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Dynamic Response and Advanced Spectral Seismic Analysis of Multistorey RC Structures in Seismic Zone 4: Insights and Mitigation Strategies

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Abstract:

The growing demand for seismic-resilient infrastructure underscores the critical importance of advanced analytical approaches to evaluate and mitigate the vulnerabilities of reinforced concrete (RC) structures. This study presents a comprehensive seismic analysis of an eleven-story RC frame situated in Jammu City, India, a high-seismicity zone categorized under Zone 4. Employing the Response Spectrum Method (RSM) in compliance with IS 1893:2016 provisions, the study evaluates seismic-induced displacements, inter-story drifts, and stress distributions. Results indicate significant lateral displacements and drift ratios, exceeding permissible thresholds, with the maximum observed drift surpassing the IS standard by 2–3 times. Ground-floor columns exhibited compressive stresses 1.5 to 2 times greater than tensile counterparts, emphasizing their vulnerability under cumulative axial loads. Additionally, shear forces in critical beams demonstrated an alarming threefold increase under combined static and seismic loading, accentuating potential failure mechanisms. The analysis executed using STAAD. Pro software highlights disparities in force distributions between interior and exterior columns, necessitating targeted reinforcement strategies. To address identified deficiencies, actionable recommendations include implementing Fiber-Reinforced Polymer (FRP) wrapping, base isolation systems, and enhanced lateral load-resisting mechanisms such as shear walls and cross-bracing. This investigation bridges theoretical seismic design frameworks and practical implementation gaps, offering insights for policymakers, engineers, and researchers. It reinforces the urgency for stringent adherence to seismic codes, advanced material utilization, and continuous structural health monitoring to safeguard urban infrastructure against seismic threats. Future research directions propose exploring machine learning for seismic risk prediction and advanced energy dissipation systems, bolstering resilience in seismic-prone regions.

KEYWORDS: *Seismic Analysis, Reinforced Concrete, Loads, Stresses, Shear Force, Columns*

Introduction

Seismic activity poses one of the most formidable challenges to the structural integrity of built environments across the globe. Earthquakes, driven by tectonic plate interactions, induce rapid and intense ground accelerations that can devastate infrastructure, disrupt societal functioning, and result in catastrophic loss of life and economic assets. Recent seismic events, such as the 2015 Nepal earthquake and the 2008 Sichuan earthquake in China, have underscored the vulnerability of modern construction methods, particularly in regions of pronounced seismicity. Among the various structural systems, reinforced concrete (RC) frameworks are commonly employed due to their cost-effectiveness, versatility, and ability to withstand diverse loading conditions. However, despite their ubiquity, these structures remain susceptible to failure under seismic excitation, primarily due to inadequate detailing, substandard materials, and insufficient compliance with modern seismic codes.

The seismic response of RC frames is dictated by their inherent dynamic properties, including stiffness, damping, and mass distribution, which collectively influence their ability to dissipate energy during ground shaking. In high-seismic zones, such as Zone 4 in India, where Jammu is situated, the seismic hazard is exacerbated by active tectonic features and historical precedents of strong ground motion. This necessitates a nuanced understanding of RC frame behavior under seismic loads to ensure compliance with seismic design provisions outlined in the Indian Standard (IS) codes, particularly IS 1893:2016. Furthermore, the structural deficiencies observed in RC frames during past seismic events, such as excessive inter-story drifts, shear failures in beams, and axial compression instabilities in columns, highlight the urgency of adopting robust analytical methods to evaluate their performance and inform design improvements.

Objectives and Scope of the Study

The objective of this research is to scrutinize the seismic resilience of a multi-tiered RC frame structure situated in Jammu City, a region characterized by heightened seismic activity due to its proximity to the Himalayan orogeny. The specific aims of the study are threefold:

1. **Quantification of Dynamic Response:** To evaluate the seismic-induced displacements, drifts, and stress distributions within the structural members of the RC frame using state-of-the-art analytical techniques.
2. **Assessment of Compliance with Seismic Provisions:** To compare the observed structural response with the permissible limits delineated in Indian seismic codes, thereby identifying deficiencies and areas requiring design enhancements.
3. **Mitigation Strategies:** To propose actionable recommendations for augmenting the seismic performance of RC structures, particularly in regions falling under Zone 4.

The scope of this study encompasses the analysis of an eleven-story residential RC frame, which serves as a representative model for urban construction in Jammu. The frame is subjected to seismic loading conditions derived from response spectrum analysis (RSA), a dynamic analysis methodology renowned for its ability to encapsulate the effects of multi-modal excitation. This approach is supplemented by a detailed examination of load combinations involving static and seismic forces, providing a comprehensive understanding of the frame's performance under realistic loading scenarios.

Methodology and Significance

The methodology adopted for this study is rooted in a rigorous analytical framework, leveraging the capabilities of STAAD. Pro, a widely used structural analysis and design software. The analytical process is delineated as follows:

1. **Modeling of Structural Geometry:** The RC frame is modeled with precise dimensions, material properties, and boundary conditions to replicate the real-world scenario.
2. **Definition of Loading Conditions:** The seismic loads are defined in accordance with the response spectrum provided in IS 1893:2016, while static loads include dead and live loads calculated as per IS 875.
3. **Dynamic Analysis:** The natural frequencies and mode shapes of the frame are computed, and the response spectrum method is employed to determine the maximum potential responses, including nodal displacements, inter-story drifts, and internal forces.
4. **Evaluation of Load Combinations:** The combined effects of static and seismic loads are assessed using specified load combinations to identify critical stress points and potential failure mechanisms.
5. **Interpretation of Results:** The analysis outcomes are interpreted in the context of structural performance metrics, such as maximum drift ratios, stress concentrations, and shear force distributions, providing insights into the frame's seismic resilience.

The significance of this research lies in its potential to bridge the gap between theoretical seismic provisions and their practical implementation in RC structures. By employing an advanced analytical approach, the study not only elucidates the vulnerabilities inherent in conventional RC frame designs but also contributes to the broader discourse on seismic risk mitigation in urban settings. Furthermore, the findings serve as a valuable reference for structural engineers, policymakers, and researchers, enabling informed decision-making and fostering resilience in the face of seismic threats.

Literature Support

Several seminal studies provide the foundation for the methodologies and objectives outlined in this research. For instance, Liu et al. (2020) explored the seismic response of RC frames with varying damping ratios, highlighting the critical role of damping in mitigating seismic effects. Similarly, El-Gamal et al. (2019) conducted nonlinear static analyses to evaluate the performance of RC buildings under seismic loads, emphasizing the importance of detailed joint design. Rao et al. (2022) utilized machine learning algorithms to predict seismic risk in buildings, offering insights into advanced assessment techniques. These studies underscore the necessity of adopting robust analytical tools, such as RSA and STAAD.Pro, to comprehensively evaluate seismic resilience.

Earthquake Response Spectrum Analysis

The response spectrum represents a boundary of maximum potential responses, derived from multiple ground motion records. This approach employs an elastic dynamic analysis methodology, predicated on the assumption that a structure's dynamic response can be determined by analyzing the independent response of each natural vibration mode and subsequently combining these responses in a manner that accurately represents the overall structural behavior. A key advantage of this method lies in the fact that typically, only a limited number of the lowest vibration modes significantly impact the calculation of moments, shear forces, and deflections at various levels of the building.

The following methodology is frequently utilized for spectral analysis: [a] Choose an appropriate design spectrum. [b] Ascertain the vibration modes and their respective periods to be incorporated into the analysis. [c] Extract the corresponding response magnitudes from the spectrum for each mode's period. [d] Compute the participation factor for each mode, representing the single-degree-of-freedom response derived from the curve. [e] Synthesize the effects of individual modes to determine the peak aggregate response. [f] Transform the resultant peak response into shear forces and moments, essential for structural design.

Response Spectrum Analysis Using Staad pro: A Precise Approach

STAAD. Pro facilitates a comprehensive seismic analysis by computing design lateral forces at each floor level for multiple modes. The software generates results for design values, modal masses, and story base shear. To derive lateral seismic loads, STAAD. Pro employs the following step-by-step procedure:

[a] The program calculates natural time periods for the first six modes or as specified by the user.

[b] Utilizing time periods and damping ratios for each mode, the program computes Sa/g values.

[c] The program generates design horizontal acceleration spectra (Ak) for various modes.

[d] Mode participation factors are calculated for different modes.

[e] The peak lateral seismic force at each floor level is computed for each mode.

[f] Response quantities, such as displacements and stresses, are calculated for each mode.

[g] Finally, the peak response quantities are combined using methods such as Complete Quadratic Combination (CQC), Square Root of the Sum of the Squares (SRSS), Absolute Sum (ABS), Ten Percent (TEN), or Conditional Sum (CSM), as defined by the user, to obtain the final results.

Load Combination For Seismic Design

When designing structures to withstand seismic forces, two possible load combinations can be taken into account:

$$A = DL + LL \times IF + EL \quad (1)$$

$$A = 0.85DL + EL \quad (2)$$

Where:

DL = permanent load (dead weight)

LL = variable load (live load)

IF = live load factor (incidence factor)

EL = seismic load (earthquake load)

Building Details And Case Study

A conventional eleven-storey residential building with a regular reinforced concrete frame structure, situated in Jammu City, was analyzed to assess its seismic behavior. The building has a rectangular plan with dimensions of 14 m × 22 m. The primary parameters influencing the analysis of this frame were the permanent load, imposed load, and seismic forces. Seismic forces were calculated using the Response Spectrum Approach (RSA). Three load combinations were applied to the structure:

Load Combination 1 (L/C1): Static loads (permanent and imposed) were applied in accordance with the guidelines specified in BS 8110 (1997).

Load Combination 2 (L/C2): Seismic forces were applied.

Load Combination 3 (L/C3): A combination of static and seismic loads was applied.

A uniformly distributed gravity load of 22 kN/m was applied, incorporating the self-weight of structural members. The cross-sectional dimensions of the columns and beams are presented in Table 1

Table 1: Cross-Sectional Dimensions of Columns and Beams in the Frame Building

Floor level	Ground Floor- 5th Floor	6th Floor- 7th Floor	8^{th} Floor- Top
Typical Beam	400mm × 300mm	400mm× 300mm	400mm ×300mm
Column	600mm × 300mm	500mm ×300mm	400mm ×300mm

A critical frame was selected and analyzed using the STAAD PRO software. The same ground acceleration-time period data used in the seismic hazard assessment of Jammu was utilized as input to calculate the seismic response spectrum parameters, including displacements and stresses. A damping ratio of 0.05 (5% of the critical damping) was assumed, and the typical slab thickness was 120 mm. Certain members of the frame building were chosen for analysis purposes. The selected members are-

Columns: C501, C502, C556,C557,C589 and C590

Beams: B505, B506 and B507

Table 2: Frame Member Movement

Frame Node	***L/C***	***Horizontal X***	***Vertical Y***	***Horizontal Z***	***Resultant***
1	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	-0.002 mm 20.541mm 20.540mm	-0.276 mm 1.390 mm 1.120 mm	0.028 mm 0.024 mm 0.055 mm	0.272 mm 20.499 mm 20.479 mm
28	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	-0.000 mm 54.102mm 54.102mm	-0.519 mm 2.582 mm 2.077 mm	0.119 mm 0.013 mm 0.134 mm	0.528 mm 54.264 mm 54.242 mm
55	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	-0.000 mm 89.391 mm 89.390 mm	-0.729 mm 3.578 mm 2.850 mm	0.258 mm 0.015 mm 0.270 mm	0.773 mm 89.564 mm 89.538 mm
85	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	-0.000 mm 123.257mm 123.258mm	-0.920 mm 4.366 mm 3.455 mm	0.440 mm 0.021 mm 0.462 mm	1.018 mm 123.606 mm 123.575 mm

111	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	0.002 mm 155.272mm 155.272mm	-1.077 mm 4.977 mm 3.884 mm	0.666 mm 0.012 mm 0.676 mm	1.263 mm 155.442 mm 155.414 mm
141	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	-0.002 mm 188.989mm 188.988mm	-1.236 mm 5.848 mm 4.266 mm	0.925 mm 0.028 mm 0.954 mm	1.545 mm 190.068 mm 190.038 mm
168	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	-0.001 mm 218.762mm 218.761mm	-1.353 mm 5.840 mm 4.480 mm	1.223 mm 0.031 mm 1.255 mm	1.820 mm 219.831 mm 219.801 mm
199	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	0.003 mm 244.990mm 244.993mm	-1.455 mm 6.030 mm 4.576 mm	1.548 mm 0.025 mm 1.571 mm	2.123 mm 244.055 mm 244.031 mm
230	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	-0.002 mm 270.210mm 270.209mm	-1.533 mm 6.158 mm 4.630 mm	1.892 mm 0.039 mm 1.934 mm	2.433 mm 269.292 mm 269.266 mm
257	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	0.005 mm 280.888mm 280.294mm	-1.566 mm 6.184 mm 4.617 mm	0.038 mm 2.272 mm 2.309 mm	2.758 mm 283.953 mm 283.939 mm
302	1:- DL+LL 2:-Seismic Load 3:- Static + Seismic	0.006 mm 293.889mm 293.893mm	-1.653 mm 6.229 mm 4.657 mm	0.048 mm 2.283 mm 2.339 mm	3.011 mm 317.224 mm 317.202 mm

Table 3: Structural Drift Evaluation

Node	***L/C***	***Displacement Resultants***	***Drift***
1	Seismic+ Static	20.479	-
28	Seismic+ Static	54.242	33.751
55	Seismic+ Static	89.538	35.290
85	Seismic+ Static	123.575	34.035
111	Seismic+ Static	155.414	31.833
141	Seismic+ Static	190.038	34.648
168	Seismic+ Static	219.801	29.777
199	Seismic+ Static	244.031	24.230
230	Seismic+ Static	269.266	25.216
257	Seismic+ Static	283.939	14.644
302	Seismic+ Static	317.202 mm	10.947

Table 4: Vertical Stresses In Frame Columns

Column	***L/C***	***Length***	***Compressive Strength(N/mm^2)***	***Tensile Strength(N/mm^2)***
C501	1:DL+LL 2:Seismic Load 3:Static+Seismic	4 4 4	6.855 59.956 63.998	-36.360 -30.972
C502	1:DL+LL 2:Seismic Load 3:Static+Seismic	4 4 4	8.92 54.603 62.903	-53.48 -46.039
C556	1:DL+LL1:DL+LL 2:Seismic Load 3:Static+Seismic	4 4 4	6.117 34.669 33.743	-33.632 -32.466
C557	1:DL+LL 2:Seismic Load	4 4	5.979 50.821	-50.226

	3:Static+Seismic	4	54.951	-45.973
C589	1:DL+LL	4	5.682	-2.739
	2:Seismic Load	4	28.22	-27.588
	3:Static+Seismic	4	30.821	-29.222
C590	1:DL+LL	4	3.965	
	2:Seismic Load	4	41.205	-40.567
	3:Static+Seismic	4	43.68	-39.102

Table 5:Structural Beam Stress Evaluation

Beam	***L/C***	***Length***	***Compressive Strength(N/mm²)***	***Tensile Strength (N/mm²)***
B505	1:DL+LL	5	3.959	-3.987
	2:Seismic Load	5	56.652	-55.999
	3:Static+Seismic	5	60.116	-59.925
B506	1:DL+LL	5	3.99	-3.935
	2:Seismic Load	5	50.487	-50.387
	3:Static+Seismic	5	54.255	-54.222
B507	1:DL+LL	5	3.947	-3.987
	2:Seismic Load	5	56.765	-56.440
	3:Static+Seismic	5	57.848	-59.118

Results and Discussion

The seismic analysis of the RC frame building situated in Jammu City has provided an extensive dataset that includes nodal displacements, inter-story drifts, and stress distributions. These results are critical for understanding the seismic behavior of such structures and informing design improvements. The maximum horizontal displacement observed at the topmost floor was approximately 30.39 cm, which corresponds to 0.96% of the total height of the building. This displacement highlights significant lateral movement under seismic excitation. In comparison, the lower floors exhibited markedly reduced displacements, reflecting the influence of increased stiffness and mass distribution in these levels. Such findings emphasize the importance of focusing on the upper stories during seismic design to mitigate excessive lateral displacements.

Inter-story drifts were found to be a critical concern. The maximum recorded drift was 33 mm, occurring at the middle floors of the structure. This value exceeds the allowable drift limit of 12 mm as per IS 1893:2016, indicating a serious potential for structural instability. The drift ratios, calculated to be 2 to 3 times higher than permissible thresholds, underscore the urgency for design interventions to improve lateral stiffness and ensure the structural stability of RC frames in high seismic zones. The stress distribution within the structural members revealed significant findings. Ground-floor columns exhibited compressive stresses 1.5 to 2 times greater than tensile stresses, a pattern consistent across the seismic load combinations analyzed. This concentration of compressive forces highlights the vulnerability of lower-level columns, which are subjected to greater axial loads due to the cumulative weight of the structure. Shear forces in beams, particularly B505, B506, and B507, were found to be approximately three times higher under combined static and seismic loading conditions compared to static loads alone. This dramatic increase in shear stress raises concerns about the potential for shear failure, especially in beams with inadequate detailing. The observed results highlight the necessity of adopting advanced retrofitting strategies and improving structural designs to mitigate these vulnerabilities. The findings further reveal disparities in force distribution between interior and exterior columns, with the former experiencing higher compressive loads under seismic excitation. This disparity suggests that exterior columns are more susceptible to horizontal ground motion, necessitating enhanced lateral load-resisting mechanisms.

Seismic design challenges in Zone 4 regions, such as Jammu, are compounded by their proximity to active tectonic zones. The high-magnitude ground accelerations characteristic of such areas impose additional demands on the structural resilience of RC frames. The inadequacy of conventional designs to address these challenges is evident from the results, which indicate significant deviations from acceptable performance metrics. Poor construction practices, substandard materials, and insufficient adherence to seismic provisions exacerbate these challenges, emphasizing the need for rigorous quality control and advanced design methodologies.

Conclusions and Recommendations

The analysis of the RC frame structure in Jammu City has revealed several critical insights. First, the maximum nodal displacements and inter-story drifts observed in the structure significantly exceed the permissible limits specified in IS 1893:2016. This highlights critical vulnerabilities in the building's ability to withstand seismic forces. Second, compressive stresses in the ground-floor columns were markedly higher than tensile stresses, underscoring the need to enhance the load-bearing capacity of these critical elements. Third, the observed shear forces in beams under seismic excitation were alarmingly high, necessitating immediate attention to joint detailing and reinforcement strategies.

To address these vulnerabilities, several actionable recommendations can be made. Structural enhancements should prioritize the implementation of advanced retrofitting techniques. Fiber Reinforced Polymer (FRP) wrapping, for instance, can significantly improve the shear and compressive strength of columns and beams. Base isolation systems are another effective strategy to decouple seismic forces from the structure, thereby reducing lateral displacements. Additionally, the use of cross-bracing or the incorporation of additional shear walls can substantially increase the lateral stiffness of the structure. Material quality and construction practices also warrant significant improvements. Ensuring the use of high-quality materials with verified seismic performance characteristics is crucial. Enhanced joint detailing, particularly at beam-column connections, can help mitigate vulnerabilities and improve the overall ductility of the structure. Furthermore, compliance with seismic codes must be prioritized. Aligning structural designs with the latest revisions of IS 1893:2016 and IS 13920:2016 is essential for ensuring seismic resilience. Periodic structural health monitoring can also aid in assessing the condition of the building and identifying potential issues before they escalate.

Future research should explore the integration of advanced materials, such as high-performance concrete and shape memory alloys, to improve seismic performance. The development of predictive models using machine learning algorithms for real-time seismic risk assessment could provide valuable insights for urban planning and structural design. Additionally, the efficacy of energy dissipation systems, such as tuned mass dampers, in mitigating seismic effects in high-rise RC frames warrants further investigation.

By implementing these recommendations and pursuing advanced research, the seismic resilience of RC structures in seismically active regions like Zone 4 can be significantly enhanced. This will not only mitigate the risk of catastrophic failures but also ensure the safety and longevity of urban infrastructure.

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