateral deformation increases with increasing target displacement from 50 mm to 150 mm.
- Maximum Global X-direction storey drift increased from approximately 0.47% at 50 mm to 0.93% at 100 mm and 1.43% at 150 mm.
- Global Y-direction drift remained relatively small, indicating that the structural response was predominantly in the Global X direction.
- Higher-storey levels experienced relatively greater deformation compared with the lower storeys.
- The maximum observed base shear was approximately 7,200 kN.
- Increasing target displacement mainly increased the displacement range, while the overall base-shear level remained approximately similar.

Overall, the pushover analysis indicates a progressive increase in lateral deformation and storey drift with increasing target displacement.

- The results provide useful information regarding the force displacement behaviour, deformation pattern and seismic response of the structure.
- The obtained displacement and drift should be compared with applicable code limits and

performance-level criteria to assess the need for strengthening or retrofitting.

REFERENCES

- [1] Hassan and A. A. Yasin, "Seismic performance evaluation of reinforced concrete buildings using pushover analysis," *Int. J. Civil Struct. Eng.*, vol. 6, no. 2, pp. 245–252, 2015.
- [2] V. Rathod and M. Ishtiyaque, "Seismic evaluation of reinforced concrete buildings with soft storey using pushover analysis," *Int. J. Eng. Res. Appl. (IJERA)*, vol. 6, no. 5, pp. 52–58, 2016.
- [3] Talahmeh, *et al.*, "Seismic strengthening of reinforced concrete structures using CFRP and concrete jacketing," *J. Struct. Eng.*, vol. 140, no. 9, pp. 1–10, 2014.
- [4] M. C. Griffith and A. V. Pinto, "Seismic behavior of masonry infilled reinforced concrete frames," *Earthquake Eng. Struct. Dyn.*, vol. 31, no. 7, pp. 1425–1444, 2002.
- [5] Lakshmanan, "Behavior of reinforced concrete beam-column joints under seismic loading," *J. Struct. Eng.*, vol. 134, no. 5, pp. 856–864, 2008.
- [6] Mukherjee and A. R. Kalyani, "Seismic strengthening of reinforced concrete structures using fiber reinforced polymer composites," *J. Struct. Eng.*, vol. 128, no. 6, pp. 748–754, 2002.
- [7] S. Agrawal and A. Chourasia, "Evaluation of seismic performance of RC buildings using nonlinear pushover analysis," *Int. J. Civil Eng. Res.*, vol. 5, no. 3, pp. 227–234, 2014.
- [8] F. Martellotta, *et al.*, "Effect of bracing systems on the seismic behavior of reinforced concrete frame structures," *Engineering Structures*, vol. 52, pp. 76–85, 2013.
- [9] B. Patel, "Seismic retrofitting techniques for reinforced concrete buildings: A review," *Int. J. Adv. Struct. Eng.*, vol. 5, no. 12, pp. 1–9, 2013.
- [10] C. Rai, *Seismic Evaluation and Strengthening of Existing Buildings*. Kanpur, India: Indian Institute of Technology Kanpur, National Institute of Technology Kanpur, National Information Centre of Earthquake Engineering (NICEE), 2005.
- [11] S. T. Dyavanal and S. A. Vasanwala, "Nonlinear static pushover analysis of multi-storey reinforced concrete buildings," *Int. J. Eng. Res. Technol. (IJERT)*, vol. 3, no. 6, pp. 101–107, 2014.
- [12] H. Krawinkler and G. D. P. K. Seneviratna, "Pros and cons of a pushover analysis of seismic performance evaluation," *Engineering Structures*, vol. 20, nos. 4–6, pp. 452–464, 1998.
- [13] M. N. Fardis, *Seismic Design, Assessment and Retrofitting of Concrete Buildings*. Dordrecht, Netherlands: Springer, 2009.
- [14] T. Paulay and M. J. N. Priestley, *Seismic Design of Reinforced Concrete and Masonry Buildings*. New York, NY, USA: John Wiley & Sons, 1992.
- [15] Applied Technology Council (ATC), *ATC-40: Seismic Evaluation and Retrofit of Concrete Buildings*. Redwood City, CA, USA: Applied Technology Council, 1996.
- [16] Federal Emergency Management Agency (FEMA), *FEMA-356: Prestandard and Commentary for Seismic Rehabilitation of Buildings*. Washington, DC, USA: Federal Emergency Management Agency, 2000.
- [17] European Committee for Standardization, *Eurocode 8: Design of Structures for Earthquake Resistance, EN 1998*. Brussels, Belgium: European Committee for Standardization, 2004.
- [18] P. Agarwal and M. Shrikhande, *Earthquake Resistant Design of Structures*. New Delhi, India: Prentice Hall of India, 2006.
- [19] S. K. Duggal, *Earthquake Resistant Design of Structures*. New Delhi, India: Oxford University Press, 2010.
- [20] Bureau of Indian Standards, *IS 1893 (Part 1): Criteria for Earthquake Resistant Design of Structures*. New Delhi, India: Bureau of Indian Standards, 2016.