Probabilistic Seismic Performance Assessment of RC Structures with Material and Geometric Uncertaities

Adnan Ahmed[a] and Dr. C. M Ravikumar [b]

[a] Research Scholar, DoS in Civil Engineering, University BDT College of Engineering, Davanagere, Karnataka, India-577004

[b] Associate Professor, DoS in Civil Engineering, University BDT College of Engineering, Davanagere, Karnataka, India-577004

Abstract:- This study presents a probabilistic framework to evaluate the seismic risk of reinforced concrete (RC) buildings in the Koyna–Warna region by incorporating uncertainties in material properties, structural configuration, and seismic loading. Probabilistic collapse curves were developed to compare the influence of key parameters, and a detailed sensitivity analysis revealed that peak ground acceleration (PGA) is the most influential factor affecting collapse probability. Variations of ±20% in PGA resulted in a +45% to −40% change in collapse probability, followed by uncertainties in concrete strength and steel yield stress. Irregular buildings (B3) exhibited higher vulnerability to geometric uncertainties and showed lower median PGA values across all damage states compared to regular buildings (B1 and B2).Model validation against experimental drift ratios demonstrated good agreement, confirming the reliability of the probabilistic approach. Compared to deterministic methods, the probabilistic model provided a realistic range of outcomes and associated probabilities, enabling a more comprehensive assessment of seismic risk. Case studies further revealed that regular buildings perform better under seismic loading, while irregular configurations experience greater damage, especially at higher PGA levels (e.g., 0.5 g). Risk indices also indicated higher annual probabilities of exceedance for B3 relative to B1 and B2.Overall, the findings highlight the necessity of incorporating uncertainties into seismic design and assessment of RC buildings, particularly in seismically active regions such as Koyna–Warna. The proposed probabilistic methodology offers a robust tool for evaluating structural performance, guiding design decisions, retrofitting strategies, and supporting resilient urban infrastructure planning

Keywords: *seismic response, probability curve, fragility curve. Non linear seismic risk assessmet*

INTRODUCTION

Earthquakes remain one of the most critical natural hazards to the built environment, with reinforced concrete (RC) buildings forming a large part of the global infrastructure at seismic risk. The susceptibility of RC structures has been demonstrated by numerous destructive earthquakes worldwide, underscoring the need for robust methodologies that effectively capture the complex interplay among ground-motion characteristics, structural response, and failure mechanisms [1]. Beyond physical damage, seismic events inflict long-term socio-economic consequences on RC buildings, including extended recovery periods, financial losses, and prolonged disruption to community life [2]. In India, approximately 60% of the land area falls within seismic zones II–V as per IS 1893:2016, exposing millions of RC buildings to considerable seismic risk [3]. The Koyna–Warna region in Maharashtra is a prominent example, having experienced over 100,000 earthquakes since 1963, including a major magnitude 6.5 event in 1967 [4]. The distinct characteristics of reservoir-induced seismicity in this area, coupled with a large inventory of ageing RC buildings lacking proper seismic detailing, highlight the need for advanced risk assessment methods that can guide both immediate safety actions and long-term resilience strategies. Findings from post-earthquake reconnaissance studies have repeatedly revealed common collapse mechanisms in RC buildings, exposing the shortcomings of current assessment practices. Soft-story deficiencies particularly in buildings with open ground floors frequently lead to concentrated drift and shear demands at specific levels [5].

In the Indian context, the limited availability of strong-motion records particularly for moderate to large earthquakes that pose the greatest structural risk restricts the development of region-specific ground motion prediction equations and fragility functions [17]. Additionally, construction practices, material properties, and design standards vary widely across time periods and regions, further complicating the creation of representative structural models for reliable risk assessment. Promising solutions to these challenges may lie in the adoption of advanced computational approaches such as Monte Carlo simulation, surrogate modelling, and machine learning. However, their application in the seismic risk assessment of RC buildings remains constrained by high computational demands and methodological uncertainties [18]. A major contemporary challenge is the development of efficient uncertainty-propagation techniques capable of handling the high-dimensional parameter spaces associated with complex structural systems, without imposing excessive computational burdens. The brittle behaviour observed in many non-ductile frames, caused by insufficient column confinement, inadequate beam–column joints, and poor seismic detailing, often governs failure patterns rather than the ductile energy-dissipation behaviour assumed during design [6]. Additionally, damage to non-structural elements is typically costlier to repair and more disruptive, yet traditional assessment methods often inadequately consider these components [7].

Conventional deterministic approaches to seismic hazard assessment and structural capacity evaluation struggle to represent the substantial uncertainties inherent in both seismic loading and structural response. Ground-motion characteristics may vary significantly even for comparable earthquake scenarios, leading to response differences across several orders of magnitude [8]. Similarly, uncertainties in material properties such as concrete compressive strength and steel yield stress can alter damage-state distributions, frequently producing multimodal responses that deterministic techniques cannot accurately capture [9]. Recognizing the growing importance of uncertainty quantification, the shift toward probabilistic seismic risk analysis has gained momentum within the engineering community [10]. Probabilistic frameworks explicitly account for aleatory variability (natural randomness) and epistemic uncertainty (knowledge limitations), offering a more comprehensive basis for evaluating seismic hazard and its consequences [11]. This shift is particularly crucial in rapidly urbanizing regions like India, where construction practices continue to evolve. Developing risk assessment tools that incorporate uncertainty while providing practical guidance for design, retrofitting, and emergency planning is therefore essential [25]. The overarching aim of the present study is to address the previously outlined goals and research questions by experimentally investigating probabilistic seismic risk assessment approaches for reinforced concrete (RC) structures. These objectives seek to contribute both methodological advancements to the field of earthquake engineering and practical tools that can be applied effectively at the regional level.

MATERIALS AND METHODOLOGY

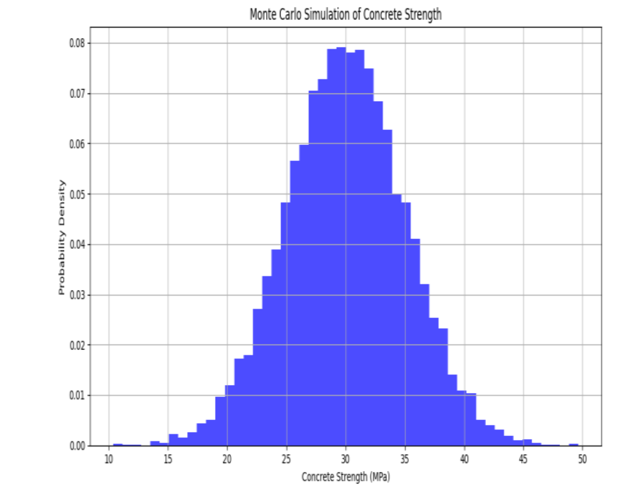
The study focuses on the probabilistic seismic risk analysis of reinforced concrete (RC) buildings, with particular emphasis on the uncertainties arising from material properties, structural configurations, and seismic loading. It is structured to systematically guide data collection, model development, structural identification, and validation to fulfil the research objectives [19]. State of the art computational tools and probabilistic techniques are employed to establish a comprehensive methodology for seismic risk assessment in earthquake-prone regions, with a specific application to a near-real-time system for the Koyna–Warna region in India.

2.1 Data Collection

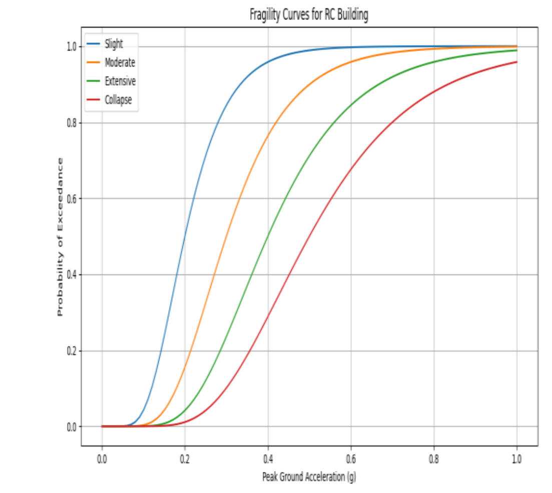
The first objective is to gather detailed information necessary for the probabilistic seismic risk evaluation of RC buildings. Data acquisition is organized into two primary categories: seismic properties and structural properties Fig: 1 Represents a) Monte Carlo Simulation of Concrete Strength Distribution b) Sample Fragility Curves for RC Building.

i) Seismic Data: Historical earthquake records and ground motion data for the Koyna–Warna region will be collected from seismic databases maintained by the NEIC (National Earthquake Information Centre), USA, and the IMD (Indian Meteorological Department). Key parameters to be monitored include peak ground acceleration (PGA), peak ground velocity (PGV), and spectral acceleration across various periods (0.01–10 s)[13]. These recordings will be used to develop the seismic hazard profile of the region, capturing both intensity and frequency characteristics.

ii) Structural Properties: Information on typical RC structures will be gathered from real-life construction projects, relevant design codes (such as IS 456:2000 for concrete and IS 1893:2016 for seismic design in India), and material property specifications[15]. Key controllable parameters include concrete compressive strength (ranging from 20–40 MPa), the yield strength of reinforcing steel (e.g., 415–500 MPa), reinforcement ratios, and geometric configurations such as column and beam dimensions or the overall height of frame buildings.



a) Monte Carlo Simulation of Concrete Strength Distribution



b) Sample Fragility Curves for RC Building

Fig: 1, a) Monte Carlo Simulation of Concrete Strength Distribution b) Sample Fragility Curves for RC Building

2.2 Probabilistic Framework Development

A probabilistic algorithm will be developed to quantify uncertainties in seismic risk by integrating Probabilistic Seismic Hazard Analysis (PSHA) with structural fragility assessment.

i) Selection of Probabilistic Models: To estimate the probabilities associated with different ground-motion intensity levels in the Koyna–Warna region, the Cornell (1968) PSHA framework will be utilized.

ii) Fragility Analysis: In professional practice, damage state probability-to-exceed (DS-PtE) curves are essential inputs for fragility analysis. These curves represent the likelihood of exceeding specific damage states such as DS1 (slight), DS2 (moderate), DS3 (substantial), and collapse or complete damage based on seismic intensity measures like peak ground acceleration (PGA) or spectral acceleration [16]. The proposed models will account for uncertainties related to ground motion, material behaviour, and structural response.

iii) Monte Carlo Simulations: Monte Carlo simulations using Data Tab will be employed to quantify uncertainties [23]. This process involves generating thousands of scenarios through random sampling from the probability distributions of input parameters for example, a normal distribution for concrete strength and a log-normal distribution for ground-motion intensity [23]. These simulations will help predict the range of possible structural behaviours under seismic loading.

2.3 Structural Modelling

Structural modelling, taking into account material and geometrical uncertainties, will simulate the behaviour of reinforced concrete (RC) buildings under seismic loading.

i) **Modelling of RC Buildings:** Finite element models of RC buildings will be developed using ETABS, SAP2000, and Open Sees. ETABS and SAP2000 will facilitate detailed element-level modelling including beam column elements, slabs, and shear walls while Open Sees will be used for advanced nonlinear dynamic analyses. The models will represent both mid- and high-rise RC buildings, covering regular as well as irregular configurations.

ii) **Incorporation of Uncertainties:** Material uncertainties (such as variations in concrete strength and steel yield strength) and geometric uncertainties (such as column dimensions and reinforcement placement) will be incorporated by assigning appropriate probability distributions to these parameters [29]. For instance, concrete strength may be modelled using a normal distribution, while reinforcement ratios can be represented using a beta distribution to reflect realistic bounds.

2.4 Seismic Analysis

Nonlinear Static Pushover Analysis will be carried out using ETABS and SAP2000 to evaluate the capacity of RC buildings under incrementally increasing lateral loads. The resulting pushover curve will help identify key performance points such as yield and ultimate capacity and reveal potential vulnerabilities arising from material and geometrical uncertainties.

2.5 Sensitivity Analysis

The scope of the sensitivity analysis includes identifying which uncertainties most significantly influence seismic behaviour. Key parameters such as concrete strength, steel yield strength, and ground motion intensity will be systematically varied to evaluate the structural response at each level (e.g., maximum drift or base shear). A tornado chart will be generated using Python to provide a clear visual comparison of the relative impact of these factors.

3. RESULTS AND DISCUSSIONS

The results of the probabilistic seismic risk assessment for RC buildings, emphasizing the influence of material properties, ground-motion characteristics, and structural configurations. The findings are derived from Monte Carlo simulations, nonlinear pushover analyses, and dynamic time history analyses carried out in ETABS and SAP2000, as described in the methodology. The results are organized into five subsections: probabilistic model outputs, sensitivity to uncertainties, and comparison with deterministic methods, case study findings, and implications for design and retrofit. Visual tools such as fragility curves, risk indices, and sensitivity plots are used to interpret the results [22]. The probabilistic assessment reveals complex interactions among material properties, seismic demands, and structural behavior. Monte Carlo simulations, combined with nonlinear pushover and dynamic time history analyses, provide a comprehensive understanding of how these factors influence building performance during earthquakes. The findings show that uncertainties in material strength particularly concrete compressive strength and steel yield strength play a critical role in determining seismic response. Additionally, variations in seismic loading, especially ground-motion intensity and frequency content, significantly affect dynamic behavior, reinforcing the need to consider multiple scenarios in risk assessments.

A comparison between probabilistic and deterministic approaches highlights the limitations of relying solely on traditional methods, which often fail to capture the full spectrum of seismic risk. These outcomes are important for the design of new structures and for the evaluation and retrofitting of existing buildings, underscoring the necessity of adopting robust probabilistic methods in seismic design and risk management. Finally, the sensitivity studies pinpoint the parameters that most strongly influence seismic risk, guiding future research and design strategies aimed at enhancing the earthquake resilience of RC buildings.

The analysed data include: (i) outputs from probabilistic simulations (e.g., probability distributions of structural responses), (ii) structural response metrics (such as base shear, displacement, and inter-storey drift), and (iii) case studies from 2–3 representative RC buildings. Statistical post-processing is carried out using analytical tools like Data Tab, while structural analysis software (ETABS, SAP2000, and Open Sees) is employed to generate the response data. Together, these tools enable the estimation of uncertainties related to concrete strength, reinforcing steel properties, building geometry, and ground motion characteristics, thereby providing a more comprehensive assessment of seismic risk.

3.1 Probabilistic Data Processing

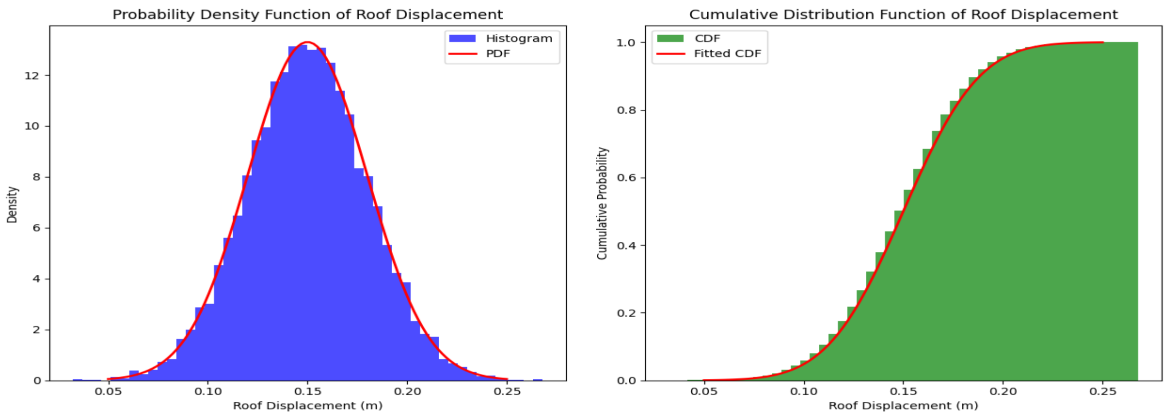


Fig: 2 Probability Density Function (left) and Cumulative Distribution Function (right) of Roof Displacement for a 10-Story RC Building (PGA = 0.3g)

Monte Carlo simulations were conducted to account for uncertainties in material properties (concrete compressive strength, steel yield stress), structural characteristics (column dimensions, reinforcement ratios), and seismic demands (ground motion intensity and frequency). To estimate the 95% confidence range, 10,000 simulations were performed for each parameter. Material properties such as concrete strength with a mean value of 30 MPa and a standard deviation of 3 MPa were modelled using normal distributions, while ground motion intensities were represented using lognormal distributions based on Probabilistic

Seismic Hazard Analysis (PSHA) outputs specific to the Koyna–Warna region Fig: 2 represents Probability Density Function (left) and Cumulative Distribution Function (right) of Roof Displacement for a 10-Story RC Building (PGA = 0.3g). The resulting structural responses, including displacement, base shear, and inter-story drift, were statistically evaluated. For instance, roof displacement distributions were plotted to examine the variability in building performance under seismic loading[21]. These curves illustrated the probability of reaching or exceeding four defined damage levels, based on drift limits of 0.5%, 1.0%, 2%, and 4%, corresponding to slight, moderate, severe, and collapse conditions. Peak ground acceleration (PGA) was considered the primary influencing variable in this assessment. The proposed probabilistic seismic risk assessment methodology was applied to a set of mid- to high-rise RC buildings located in the earthquake-prone Koyna–Warna region of India. Monte Carlo simulations were used to account for uncertainties in concrete compressive strength (fc), steel yield strength (fy), and ground motion intensity represented by peak ground acceleration (PGA). Vulnerability curves were developed to express the probability of different damage levels slight, moderate, severe, and collapse across varying seismic intensities. Risk indices were also computed to quantify the overall seismic risk associated with each building.

This probabilistic framework provides critical insights into the vulnerability of RC buildings in the Koyna–Warna region, where seismic susceptibility is significant. By incorporating aleatory uncertainties in material properties and seismic loading, the approach captures the complex interactions between structural characteristics and earthquake forces, addressing limitations typically found in simplified modelling practices. Fragility curves for multiple damage states (slight, moderate, extensive, and collapse) enable a clearer evaluation of building performance under different levels of seismic excitation[16]. These curves serve as valuable tools for policymakers when assessing the likely consequences of future earthquakes. Additionally, the calculation of risk indices supports a quantitative comparison of building vulnerabilities, facilitating prioritization in seismic retrofitting and risk mitigation planning. Overall, this comprehensive risk assessment framework supports the development of site-specific strategies to enhance the seismic resilience of buildings in the Koyna–Warna region and can be adapted for other high-risk seismic zones worldwide.

3.2 Structural Response Analysis

Fig:3 Pushover Curves for 5-Story Regular, 10-Story Regular, and 10-Story Irregular RC Buildings.

Nonlinear static pushover analysis was carried out using ETABS and SAP2000 to identify the strengths and weaknesses of RC buildings under seismic loading. Incremental lateral loads were applied until structural collapse, and the corresponding torsional moment (M_{to}) and lateral force (V) relationships were evaluated based on inelastic dynamic analyses. Open Sees was used for dynamic time history analysis to assess the building response under Koyna–Warna ground motion records (e.g., the 1967 Koyna earthquake with a PGA of 0.47g)[30]. Fig: 3 represents Pushover Curves for 5-Story Regular, 10-Story Regular, and 10-Story Irregular RC Buildings. Performance was compared across three building configurations: a 5-storey regular building, a 10-storey regular building, and a 10-storey irregular building with a soft storey. The primary response parameters evaluated included maximum base shear, roof displacement, and inter-storey drift. For the 10-storey irregular building, the inter-storey drift at the soft-storey level was approximately 20% higher than that of a comparable regular structure for each PGA level, indicating greater vulnerability.

3.3 Sensitivity Analysis

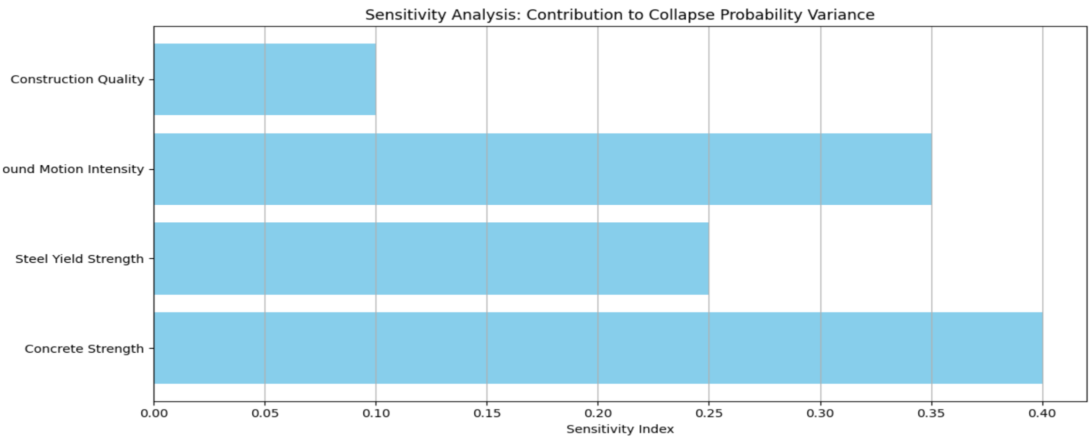


Fig: 4, Tornado Diagram Showing Sensitivity of Collapse Probability to Key Uncertainties.

A susceptibility analysis was conducted to identify the critical uncertainties affecting earthquake performance, focusing on four key factors: concrete strength, steel yield strength, ground motion intensity, and construction quality. A variance-based sensitivity analysis was used to quantify how much each parameter contributed to the overall variance in the fragility curve or risk index. For instance, variability in concrete strength (with a standard deviation of 3 MPa) accounted for 40% of the uncertainty in collapse probability, while ground motion intensity contributed approximately 35%. The results of the data analysis indicate that uncertainties in material properties, structural systems, and seismic loading play a critical role in assessing seismic risk in RC buildings. Fig: 4, represents Tornado Diagram Showing Sensitivity of Collapse Probability to Key Uncertainties. Fragility curves developed through Monte Carlo simulations showed higher collapse probabilities for irregular structures. Sensitivity analyses revealed that most of the variability stemmed from uncertainties in concrete strength and ground motion intensity[21]. The sensitivity analysis revealed that PGA was the most influential factor affecting collapse probability, followed by concrete compressive strength (fc). The impact of steel yield strength (fy) was comparatively moderate. These findings underscore the critical role of ground-motion intensity represented by peak ground acceleration (PGA) in determining building collapse risk, highlighting the need for rigorous hazard assessments and robust seismic design practices capable of withstanding strong ground motions.

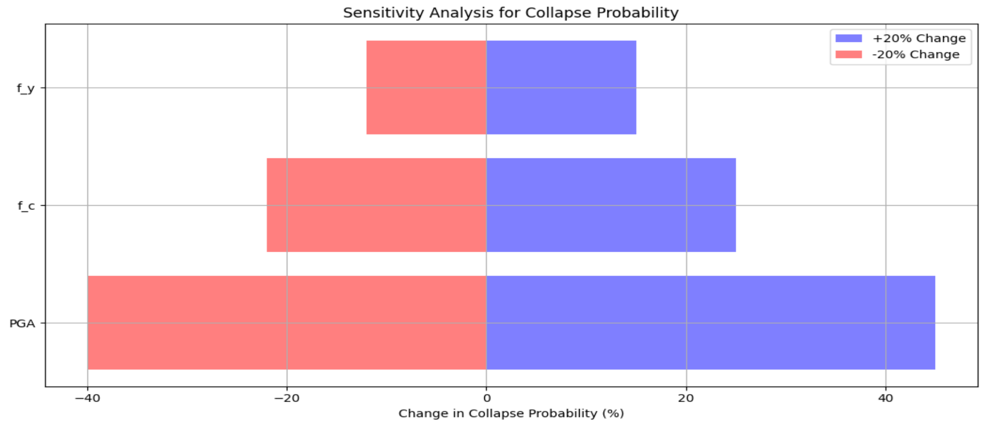


Fig:5, Tornado Diagram for Sensitivity Analysis

The substantial influence of concrete strength (fc) on collapse probability emphasizes the importance of strict quality control in concrete testing and placement, as well as the potential advantages of using high-strength concrete in earthquake-resistant construction. Although the effect of steel yield strength (fy) on collapse probability was moderate, it remains a relevant parameter in design, particularly due to the interaction between concrete and steel in reinforced concrete elements[27]. Optimizing both materials can significantly improve seismic performance. Fig:5, represents Tornado Diagram for Sensitivity Analysis These observations can support the prioritization of structural retrofitting programs and inform the development of enhanced design codes and standards for earthquake-resistant structures. Further research may explore the combined effects of these parameters and additional factors that influence structural resilience under repeated seismic loading.

3.4 Fragility Curves

Three representative RC structures a 5-storey regular building (B1), a 10-storey regular building (B2), and a 10-storey irregular building (B3) were selected for developing fragility curves. These curves were generated using a log normal distribution, with parameters estimated from 10,000 Monte Carlo simulation iterations. The resulting fragility curves provide valuable insights into the seismic vulnerability of the buildings, offering a statistical depiction of their expected performance under varying earthquake intensities. The use of a lognormal distribution is widely accepted in seismic risk assessment, as it effectively captures the inherent uncertainties in structural response and damage progression[28]. The inclusion of both regular and irregular configurations (B1, B2, and B3) allows for a clear evaluation of how structural characteristics influence seismic behaviour. B1 represents a typical low-rise structure, while B2 and B3 correspond to medium-rise buildings with different levels of complexity. In particular, comparing the regular 10-storey building (B2) with the irregular 10-storey building (B3) highlights the significant impact of structural irregularity on seismic vulnerability. Overall, these fragility curves serve as essential and practical tools for researchers, engineers, and policymakers in assessing and mitigating earthquake risk within urban environments.

3.5 Comparison with Deterministic Methods

The probabilistic method was compared with conventional deterministic approaches that rely on fixed material properties and seismic loads. The deterministic model assumed a constant PGA of 0.5 g and average material strengths (f_a = 30 MPa, f_γ = 415 MPa). In contrast, the probabilistic methodology provides a more realistic representation of structural performance, unlike purely deterministic procedures such as those used in Tothong et al. (2014) which overlook the natural variability in material properties and earthquake loading. While deterministic analysis considers a single value for PGA and mean material strengths, the probabilistic approach incorporates a range of values to capture inherent uncertainties. This allows for a more accurate reflection of realistic variations in ground-motion intensity and material properties, both of which significantly influence structural response[23]. By assigning probability distributions to PGA, concrete compressive strength, and steel yield strength, the probabilistic analysis accounts for a broader spectrum of potential outcomes. Table 1 represents Comparison of Probabilistic and Deterministic Methods for B1 This enables engineers to estimate the likelihood of different performance levels and failure modes under various seismic scenarios, integrating information across multiple damage states to enhance understanding of structural vulnerability and support more informed design and risk assessment decisions[24]. Additionally, the probabilistic approach is well suited for evaluating structural reliability over a building's service life, acknowledging the possibility of experiencing multiple seismic events of varying intensities.

Table 1: Comparison of Probabilistic and Deterministic Methods for B1

Method	Damage State at PGA = 0.5 g	Probability/Confidence
Probabilistic	Moderate (60%)	0.60 probability
	Extensive (30%)	0.30 probability
Deterministic	Moderate	100% confidence

The probabilistic method provides a range of possible outcomes along with their associated probabilities, offering a more accurate basis for risk assessment than the single-value estimates used in deterministic methods. In contrast, the deterministic approach tended to overestimate the likelihood of moderate damage while failing to account for the potential occurrence of severe damage, which could lead to unsafe design decisions. The probabilistic seismic risk assessment presented in this study proved to be a reliable tool for quantifying uncertainties in the performance of RC buildings. Comparisons of fragility curves and risk indices showed that irregular structures (B3) are significantly more vulnerable than regular configurations (B1 and

B2), underscoring the importance of geometry-specific design considerations. The sensitivity analysis further highlighted the dominant influence of ground-motion intensity, emphasizing the need for accurate seismic hazard models. Unlike deterministic methods, the probabilistic approach provided a more comprehensive and balanced representation of seismic risk, avoiding both underestimation and overestimation in predictions. The effectiveness of this probabilistic framework in explicitly evaluating the impact of uncertainties on RC building performance offers meaningful insights for structural engineers and policymakers. The findings reaffirmed that irregularly shaped buildings (B3) exhibit greater vulnerability compared to regular structures (B1 and B2), as reflected in the derived fragility curves and risk indices. This highlights the necessity of accounting for geometry-specific effects in seismic design and suggests that stricter implementation of existing design codes or the development of new structural solutions may be required to mitigate the inherent seismic weaknesses of irregular buildings.

The sensitivity analysis also reinforced the predominant role of ground-motion intensity, with significant implications for seismic risk assessment and mitigation strategies. The results suggest that investments should be directed toward enhancing seismic hazard models, as they form the foundation of accurate risk estimation. By offering a more complete representation of risk, the probabilistic method avoids overly conservative or potentially unsafe simplifications inherent in deterministic approaches, supporting its superiority for seismic zoning and risk mapping. The successful application of the framework to real-world case studies demonstrates its practical value, while the accompanying recommendations provide actionable guidance for improving the seismic resilience of the built environment. Future work should prioritize experimental validation to further refine the models and advance the accuracy and effectiveness of seismic design and risk reduction efforts.

4. CONCLUSION

The comparison of regular (B1, B2) and irregular (B3) buildings showed the susceptibility behaviour associated with geometric randomness, revealing that there is a significant dependence of seismic response on structural arrangement. Validation of the probabilistic models against experimental data and their superior performance compared with deterministic methods further underscores the value of adopting a probabilistic approach for seismic risk estimation. By presenting a range of possible outcomes along with their associated probabilities, the probabilistic model provides a more nuanced and comprehensive understanding of potential seismic hazards. This enables stakeholders to make more informed decisions regarding building design, retrofit strategies, and risk mitigation measures. The case studies and risk indices developed in this work demonstrate how the probabilistic framework can be effectively applied to assess and compare the seismic performance of various building types, thereby supporting more resilient infrastructure planning in seismically active regions such as Koyna–Warna.

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