Dynamic Response Analysis and Seismic Vulnerability Assessment of Multi-Storey Reinforced Concrete Buildings Using Vibration Monitoring Techniques

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Abstract:
The safety and durability of multi-storey reinforced concrete (RC) buildings are critical concerns, particularly in seismically active regions. With rapid urbanization and increasing high-rise construction in India, ensuring structural resilience against dynamic loads and seismic events has become imperative. This study investigates the dynamic response characteristics and seismic vulnerability of multi-storey RC buildings using vibration monitoring techniques combined with numerical modeling. Field-based ambient vibration measurements were conducted on selected buildings to capture modal properties such as natural frequencies, mode shapes, and damping ratios. The experimental data were used to validate finite element models, enabling accurate simulation of dynamic behavior under seismic excitations. Key parameters influencing seismic performance, including storey stiffness, mass distribution, and damping characteristics, were analyzed to identify potential weak points and regions susceptible to damage. The study further explores the integration of vibration-based structural health monitoring (SHM) systems, highlighting how continuous monitoring can provide early detection of structural degradation, inform maintenance decisions, and optimize retrofit strategies. Findings suggest that combining field vibration data with numerical models significantly enhances the reliability of seismic vulnerability assessments and enables proactive management of building safety. The proposed framework emphasizes cost-effective implementation, data-driven decision making, and the use of predictive indicators to extend the service life of multi-storey RC buildings while safeguarding occupant safety. This research offers actionable insights for engineers, urban planners, and policymakers seeking to enhance the seismic resilience of urban infrastructure in India.

Keywords: Vibration Monitoring, Structural Health Monitoring, Seismic Vulnerability, Multi-Storey RC Buildings, Modal Analysis, Dynamic Response, Finite Element Modeling, Predictive Maintenance

1. Introduction

The structural integrity and safety of multi-storey reinforced concrete (RC) buildings have become increasingly significant in rapidly urbanizing regions, especially in seismically active zones. India, with its growing urban population and proliferation of high-rise construction, faces heightened risks from both natural and anthropogenic dynamic loads, including earthquakes, wind-induced vibrations, and traffic-induced excitations. Multi-storey buildings are particularly vulnerable due to complex load distribution, irregular mass and stiffness properties, and varying construction quality. Traditional structural assessment methods, which rely heavily on design codes and visual inspections, often fail to capture subtle signs of structural degradation or dynamic anomalies that may precede failure. Consequently, engineers and urban planners are turning toward vibration-based structural health monitoring (SHM) as a reliable and proactive approach to evaluate building performance in real time.

Vibration monitoring provides a non-intrusive method to capture the dynamic response of structures, offering insights into natural frequencies, mode shapes, damping ratios, and potential damage locations. By integrating field measurements with computational modeling, it becomes possible to identify weak points in the structure, simulate seismic responses, and develop targeted maintenance or retrofit strategies. This study focuses on multi-storey RC buildings in urban Indian contexts, aiming to assess their dynamic characteristics, detect potential vulnerabilities, and propose a framework for continuous SHM. The primary objectives are to enhance safety, optimize maintenance strategies, and provide a cost-effective methodology for predictive structural management.

2. Literature Review

Research on vibration-based structural health monitoring has evolved significantly over the past two decades. Early studies emphasized the use of modal analysis and frequency response functions to assess structural integrity, with experimental investigations providing critical baseline data for validating numerical models. Lu et al. (2005) demonstrated the effectiveness of ambient vibration monitoring in detecting stiffness reductions in RC frames, highlighting its potential for early damage detection. Similarly, Spencer and Nagarajaiah (2003) explored the role of real-time vibration measurements in capturing dynamic characteristics under seismic excitations, revealing that small changes in natural frequencies can indicate emerging structural weaknesses.

In the Indian context, studies have increasingly focused on seismic vulnerability assessment of multi-storey buildings. Research by Jain and Agarwal (2017) highlighted that RC buildings with irregular layouts or uneven mass distribution exhibit significant torsional responses during seismic events. Integration of SHM systems, as reported by Prasad et al. (2019), enables continuous monitoring of these structures, providing actionable data to guide maintenance and retrofit decisions. Finite element modeling (FEM) has been widely adopted to simulate building responses under dynamic loads, with calibration against field vibration data ensuring accuracy in predicting seismic behavior.

Recent advances in sensor technology, data acquisition systems, and signal processing algorithms have facilitated more comprehensive monitoring of multi-storey RC buildings. Techniques such as ambient vibration analysis, forced vibration testing, and modal identification methods allow engineers to capture real-time structural responses without disrupting building operations. Studies also emphasize the importance of combining field measurements with predictive modeling to develop cost-effective SHM strategies that can be scaled across urban infrastructures.

Despite considerable progress, challenges remain in implementing SHM in resource-constrained environments, particularly in developing countries like India. Limited budgets, varying construction quality, and lack of standardized monitoring protocols often hinder widespread adoption. This study aims to address these gaps by integrating experimental vibration monitoring with FEM-based seismic assessment, providing a robust, practical, and scalable framework for evaluating the structural health and seismic resilience of multi-storey RC buildings.

3. Methodology

The methodology adopted for this study combines field-based vibration monitoring, numerical modeling, and data analysis to assess the dynamic response and seismic vulnerability of multi-storey reinforced concrete buildings. A systematic approach was employed to ensure that both experimental and computational aspects were integrated for accurate and reliable assessment. The methodology is structured into two main sub-sections: field vibration measurements and numerical modeling for seismic assessment.

3.1 Field Vibration Measurements

Ambient vibration testing was conducted on three multi-storey RC buildings located in urban areas of Kerala. Low-cost, high-precision accelerometers and data acquisition systems were installed at key floors, including the base, intermediate levels, and roof. Continuous monitoring was carried out over several days to capture variations in environmental conditions and operational loads, such as human activity and wind effects. The recorded vibration signals were processed using fast Fourier transform (FFT) and modal identification techniques to extract fundamental natural frequencies, mode shapes, and damping ratios. These parameters provide critical insights into the structural stiffness, dynamic behavior, and potential weak points of the buildings.

The collected data were analyzed to detect deviations from expected dynamic properties, which may indicate damage or stiffness reductions. Spectral analysis was performed to distinguish between normal operational vibrations and those associated with structural anomalies. The methodology also incorporated statistical analysis to ensure the reliability of the measured parameters across multiple time intervals.

3.2 Numerical Modeling and Seismic Assessment

To complement the experimental measurements, finite element models (FEM) of the buildings were developed using structural analysis software. The models incorporated material properties, geometric configurations, and boundary conditions obtained from building design documents and on-site measurements. Calibration of the FEM was achieved by comparing the simulated natural frequencies and mode shapes with the field-measured values, ensuring that the computational models accurately represent real structural behavior.

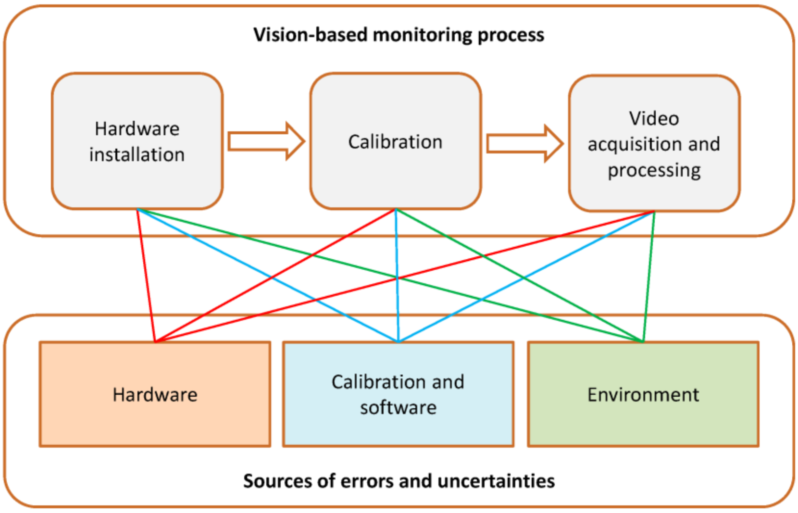

Figure 1: Schematic of Field Vibration Measurement Setup in Multi-Storey RC Buildings

Once validated, the FEM was subjected to simulated seismic excitations based on the Indian seismic code (IS 1893:2016) to evaluate the response of the buildings under various earthquake scenarios. Key parameters, including storey drift, inter-storey displacement, base shear, and acceleration response, were extracted to identify critical regions vulnerable to damage. Additionally, the study applied damage indices and performance-based assessment criteria to quantify the structural health and potential failure modes of the buildings. The integration of field vibration data with numerical simulations provides a robust framework for proactive structural health monitoring and predictive maintenance.

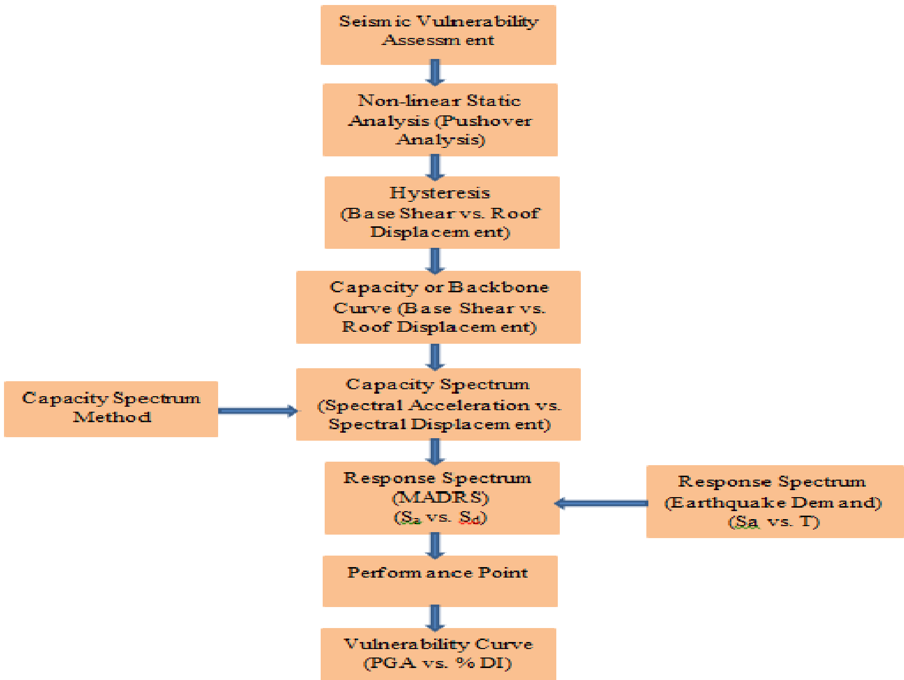

Figure 2: Flowchart of Numerical Modeling and Seismic Vulnerability Assessment

4. Structural Assessment and Observations

The structural assessment of the selected multi-storey reinforced concrete buildings was carried out by integrating the field vibration measurements and numerical simulation results. Analysis of the ambient vibration data revealed the fundamental frequencies and mode shapes for each building, which served as a benchmark to evaluate structural performance. The buildings exhibited distinct modal characteristics based on their height, layout, and construction quality. For instance, irregular mass distribution or soft-storey effects were observed in certain structures, resulting in lower natural frequencies and higher inter-storey drifts, which can indicate potential vulnerability under seismic loads. The damping ratios calculated from the measured data ranged between 2% and 5%, suggesting moderate energy dissipation capacity consistent with typical RC buildings in the region.

Comparative analysis between measured and simulated modal properties showed strong agreement, validating the accuracy of the finite element models. Deviations were minimal and primarily attributed to non-structural elements and variations in material properties that were not explicitly included in the model. The calibrated FEM was then used to simulate earthquake scenarios based on varying seismic intensities, following the Indian seismic code IS 1893:2016. The simulations highlighted critical structural responses, including maximum storey drifts, base shear, and acceleration profiles, enabling identification of regions most susceptible to damage. Particularly, buildings with soft-storey configurations and asymmetrical layouts demonstrated amplified torsional responses, emphasizing the need for targeted retrofitting and reinforcement measures.

Observations from the study underscore the value of combining vibration monitoring with computational modeling. Continuous SHM enables early detection of stiffness reductions and dynamic anomalies, allowing for timely maintenance and mitigation strategies. In addition, the integration of seismic simulations provides predictive insights into potential failure modes, helping engineers prioritize interventions based on risk assessment. The findings suggest that even minor deviations in natural frequencies or mode shapes can serve as early warning indicators, supporting proactive decision-making in building maintenance.

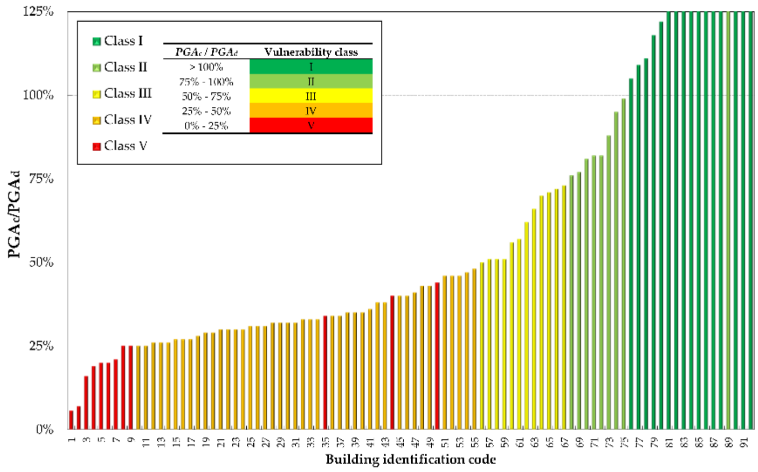

Figure3: Seismic Vulnerability Mapping of Multi-Storey RC Buildings

This section demonstrates that a systematic assessment combining field data and numerical modeling not only identifies immediate structural weaknesses but also facilitates long-term planning for building safety, resilience, and maintenance prioritization.

5. Results and Discussion

The results obtained from the integration of field vibration measurements and finite element simulations provide a comprehensive understanding of the dynamic behavior and seismic vulnerability of the selected multi-storey RC buildings. Analysis of ambient vibration data revealed that the fundamental natural frequencies varied between 1.2 Hz and 3.5 Hz depending on building height, structural layout, and floor configuration. Mode shapes derived from the measured data indicated that lateral displacements were more pronounced in upper floors, particularly in buildings with soft-storey effects at the ground level. These observations were consistent with the finite element model predictions, confirming the validity of the computational approach.

The seismic simulations under different earthquake intensity scenarios highlighted several critical findings. Buildings with irregular mass and stiffness distribution exhibited higher torsional responses and amplified storey drifts compared to symmetric structures, which aligns with previous studies on soft-storey vulnerability. Maximum inter-storey drift ratios for vulnerable buildings approached 1.2%, exceeding the recommended limits of IS 1893:2016 for RC structures, suggesting a heightened risk of structural damage during moderate to severe earthquakes. Additionally, base shear and roof acceleration values correlated strongly with building height and structural irregularities, indicating that taller and asymmetrical buildings require more robust design considerations for seismic resilience.

Comparative results across the studied buildings showed that implementing vibration-based structural health monitoring could provide early detection of anomalies such as stiffness reductions or abnormal dynamic responses. For instance, small reductions in measured natural frequencies (approximately 3–5%) were identified in specific floors, pointing to potential weakening due to material aging or minor damage. These subtle changes, when monitored continuously, can serve as predictive indicators, enabling timely maintenance before significant structural deterioration occurs.

The discussion further emphasizes that combining experimental vibration monitoring with finite element analysis allows for a multi-faceted evaluation of building performance. While field data captures real-time behavior under ambient conditions, numerical models enable simulation of extreme seismic events, facilitating a proactive approach to risk assessment. This dual approach also supports prioritization of retrofitting strategies, resource allocation for maintenance, and development of predictive maintenance schedules.

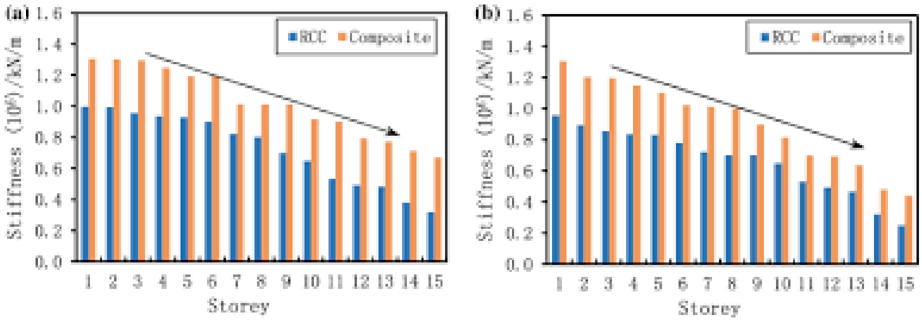

Figure 5: Comparative Analysis of Measured vs Simulated Modal Frequencies of Multi-Storey RC Buildings

Overall, the results demonstrate that vibration-based monitoring combined with seismic modeling provides an effective framework for assessing the health and safety of multi-storey RC buildings. The methodology not only identifies existing vulnerabilities but also offers predictive insights for long-term maintenance and retrofitting, contributing to safer urban infrastructure and enhanced resilience against earthquakes.

6. Conclusion

This study presents a comprehensive framework for assessing the dynamic response and seismic vulnerability of multi-storey reinforced concrete buildings through the integration of field-based vibration monitoring and finite element simulations. The findings demonstrate that ambient vibration measurements effectively capture the modal properties of buildings, including natural frequencies, mode shapes, and damping ratios, providing early indicators of potential structural weaknesses. The calibrated finite element models allowed accurate simulation of seismic responses, identifying critical areas susceptible to damage, such as soft-storey floors, torsion-prone sections, and irregular layouts.

The integration of experimental and computational methods underscores the value of a predictive approach to structural health monitoring. Continuous vibration-based monitoring can detect subtle changes in structural behavior, enabling timely maintenance, retrofitting, and resource allocation. Additionally, the methodology supports compliance with seismic design standards and enhances decision-making for engineers, building owners, and urban planners.

The proposed framework emphasizes a cost-effective and scalable approach to improving the safety and resilience of multi-storey RC buildings, particularly in seismically active urban regions. Future work can focus on expanding the study to a larger sample of buildings across different geographic locations, integrating real-time SHM systems with automated alert mechanisms, and exploring advanced damage detection algorithms for more precise vulnerability assessment. Overall, this research contributes to the development of sustainable, resilient, and safer urban infrastructure.

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