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Fragility Analysis of RC Framed Using Incremental Dynamic Analysis

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Abstract

This study presents a comprehensive assessment of the seismic performance of framed structural systems using nonlinear dynamic analysis techniques. The methodology involves subjecting a structural model to a series of ground motion records, each scaled progressively to simulate increasing seismic intensity levels. This approach enables the evaluation of structural behavior across a broad range of performance states, from initial elastic response to ultimate collapse. Critical engineering demand parameters, such as inter-storey drift and base shear, are tracked throughout the analysis to characterize the development of structural damage. Based on the dynamic response data, analytical fragility curves are constructed to quantify the likelihood of exceeding predefined damage states under varying seismic intensities. These curves serve as a probabilistic tool for identifying potential vulnerabilities and for estimating seismic risk. The outcomes contribute valuable insights into structural reliability under earthquake loading and support the implementation of performance-based assessment frameworks. By integrating contemporary analytical procedures and recent developments in seismic evaluation, the study enhances the accuracy and applicability of fragility-based approaches in structural engineering.

Key Words: Nonlinear analysis, Fragility analysis, RC framed Structure, Ground Motion, Peak Ground Acceleration, Incremental Dynamic Analysis

Introduction

Seismic risk assessment is a fundamental aspect of structural engineering, particularly in earthquake-prone regions. One of the primary objectives in earthquake engineering is to evaluate the vulnerability of structures and understand their behavior under varying seismic loads. Reinforced concrete (RC) framed structures, which are commonly used in buildings and infrastructure, often represent a significant portion of a city's built environment. Understanding how these structures perform during an earthquake is essential for ensuring public safety and optimizing the design and retrofitting of buildings to withstand seismic events.

Traditional seismic analysis methods, such as linear static or dynamic analyses, may not adequately capture the complex, nonlinear behavior of RC structures under large seismic forces. When subjected to strong ground motions, RC frames exhibit inelastic behavior, including plastic deformations, damage progression, and potential failure modes, which cannot be captured accurately by linear models. Therefore, nonlinear seismic analysis techniques are crucial to obtaining a more realistic picture of a structure's seismic vulnerability. Incremental Dynamic Analysis (IDA) requires the use of multiple earthquake ground motion records to evaluate structural performance under varying seismic intensities. A ground motion suite refers to a set of recorded or synthetic earthquake accelerograms that represent the seismic hazard characteristics of a specific site or region. These ground motions must capture a wide range of frequency content, durations, and intensities to assess the nonlinear behavior of RC structures accurately. The suite should ideally be scaled or selected based on the target response spectrum, soil conditions, and site-specific seismicity. The accuracy and reliability of the resulting fragility curves, which relate the probability of exceeding damage states to seismic intensity measures, are highly dependent on the representativeness and diversity of the ground motion suite used in the IDA.

Fragility curves are probabilistic tools that describe the likelihood of a structure reaching or exceeding a specific level of damage under varying seismic intensity. To construct these curves, three key concepts come into play: Intensity Measure (IM), Engineering Demand Parameter (EDP), and Damage Measure (DM). Each represents a different stage in the cause-effect chain of earthquake engineering. These curves provide a probabilistic relationship between a chosen intensity measure (IM), such as spectral acceleration or peak ground acceleration, and the likelihood of exceeding a particular limit state, such as immediate occupancy, life safety, or collapse prevention.

1. O bjectives

- To develop a seismic Non-linear Model for RC building using relevant software.
- To perform Incremental Dynamic Analysis under the suit of Ground Motion.
- To create Fragility curves for RC buildings for various damage states.

3. Methodology For the Study

3.1 Modeling Approach

The representative model is Reinforce concrete frame in Seismic Zone IV, and the Response Factor is 3, as well as the Importance Factor is 1.5. It is a typical reinforced concrete ground + ten-story frame, with a soil type is medium. In plan, the structure height is 33.45m, with the ground story height is 3.45m and the typical story height is 3m, respectively, as shown in Fig. 1. Sectional dimensions and reinforcement details of structural frame members are shown in Table 1. Linear Response spectrum analysis was carried out to confirm the Frame sections for seismic loading. Under seismic loading, buildings tend to experience deformations that go beyond the linear elastic range. To accurately capture this behavior, nonlinear analysis methods are essential. In such analyses, two types of nonlinearities must be considered to reflect the true response of structural elements. The first is material nonlinearity, which accounts for the inelastic behavior of materials such as concrete and steel once they exceed their yield limits. The second is geometric nonlinearity, which considers changes in the structure's configuration and stiffness due to large deformations or displacements during seismic events. Together, these nonlinear effects are crucial for realistically assessing the seismic performance of the building.

3.2 Non-linear modelling

Modeling of Frame elements :

When a building is subjected to seismic loading, it undergoes deformations that are nonlinear. To accurately understand how the structure behaves during an earthquake, nonlinear analysis methods are necessary. This involves considering two main types of nonlinearity in the structural elements: material nonlinearity, which accounts for the inelastic behavior of materials like concrete and steel, and geometric nonlinearity, which considers the effects of large deformations on the structure's stability and strength.

Material Nonlinearity: The reinforced concrete (RC) frame is modeled using two-node finite elements to represent both beams and columns. To realistically capture the inelastic behavior of the structure under seismic loading, material nonlinearity is incorporated through the lumped plasticity approach. In this method, plastic deformations are concentrated at the ends of structural members using nonlinear hinges, which effectively simulate localized yielding and damage. For beams and columns, different types of hinges are assigned based on the expected deformation behavior. Flexural hinges are used to model bending-related deformations and are treated as deformation-controlled elements, meaning their performance is governed by rotational capacity. In contrast, shear hinges are considered force-controlled, as they fail when shear forces exceed their limits without significant deformation warning.

Columns are modeled using coupled P-M2-M3 flexural hinges, which account for the interaction between axial load (P) and biaxial bending moments (M2 and M3). This coupling is important for capturing complex behavior such as P–Δ effects and instability under combined loading. Beams are typically subjected to bending about their strong axis, and are therefore modeled using uncoupled M3 hinges, which focus on rotation about the major axis only. To streamline the hinge assignment process, the Auto Hinge feature in SAP2000 is utilized. This feature automatically applies hinge properties to RC members based on predefined acceptance criteria, following guidelines provided in FEMA 356[5] and ASCE 41. This ensures that the nonlinear behavior of the structural elements is modeled by widely accepted performance standards, allowing for a more accurate assessment of the building's seismic performance.

Geometric Nonlinearity: In structural engineering, the P-Delta effect represents a significant second-order geometric nonlinearity, particularly relevant under seismic loading conditions. This effect arises when the equilibrium of a structure is influenced by its deformed configuration, leading to additional internal forces and moments that can amplify displacements and alter the structure's response. SAP2000 includes this P-Delta option.

3.3 P erforming Incremental Dynamic Analysis

3.3.1 Model Description and Analysis

A ground+ten-storey Reinforced Concrete (RC) frame structure 20m X 22.5m with base fixed is considered for this study, as shown in Fig. 1(a) and Fig. 1(b). Time History Analysis is carried out by applying Nonlinear Direct Integration using the Software SAP2000. The columns as well as beams are modeled as frame elements, and the floor slab is considered to be a rigid diaphragm and is modeled as a membrane element for the slab system. The typical plan view and elevation as shown in the figure. The frame elements, along with details, are specified in Table 1a) & Table 1 b.

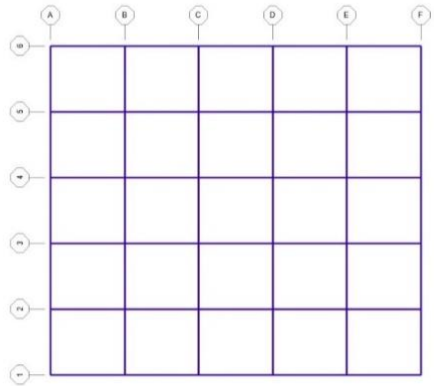

Fig. 1 a). Plan of RC Frame

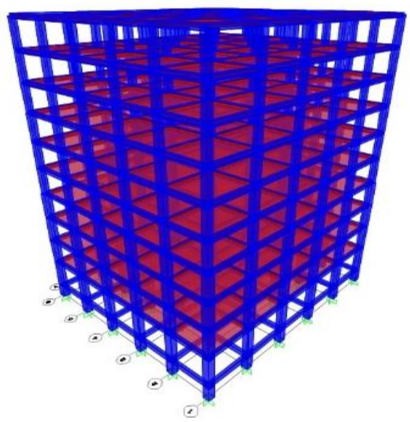

Fig. 1 b). Elevation of RC Frame

Table 1 a). Reinforcement details of Columns

Members	Size in mm	Main steel	Remark
C1	600 x 600	18-16 Φ	Up to storey 4
C2	500 x 500	16-16 Φ	Storey 4 to 7
C3	450 x 450	14-16 Φ	Storey 7 to 10

Table 1 b). Reinforcement details of Beams

Title		Main steel	Remark

	Size in mm	At top	At bottom	
B1	300 x 450	4-16 Φ	4-16 Φ	Up to storey 5
B2	300 x 450	3-16 Φ	3-16 Φ	Storey 6 to 10

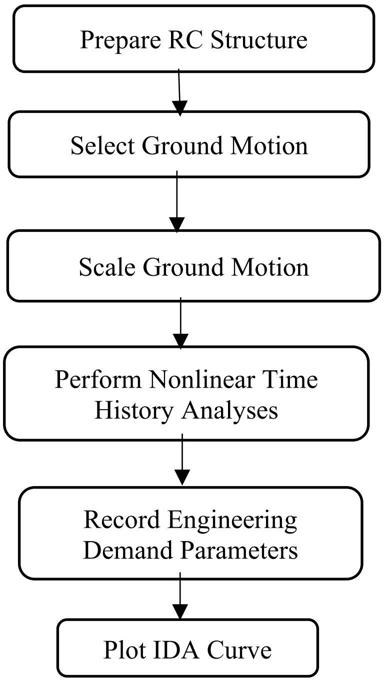

Fig. 2. Incremental Dynamic Analysis Procedure

3.3.2 Selection of Ground Motion Records

The selection of ground motion records is performed in Incremental Dynamic Analysis (IDA), as it directly influences the accuracy and reliability of the structural seismic performance and resulting fragility curves. For IDA, a suite of ground motions is selected and scaled to increasing intensity levels to evaluate how a structure behaves under progressively severe seismic demands until collapse or target damage states are reached. The selected records should represent the seismic hazard expected at the site, considering factors such as earthquake magnitude, source-to-site distance, local soil conditions, and faulting mechanisms. Typically, records from moderate to large magnitude events (e.g., Mw 6.5–7.5) and appropriate distance ranges (e.g., 10–50 km for far-fault events) are preferred. It is essential to select motions that match the site's soil profile (rock, stiff, or soft soil), which is commonly represented by the average shear wave velocity in the top 30 meters (Vs30). For Incremental Dynamic Analysis, ground motion records are taken from the strong motion database of the Berkeley Pacific Earthquake Engineering Research Center (PEER)[8]. The selected ground motion (GM) records are shown in Table 2.

Table 2. Suite of Ground motion records

RSN No.	Event	Year	Magnitude	Rjb (Km)	PGA (g
126	Gazli USSR	1976	6.8	3.92	0.70
143	Tabas Iran	1978	7.35	1.79	0.85
765	Loma Prieta	1989	6.93	8.84	0.41
825	Capemend CPM	1992	7.01	0	1.49
848	Landers	1992	7.28	19.74	0.417
1077	Northridge	1994	6.69	17.28	0.88
1617	Duzce Turkey	1999	7.14	3.93	0.513
8166	Duzce Turkey	1999	7.14	3.58	0.353
4456	Montenegro Yugoslavia	1979	7.1	0	0.300

3.3.3 Scaling of Ground Motion Records

For Scaling Ground Motion Records, the one-step scaling method is used. Probabilistic seismic demands in IDA are estimated by applying a series of real earthquake ground motions to a building model, gradually increasing their intensity using a seismic intensity measure (IM), typically spectral acceleration $Sa(T_1)$. According to ASCE 7-10, the average spectral acceleration of selected ground motions should exceed the design spectrum within $0.2T_1$ to $1.5T_1$, where T_1 is the building's fundamental period. Various scaling methods exist, such as direct scaling at T_1 (Vamvatsikos & Cornell, 2002) [21], geometric mean scaling over a period range (Shakib & Pirizadeh, 2010) [13], and the two-step method from FEMA P-695 (2009) [6], all aiming to align ground motion intensity with structural characteristics for accurate IDA. In IDA, the one-step scaling approach streamlines the process by incrementally scaling each ground motion record through discrete intensity levels in a single analysis sequence, rather than computing fully separately at each level.

3.3.4 Selection of Intensity Measure (IM), Damage Measure (DM), and Damage State (DS)

In this study, the intensity measure (IM) used is spectral acceleration at the structure's fundamental period with 5% damping, Sa(T1, 5%), as it reflects both ground motion and structural response. The structure's behavior under seismic loading is measured using Engineering Demand Parameters (EDPs). Based on the recommendations of Vamvatsikos and Cornell (2002)[21], the maximum inter-story drift ratio is chosen as the EDP, as it closely relates to structural performance and is widely used in design codes like FEMA 356 (2000)[5] and HAZUS (2003). During earthquakes, structures undergo various damage states. As this study relies on numerical simulations, physical damage like cracks cannot be directly observed. Therefore, damage states are defined based on inter-story drift limits taken from FEMA 356[5]. Three damage states are considered: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), where the drift limits for IO and LS are based on FEMA 356[5] guidelines.

3.3.5 D
evelopment of the Fragility Curve

The fragility curve shows the probability of occurrence of a certain damage state for a given seismic intensity. In this study, a set of nine earthquake ground motions was used to perform Incremental Dynamic Analysis (IDA) on a structural model. For each ground motion, the building was analyzed under increasing intensity levels until significant levels of maximum drift were reached. The following is the equation for developing the fragility curve,

$$\boldsymbol{P}\left(\frac{\boldsymbol{DS}}{\boldsymbol{Sa}}\right) = \emptyset(\boldsymbol{Ln}(\boldsymbol{Xi}) - \boldsymbol{\lambda})/\boldsymbol{\beta})$$

$$\boldsymbol{\beta} = \sqrt{[\sum(\boldsymbol{Ln}(\boldsymbol{Xi}) - \boldsymbol{\lambda})^2)/\boldsymbol{N} - \mathbf{1}]}$$

Where,

P(DS/Sa) = Probability of Damage state exceeding the spectral acceleration.

∅ = Normal Distribution

Ln(Xi) = Natural logarithm of spectral acceleration value obtained from IDA curve

λ = Median of Fragility Curve

β = Standard Deviation

N = Number of Ground Motion Records

Plot the curve taking Intensity Measure on the X-axis and Probability on the Y-axis, which is known as the fragility curve derived by Baker, J. W.

When calculating of fragility curve for Life Safety Damage, Interstory drift will be 2%, for Immediate Occupancy, Interstory drift will be 1% and for Collapse Prevention, Interstory drift will be 4%.

4. Results

4.1 Incremental Dynamic Analysis (IDA) – X Direction & Y Direction

Fig. 3 IDA Curve in X-Direction shows the Incremental Dynamic Analysis (IDA) curves for the RC Framed Structure in the X-direction, and Fig. 4 IDA Curve in Y-Direction shows the Incremental Dynamic Analysis (IDA) curves for the RC Framed Structure in the Y-direction subject to a suite of ground motion records. The graph plots Spectral Acceleration (Sa) on the vertical axis against maximum inter-story drift ratio (%) on the horizontal axis. Each curve represents the response of the structure to a different ground motion scaled incrementally.

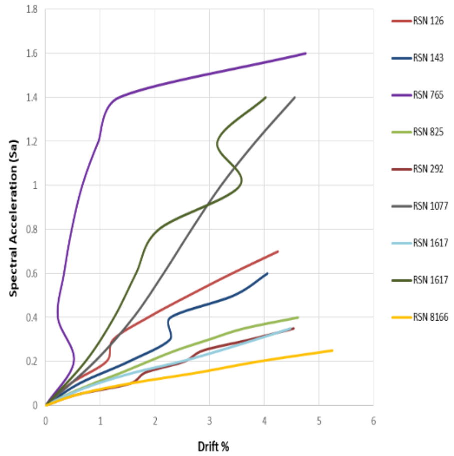

Fig. 3. IDA Curve in X-Direction

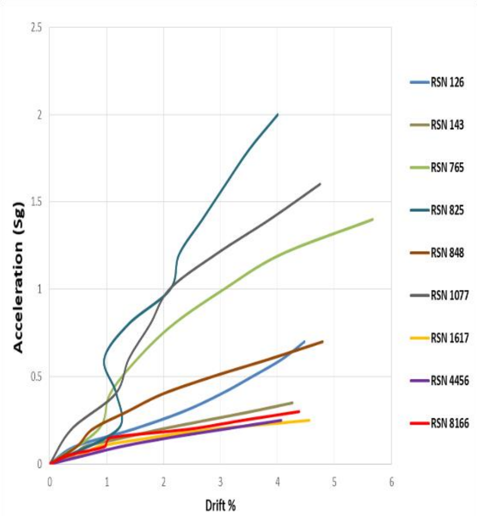

Fig. 4. IDA Curve in Y-Direction

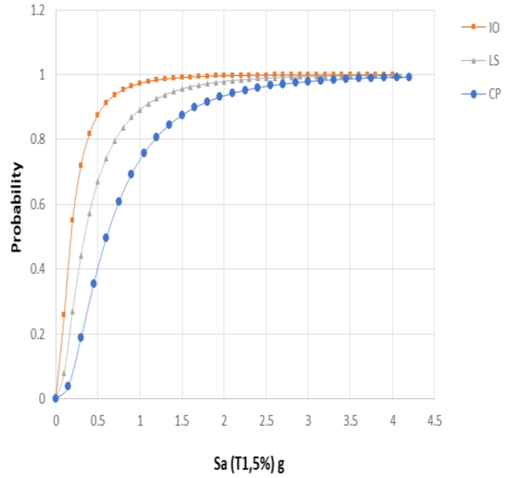

Fig. 5. Fragility Curve in X-Direction

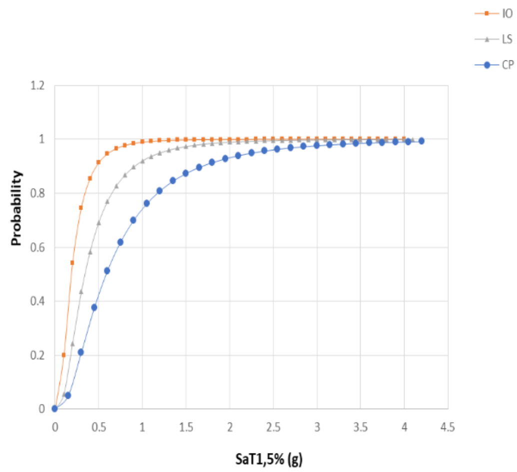

Fig. 6. Fragility Curve in Y-Direction

4.2 Fragility Curve – X Direction & Y Direction

Fig. 5 Fragility Curve in X-Direction and Fig. 6 Fragility Curve in Y-Direction present the lognormal fragility curves for the RC framed structure in the X-direction and Y-direction, developed based on Incremental Dynamic Analysis (IDA) results. The curves represent the probability of exceeding three key performance levels, Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) as a function of spectral acceleration Sa(T1,5).

The horizontal axis shows the seismic intensity in terms of spectral acceleration (g), while the vertical axis shows the probability of exceedance.

5. Discussion

5.1 IDA Curve in X-Direction

The IDA curve in the X-direction illustrates the nonlinear seismic response of the RC framed structure under various ground motions. The initial segments of the curves exhibit elastic behavior up to approximately 1% drift. Beyond this, nonlinear responses and damage progression are observed.

Ground motions such as RSN 765 and RSN 1027 resulted in higher spectral accelerations (>1.5g), indicating severe demand, whereas RSN 8166 and RSN 292 caused moderate responses (<0.6g). A few curves exhibit softening or plateauing beyond 3%

drift, suggesting structural instability or collapse potential.

Overall, the IDA results highlight significant variability in seismic demand and confirm the necessity of probabilistic approaches in fragility assessment.

5.2 IDA Curve in Y-Direction

The IDA curve in the Y-direction shows how the RC framed structure responds when earthquake intensity increases from small to large. Initially, all the ground motions produced a steady, linear response up to about 1% drift, meaning the structure remained elastic and undamaged in this range.

As the intensity grew, some records like RSN 765 and RSN 1077 caused a sharp rise in spectral acceleration, indicating early stiffness loss and potential damage. These motions triggered higher demands on the structure at smaller drift levels, suggesting a more brittle behavior. In contrast, motions like RSN 292 and RSN 8166 showed a smoother, more gradual increase in Sa, reflecting better energy absorption and a more ductile response.

Overall, the curves clearly show that the same structure can behave very differently under different earthquake records in the Y-direction. This highlights the importance of considering a variety of ground motions when assessing seismic performance and supports the use of IDA for capturing these differences in behavior.

5.3 Fragility Curve in X-Direction

Fig. 5 Fragility Curve in X-Direction shows how the RC framed structure responds to increasing seismic intensity in the X-direction. The fragility curves reflect the likelihood of the structure reaching different levels of damage: Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP), as spectral acceleration (Sa) increases.

At lower shaking levels (around 0.2g), the probability of minor damage (IO) already becomes noticeable, suggesting the structure is sensitive to even moderate earthquakes. As the shaking intensifies, the chance of more serious damage increases — the LS curve shows a 50% probability around 0.6g, meaning that half the time, the building could experience significant structural distress at that level. Beyond 0.9g, the CP curve flattens out, indicating that the structure is almost certain to collapse if such high intensity is reached.

This behavior confirms that as ground motion becomes more intense, the structure progressively loses its ability to withstand further damage. The smooth transition between curves gives confidence in the fragility model and highlights the need for targeted retrofitting or design improvements in this direction.

5.4 Fragility Curve in Y-Direction

The fragility curve in the Y-direction provides a clearer picture of how the RC-framed structure behaves as earthquake intensity increases. From the graph, we can see that the probability of reaching the Immediate Occupancy (IO) level starts to rise even at low spectral acceleration (around 0.2g), meaning the building may experience light damage early on. As the shaking becomes stronger, the structure is more likely to reach the Life Safety (LS) level. This happens around 0.5g, where there's about a 50% chance the structure will be significantly affected, requiring repairs but still preventing collapse.

At higher acceleration levels, above 0.9g, the chance of Collapse Prevention (CP) being exceeded reaches almost 100%. This shows that the structure becomes very vulnerable at this stage and could potentially fail.

Overall, the Y-direction fragility curve shows a progressive increase in damage risk, and it highlights how important it is to evaluate structural performance in both directions for safer design.

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Declarations

1. Funding Declarations:
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2. Competing Interests:

I declare that the authors have no competing interests as defined by Springer or other interests that might be perceived to influence the results and/or discussion reported in this paper.

3. Authors' Contributions:

P.S.B. conducted the ground motion analysis, performed the modelling, and drafted the main manuscript text. R.M.D. and S.P.P. assisted with data interpretation and figure preparation. All authors reviewed and approved the final manuscript.

4. Data Availability:

The ground motion records used in this study were obtained from the PEER Ground Motion Database, which is publicly accessible at https://ngawest2.berkeley.edu. Also, the code provisions mentioned in the paper can be found on their specific websites. All other data generated or analyzed during the study are included in this published article.