



FRAGILITY ANALYSIS OF AN RC BUILDING USING PLASTIC ANALYSIS

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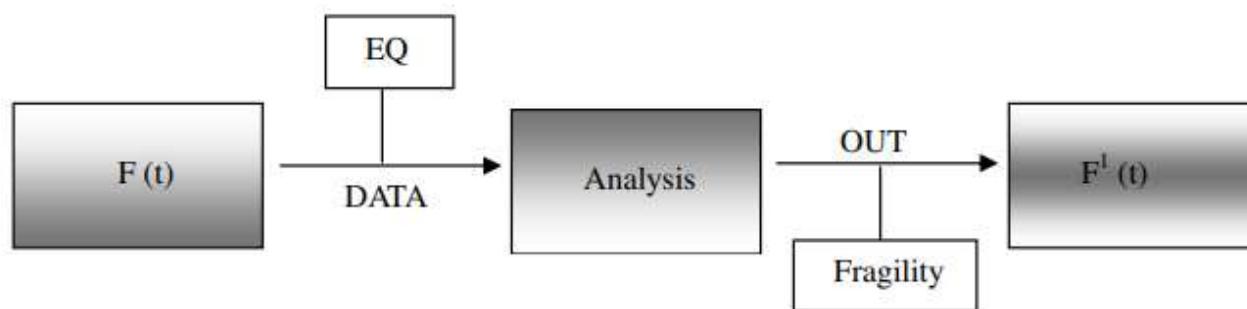
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Abstract: The seismic vulnerability of reinforced concrete (RC) buildings is a critical concern in earthquake-prone regions, where structural failure can result in significant life and economic losses. Traditional seismic evaluation methods based on linear elastic analysis often fail to capture the nonlinear, post-yield behavior of RC structures under high-intensity ground motions. This study presents an integrated approach to fragility analysis by incorporating plastic analysis to more accurately assess the seismic performance of RC buildings. A five-story RC frame structure is modeled using nonlinear finite element techniques, and subjected to incremental dynamic analysis (IDA) with a suite of ground motions scaled between 0.1g and 1.0g. Key seismic response parameters—such as inter-story drift, displacement, and damage indices—are evaluated. Plastic hinge formation and force redistribution are simulated to represent inelastic behavior under extreme loads. Based on these results, fragility curves are developed using lognormal cumulative distribution functions for different damage states: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). The fragility model is validated against empirical data and benchmark studies, showing strong alignment with expected performance levels. The study provides a refined methodology for seismic risk assessment, supporting improved retrofitting strategies and disaster mitigation planning for existing and new RC structures.

Keywords: Seismic fragility, reinforced concrete, plastic analysis, nonlinear behavior, damage probability, earthquake engineering.

I. INTRODUCTION

Reinforced Concrete (RC) buildings are widely adopted in urban infrastructure due to their structural robustness and cost-effectiveness. However, in regions prone to seismic activity, ensuring their resilience against earthquakes becomes a critical engineering challenge. Traditional linear elastic analysis, which assumes purely recoverable deformations, often fails to capture the true behavior of RC structures under strong seismic loading. This is where fragility analysis, when combined with plastic analysis, offers a more reliable and nuanced approach to seismic risk assessment. Fragility analysis is a probabilistic tool that quantifies the likelihood of a structure reaching or exceeding various damage states under earthquake excitations. It involves the generation of fragility curves, which describe the relationship between ground motion intensity and the probability of structural damage. These curves help engineers and decision-makers assess risk levels and develop targeted retrofitting and mitigation strategies.



To enhance the accuracy of fragility predictions, plastic analysis is integrated into the modeling process. Unlike elastic methods, plastic analysis considers the inelastic behavior of structural elements, including the formation of plastic hinges and redistribution of internal forces. This allows for a more realistic assessment of how RC buildings behave beyond their yield point—especially critical for seismic loading, which induces significant nonlinear deformation in both concrete and steel reinforcement. By combining fragility and plastic analysis, engineers can better simulate collapse mechanisms, assess ultimate load capacities, and predict performance under different seismic intensities. This integrated approach not only advances the understanding of structural

vulnerabilities but also contributes to more resilient urban infrastructure by informing design codes, retrofitting strategies, and disaster preparedness frameworks.

1.1 Problem statement

The seismic vulnerability of Reinforced Concrete (RC) buildings remains a pressing concern in earthquake-prone regions, where structural failures can result in significant human and economic losses. Traditional structural analysis methods, primarily based on linear elastic assumptions, often fall short in capturing the nonlinear and inelastic behavior that RC buildings exhibit during strong ground motions. These methods do not adequately consider the formation of plastic hinges, force redistribution, and the progressive degradation of structural elements under seismic loading. Although fragility analysis has emerged as a key tool in probabilistic seismic risk assessment, many existing fragility models rely heavily on elastic approximations, overlooking critical post-yield behaviors. This simplification results in an incomplete understanding of how RC buildings actually respond to earthquake forces, especially those constructed before modern seismic design codes. Without accounting for plastic deformations, these models may underestimate or misrepresent damage probabilities, leading to ineffective mitigation and retrofitting strategies. There is thus a clear need to integrate plastic analysis into fragility modeling to more accurately reflect the true seismic performance of RC buildings. Addressing this gap is essential for developing realistic fragility curves, enhancing seismic resilience, and supporting data-driven decisions in urban planning, structural design, and disaster risk reduction.

2. LITERATURE REVIEW

The assessment of seismic vulnerability in Reinforced Concrete (RC) structures has evolved considerably with the advancement of fragility analysis methodologies. Traditionally, seismic performance evaluations were grounded in deterministic and linear elastic models. However, with the increasing demand for performance-based design and the growing recognition of inelastic behaviors in RC buildings, fragility analysis integrated with plastic modeling has gained prominence.

Cornell (1968) first introduced the concept of probabilistic seismic hazard analysis, laying the groundwork for modern fragility assessments. Fragility curves, which represent the probability of reaching or exceeding specific damage states under varying seismic intensities, have since become essential tools in seismic risk evaluation. According to Shome et al. (2001), these curves are derived using statistical techniques based on structural response data, enabling a probabilistic understanding of building performance. Ghobarah et al. (2005) emphasized the importance of using nonlinear dynamic analyses to simulate the behavior of RC buildings under earthquake loads. They argued that relying solely on linear elastic models leads to underestimation of damage probabilities, especially for moderate to severe seismic events. Moehle et al. (2005) also reinforced the relevance of fragility curves in designing retrofitting strategies and prioritizing vulnerable structures in densely populated regions.

Traditional seismic analysis methods assume elastic behavior, which fails to capture post-yield deformations. In contrast, plastic analysis accounts for material nonlinearity and the redistribution of forces after yielding, thus offering a more realistic view of structural performance (Ibarra & Krawinkler, 2005). RC buildings, in particular, undergo plastic deformation through the formation of plastic hinges at critical locations such as beam-column joints. These mechanisms are fundamental in assessing collapse scenarios. Nguyen and Miranda (2009) integrated plastic behavior into fragility analysis using incremental dynamic analysis (IDA). Their results showed that including plastic deformation substantially improved the accuracy of predicted damage states, especially in mid-rise and high-rise RC frames subjected to near-fault ground motions.

Chopra and Goel (2001) developed fragility models using capacity-spectrum methods and pushover analysis. Their findings stressed the limitations of static analysis in capturing dynamic responses, especially for irregular or torsionally flexible buildings. The evolution of fragility analysis thus necessitated the use of nonlinear time-history methods, as supported by the works of Mehanny et al. (2019), who demonstrated that such analyses provide detailed insights into damage progression and hinge formation in RC frames. Empirical studies have played a significant role in validating fragility models. Ozturk and Sucuoglu (2010) conducted post-earthquake assessments of RC buildings in Turkey and found that older structures, designed before modern seismic codes, exhibited high vulnerability due to inadequate detailing and poor-quality materials.

Contemporary studies have embraced probabilistic tools such as Monte Carlo simulations and Bayesian updating to refine fragility curves. Liu et al. (2017) applied these techniques to account for uncertainties in material properties, ground motion variability, and structural configurations. Their research highlighted how statistical tools could be used to estimate fragility with greater confidence intervals, enabling risk-informed decision-making. More recently, researchers have emphasized the importance of damage probability matrices and performance limit states. Cosenza and Manfredi (2001) introduced matrix-based approaches to better capture the variability in component-level damage, supporting multi-scale fragility assessment.

Research Through Innovation

3. METHODOLOGY

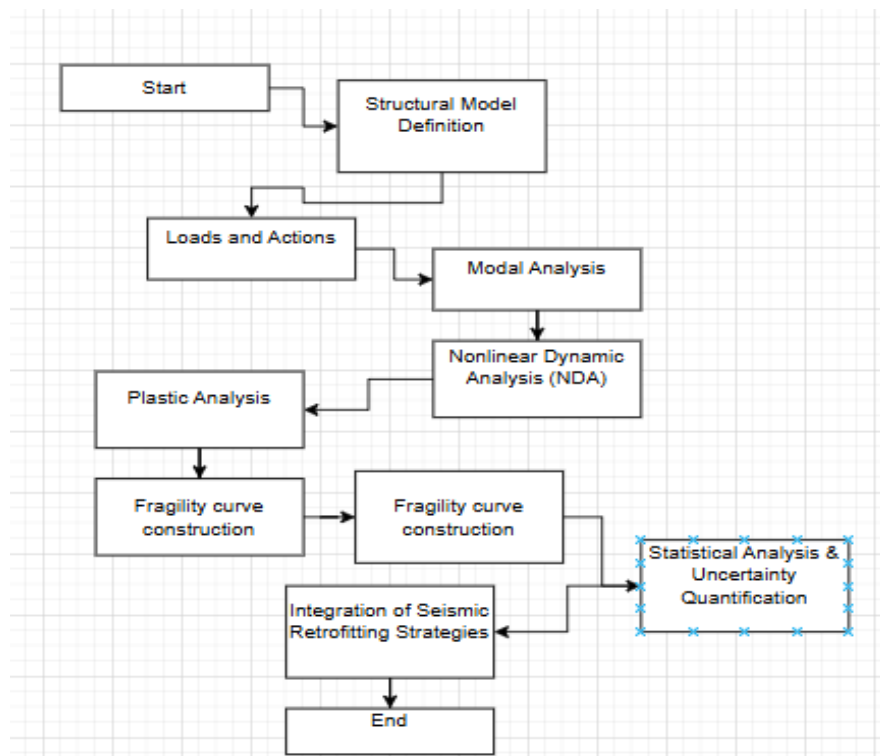


Figure 2. Flowchart of the Fragility Analysis Process for Seismic Vulnerability Assessment

The methodology adopted for this study involves a comprehensive seismic vulnerability assessment of a reinforced concrete (RC) building through the integration of fragility analysis and plastic analysis. A five-story RC frame structure, designed according to Eurocode standards, is selected for analysis. The first step involves developing a detailed finite element model of the building, incorporating material nonlinearities for both concrete and steel reinforcement. Material properties are defined using idealized stress-strain relationships to capture inelastic behavior and the formation of plastic hinges. Modal analysis is performed to identify the building's natural periods and mode shapes, which are essential for dynamic response evaluation. Subsequently, Nonlinear Dynamic Analysis (NDA) is conducted using ten ground motion records, scaled across varying Peak Ground Accelerations (PGA) from 0.1g to 1.0g. The structure's seismic responses, including inter-story drift and displacement, are extracted for each seismic intensity.

Plastic analysis is then employed to simulate post-yield behaviour, identifying plastic hinge formation and force redistribution. These outputs are used to classify damage states based on standard thresholds such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). Finally, fragility curves are developed using a lognormal cumulative distribution function and maximum likelihood estimation to quantify damage probabilities.

4. ANALYSIS OF RC FRAME STRUCTURE

5.1 Geometry and Design of RC Frame Structure Model

A ten-storey reinforced concrete (RC) building frame with four bays in both the longitudinal and transverse directions is considered in this study, as illustrated in Figure 7: (a) plan view and (b) elevation view. Each storey has a uniform height of 3.6 meters, and each bay measures 4.8 m × 4.8 m. This frame typology is representative of conventional multi-storey construction practices in India and has been extensively used by researchers for seismic analysis of RC structures. The structural design of the frame is carried out in accordance with the provisions of the Indian Standard Code IS 456:2000.

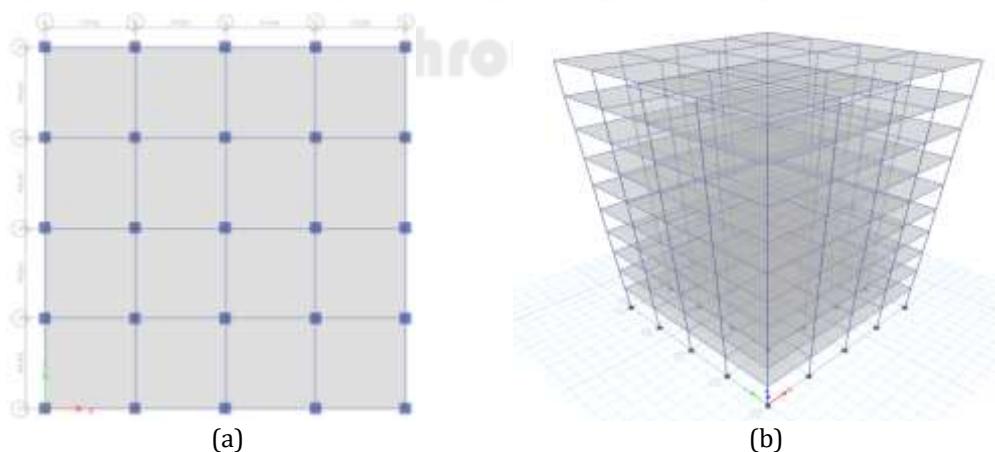


Figure 7. (a) Plan; (b) Elevation

Table 3 Frame members

Sr. No	Member	Size/thickness	Remark
1	Column	600 x 600	All storey
2	Beam	300 x 500	All storey
3	Slab	140	All storey

To investigate the effects of masonry infill and shear wall stiffness, on the seismic response of reinforced concrete (RC) frames, three different frame configurations were developed. These models represent *original frames* with no retrofitting or strengthening applied. The configurations are summarized as follows:

- Model 1: Bare Frame

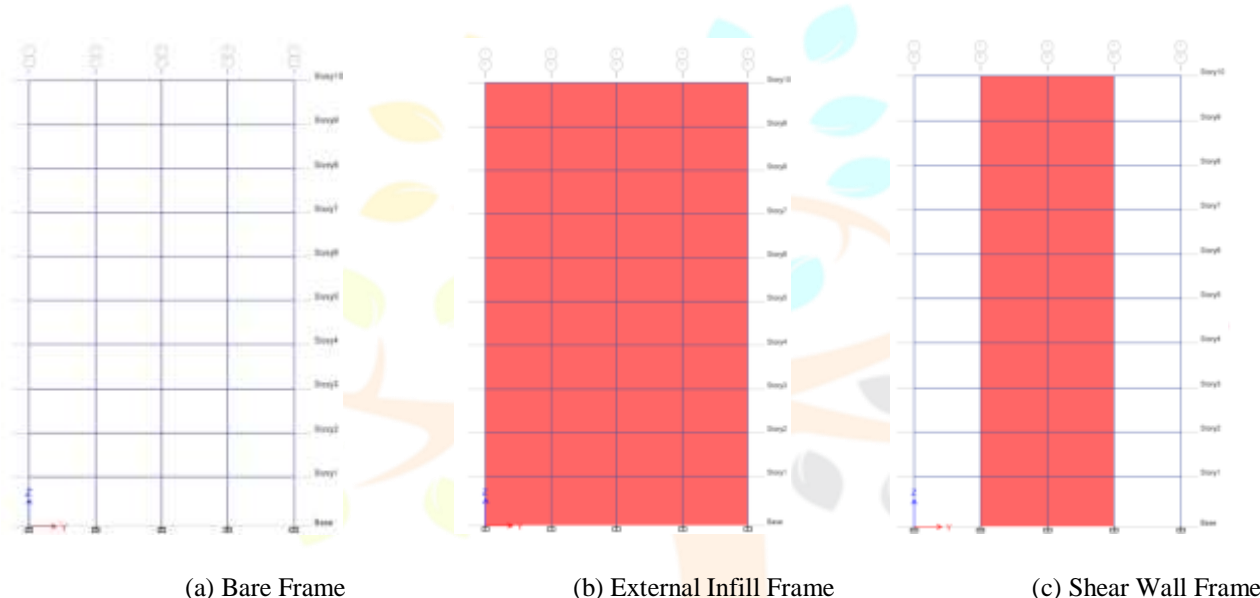
RC frame without any masonry infill in all storeys.

- Model 2: External Infill Frame

Masonry infill walls are provided only in the external bays, while the internal bays remain open.

- Model 3: Shear wall Frame

Shear walls are provided only in the internal bays, leaving the exterior bays open.

**Figure 8. Elevation of models**

5.2 Preliminary Data

The structural analysis of the building is carried out by considering various loads and design parameters in accordance with Indian Standards IS 456:2000 and IS 1893:2016. The applied loads are specified as follows:

- Floor finish load: Uniformly applied between 0.75 kN/m² and 1.0 kN/m² on all floors.
- Live load: 3.0 kN/m² on all floors except the roof, where a 25% live load reduction is applied, as per the provisions of IS 1893:2016.
- Wall load: A uniformly distributed load of 10.0 kN/m is considered, based on a masonry wall thickness of 230 mm.

Seismic analysis is performed using the response spectrum method, following IS 1893:2016 guidelines for Seismic Zone V, with the following parameters:

- Zone factor (Z): 0.36
- Importance factor (I): 1.0
- Soil type: Medium soil (Type II)
- Response reduction factor (R): 5
- Damping ratio: 5%

Load combinations are formulated by IS 456:2000 and IS 1893:2016 to ensure structural safety under both static and dynamic loading conditions.

6. RESULTS AND DISCUSSION

6.1 Fundamental time

The fundamental time of the bare frame structure is significantly higher compared to that of Shear wall and infill frame models. The fundamental period for external infill frame is reduced as compared to shear wall frame and RC bare frame. This is because of greater stiffness of external infill model compare shear wall frame and RC frame model.

Table 4. Fundamental time

1	BARE	1.586002
2	SHEAR	0.42953
3	INFILL	0.24094

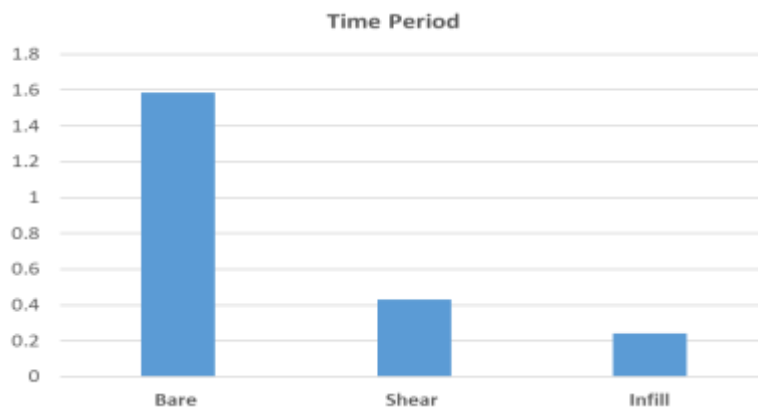


Figure 9. Fundamental time

6.2 Non-linear Analysis and calculation of fragility curves

Nonlinear Dynamic Analysis (NDA) is conducted using ten ground motion records, scaled across varying Peak Ground Accelerations (PGA) from 0.1g to 1.0g. The structure's seismic responses, including inter-story drift and displacement, are extracted for each seismic intensity.

Selected ground motion for the study

GM ID	Earthquake Name	Year	Recording Station Name	M	Site condition	Source (Fault Type)	Site source Distance (km)
1	Umbria Marche, Italy	1997	Aquilpark-Citta	6.9	C	Strike-slip	44.58

Plastic analysis is then employed to simulate post-yield behaviour, identifying plastic hinge formation and force redistribution. These outputs are used to classify damage states based on standard thresholds such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). Finally, fragility curves are developed using a lognormal cumulative distribution function and maximum likelihood estimation to quantify damage probabilities.

Calculation of Fragility Curves

$$P(LS | IM) = \Phi \left(\frac{\ln(IM/\theta)}{\beta} \right)$$

Where:

- Φ : Standard normal CDF
- θ : Median capacity (from your $\theta = e^{\mu}$ table)
- β : Dispersion (from your table)

1. Log-transform each capacity:

$$y_i = \ln(x_i), \quad i = 1, 2, \dots, n$$

2. Compute the mean of the logs:

$$\mu = \frac{1}{n} \sum_{i=1}^n y_i$$

3. Compute the sample standard deviation of the logs:

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (y_i - \mu)^2}$$

4. Back-transform to get the fragility parameters:

$$\theta = e^{\mu}, \quad \beta = \sigma$$

• $P(IO | IM)$:

$$P(IO | IM) = \Phi\left(\frac{\ln(IM/\theta_{IO})}{\beta_{IO}}\right)$$

• $P(LS | IM)$:

$$P(LS | IM) = \Phi\left(\frac{\ln(IM/\theta_{LS})}{\beta_{LS}}\right)$$

• $P(CP | IM)$:

$$P(CP | IM) = \Phi\left(\frac{\ln(IM/\theta_{CP})}{\beta_{CP}}\right)$$

Results

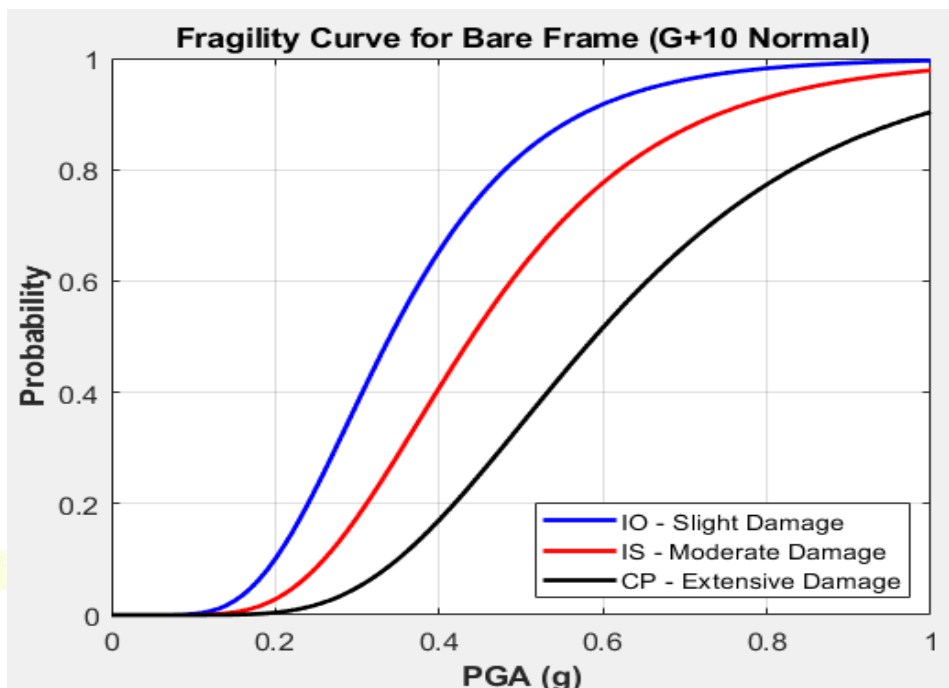


Figure 11. Fragility Curves for G+10 Normal RC Building without Shear or Infill Walls

The graph displays the probability of exceeding various damage states—IO, LS, and CP—for a G+10 normal RC building without additional lateral load-resisting systems. The Immediate Occupancy (IO) state reaches 50% at ~0.35g, Life Safety (LS) at ~0.42g, and Collapse Prevention (CP) at ~0.50g. The curves indicate moderate seismic resistance, with a performance level between that of shear wall and infill wall systems, highlighting the vulnerability of standard RC frames under increasing seismic intensities.

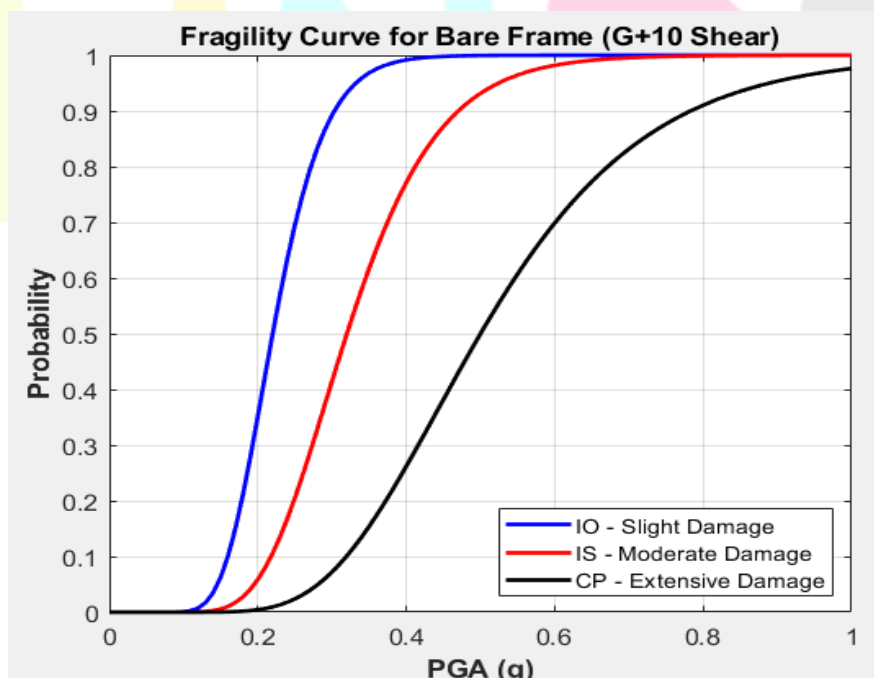


Figure 10. Fragility Curves for G+10 RC Building with Shear Wall under Varying PGA Levels

The figure illustrates the seismic fragility curves for a G+10 RC building with shear walls. The Immediate Occupancy (IO) state reaches 50% probability at approximately 0.25g, Life Safety (LS) at ~0.35g, and Collapse Prevention (CP) at ~0.50g. Compared to infill wall systems, the shear wall structure shows improved seismic resistance, particularly for LS and CP states, indicating its enhanced ability to prevent severe damage and structural failure during moderate to high PGA levels.

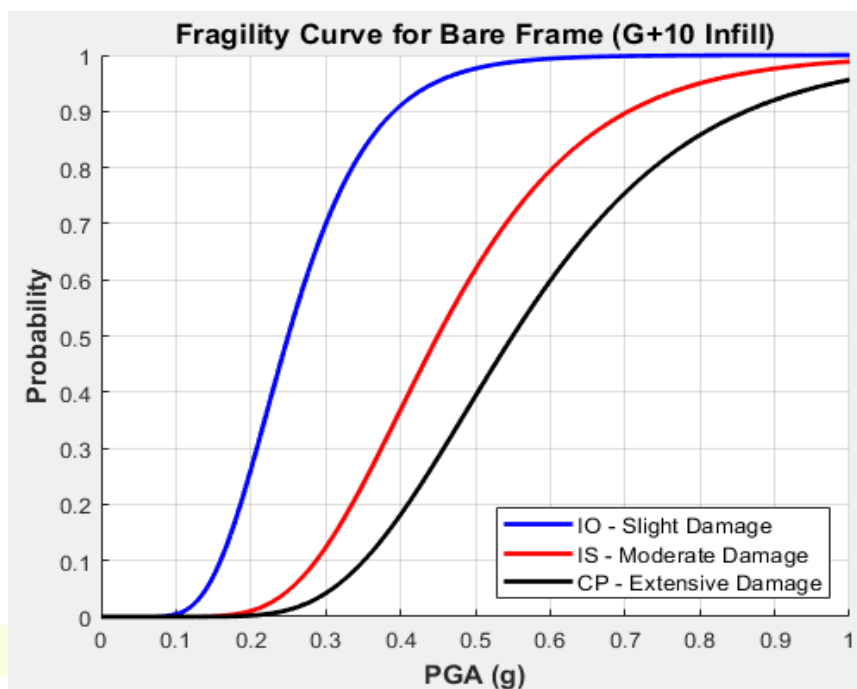


Figure 8. Fragility Curves for G+10 RC Building with Infill Wall under Varying PGA Levels

The graph shows the probability of exceeding different damage states—Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP)—as a function of Peak Ground Acceleration (PGA). The IO state reaches 50% probability at ~0.25g, LS at ~0.45g, and CP at ~0.55g. This indicates that the RC building with infill walls is highly sensitive to seismic activity, with significant structural performance degradation beginning at moderate PGA levels.

Based on implemented NLTHA following FEMA P-58 guidelines, The conclusions are:

- **G+10 Normal:** This structure is the most vulnerable, with a high probability of exceeding IO at low PGA (e.g., ~0.2g), LS at moderate PGA (~0.4g), and CP at higher PGA (~0.6g). It requires significant seismic retrofitting.
- **G+10 Shear wall:** The addition of shear walls improves performance, shifting the curves rightward (e.g., IO ~0.3g, LS ~0.5g, CP ~0.7g), indicating better resistance to seismic forces.
- **G+10 Infill Wall:** Infill walls further enhance seismic capacity (e.g., IO ~0.4g, LS ~0.6g, CP ~0.8g), making it the most resilient configuration among the three.

7. CONCLUSION

Comparative Seismic Performance of RC Frames

- **Bare Frame:**
 - Exhibits the highest vulnerability due to low lateral stiffness and lack of energy dissipation elements.
 - Fragility curves indicate early transition into damage states, even at low seismic intensities.
 - Suitable only for low-risk seismic zones or with retrofitting.
- **Shear Wall Frame:**
 - Shows improved stiffness and energy absorption, delaying the onset of damage states.
 - Fragility curves reveal a moderate shift toward higher PGA thresholds for damage.
 - Performance varies with infill distribution and strength; can be unpredictable under large seismic events due to brittle failure.
- **Infill Wall Frame:**
 - Demonstrates maximum resistance among the three configurations.
 - Fragility curves show a significantly reduced probability of exceeding critical damage states.
 - Suitable for seismic-prone regions; provides stable and ductile behavior under dynamic loads..

There is also potential to apply the developed fragility curves in regional risk assessments and urban disaster planning models, contributing to more informed policy and zoning decisions. Incorporating uncertainty quantification more robustly through stochastic ground motion models and Bayesian updating techniques could further refine the reliability of predictions. Lastly, real-time monitoring and updating of fragility curves using sensor data from instrumented buildings can make this approach dynamic and responsive to changing conditions, paving the way for smart infrastructure resilience frameworks.

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