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Risk Targeted Seismic Design of 10-storey RC Frame Building

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Abstract - Current seismic design practices, primarily based on uniform hazard spectra, often fail to guarantee a consistent collapse probability for structures across different regions. Such failures are mainly due to inherent uncertainties in collapse capacity and variations in hazard curve shapes, leading to an unequal distribution of seismic risk. The present study investigates a typical 10-storey RC frame building designed according to Indian seismic codes located in zone III. The full-scale model of the RC frame is analysed using the Incremental Dynamic Analysis (IDA), considering a suite of scaled ground motion records to assess their collapse behaviour under varying earthquake intensities. The results from IDA are then utilised to generate building-specific fragility curves, quantifying the probability of collapse as a function of spectral acceleration. Furthermore, site-specific hazard curves are developed for the chosen locations, considering the regional seismicity and ground motion characteristics. A risk-targeted design approach is used to convolve the hazard curves with the building-specific fragility curves to estimate the annual collapse rate and the collapse risk over a 50-year period. This study highlights the importance of transitioning from the uniform hazard spectrum paradigm to risk-targeted design methodologies to achieve a more equitable and consistent level of seismic safety across various locations and building types, with findings revealing that risk-targeted designs are approximately 50% heavier than those based on IS codes, particularly impacting the columns of lower floors for 1% target collapse risk.

***Keywords*:** RC frame building, Incremental dynamic analysis, Ground motions, Fragility curve, Hazard Curve

1. Introduction

Variations in the shapes of hazard curves across different locations introduce a significant layer of complexity in seismic design, as the relationship between the Maximum Considered Earthquake (MCE) and the Design Basis Earthquake (DBE) differs across regions. This variability implies that structures designed with the same DBE may face different levels of risk due to potentially varying MCE values in their respective areas. For instance, a structure designed for a particular DBE in a low-MCE region might have a lower probability of collapse compared to a structure designed for the same DBE in a region with a higher MCE. To address this issue, the concept of risk-targeted seismic design has emerged, aiming to adjust design ground motions to achieve a targeted collapse risk. This approach ensures a uniform probability of collapse by carefully accounting for uncertainties in collapse capacity and regional differences in hazard curve shapes, allowing engineers to design structures with consistent and uniform collapse risks.

The collapse risk of structures is determined by combining fragility curves, which depict the probability of damage exceedance relative to an intensity measure, with collapse curves. Various statistical methods have been developed for fitting fragility curves, providing more reliable assessments of structural vulnerability [1-3]. The multi-strip analysis approach has been identified as particularly effective, delivering accurate results with fewer scaling requirements during incremental dynamic analysis [4-6]. This method enhances the precision of seismic performance evaluations by reducing computational demand without compromising accuracy.

Recent research has emphasised the need for risk-targeted adjustments to seismic design ground motions to address inconsistencies in collapse probabilities across regions. Current NEHRP Provisions and standards like ASCE 7-05 assume uniform collapse probabilities, but uncertainties in structural capacity and regional seismic hazards create uneven risks [7].

Modifications to seismic design maps have been proposed to achieve consistent collapse probabilities, with significant reductions in ground motions for areas such as the New Madrid Seismic Zone, while most regions experience minimal changes (<15%). A framework integrating risk-targeted hazard spectra, combining hazard curves and fragility functions, has been introduced to ensure uniform seismic risks for buildings and communities, as seen in New Zealand's updated practices [8]. Advances in assessing the mean annual frequency of collapse (λc) offer more efficient and accurate predictions of building performance during earthquakes, reducing uncertainties in seismic risk estimations [9]. These developments highlight the global transition toward performance-based seismic design, ensuring structural safety aligns with hazard and risk profiles.

There is a need to improve the accuracy and efficiency of seismic performance evaluations by refining methods for fragility curve fitting and collapse risk estimation. Existing approaches, such as multi-strip analysis, have shown promise in reducing computational demands while maintaining accuracy. However, further research is necessary to enhance their applicability across varying structural systems and hazard conditions. The present study is performed for a 10-story building to develop a risk-targeted design framework, advancing the reliability of seismic risk assessments.

2. Problem Statement

2.1. Building Geometry, Material Properties and Loading Details

A 10-story reinforced concrete (RC) frame building with a base area of 20 m by 20 m and a story height of 3 meters is modelled using MIDAS Gen, 2023 [10]. The structure is situated in Surat, classified as Zone III on medium soil (Type II) per IS 1893 Part-1 guidelines [11].

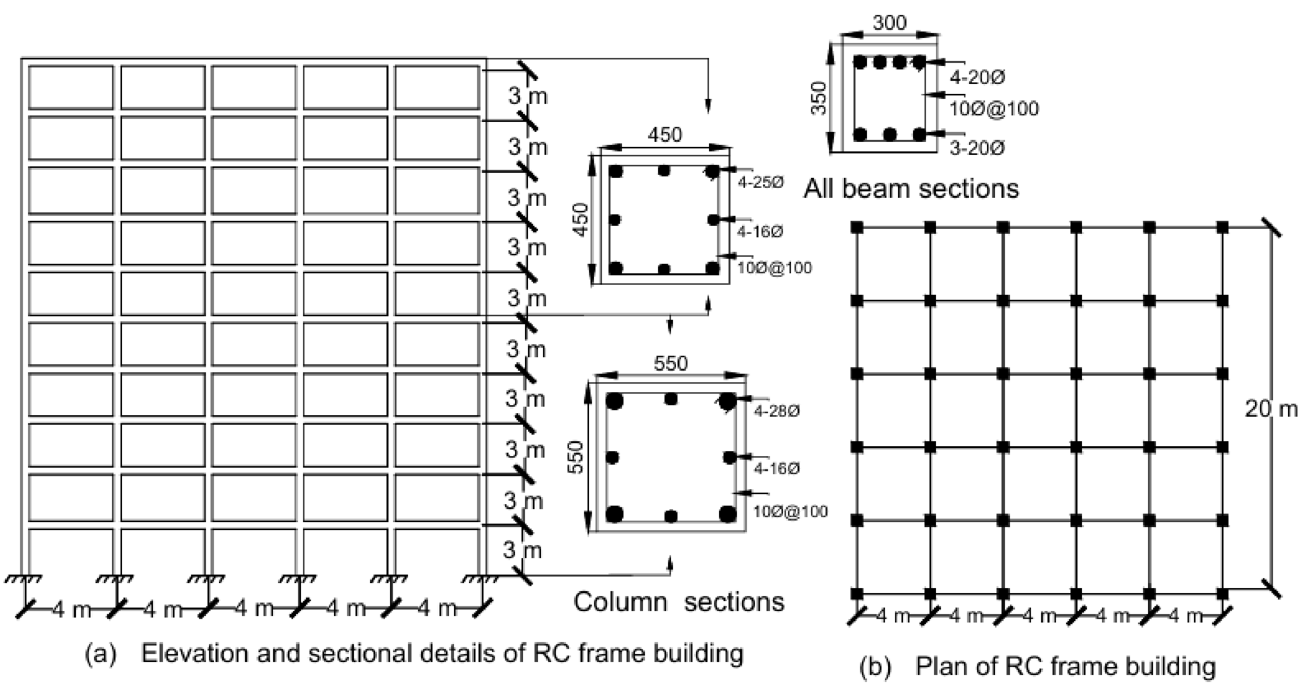

Fig. 1: (a) Elevation, sectional details and (b) plan of 10 storey RC frame building.

The beam dimensions throughout the building height are uniform at 300 mm X 350 mm. The column dimensions vary, with the lower five floors constructed with 550 mm X 550 mm columns and the upper five floors with columns sized at 450 mm X 450 mm. Typical floors are subjected to a live load of 2 kN/m², while the roof level has a live load of 1.5 kN/m², with wall loads from 230 mm thick outer walls and 115 mm thick inner walls. A slab thickness of 125 mm is specified. The materials used include M30-grade concrete and Fe500 steel. An importance factor of 1 is assigned, and a response reduction factor of 5 is applied, as the building is designed as a special moment-resisting frame. Stiffness modifiers are incorporated with values of 0.35 for beams and 0.70 for columns. The building is designed and detailed following the guidelines of IS 456, 2000 and IS 13920, 2016, as shown in Figure 1 [12-13].

2.2. Ground Motion Selection

The earthquake ground motion for the study is selected by following FEMA P695 (2009) guidelines [14]. The ground motions are chosen from the PEER-NGA database by appropriately considering Magnitude, site condition, and type of ground motion. The selected ground motions are then normalised using their peak ground velocity by multiplying them with the normalisation factor. The normalised ground motions are subsequently matched to the target response spectrum of Zone III within the time interval defined from the building's fundamental period. Table 1 lists the selected ground motions with their details.

Table 1: Earthquake ground motion data.

EQ	RSN	Direction	Event	Station	PGA(g)	PGV(cm/s)	Magnitude
1	850	H1	Landers	Desert Hot Springs	0.17	19.46	7.28
2	850	H2	Landers	Desert Hot Springs	0.15	20.88	7.28
3	1101	H1	Kobe, Japan	Amagasaki	0.28	33.57	6.9
4	1101	H2	Kobe, Japan	Amagasaki	0.33	44.83	6.9
5	1158	H1	Kocaeli, Turkey	Duzce	0.31	58.87	7.51
6	1158	H2	Kocaeli, Turkey	Duzce	0.36	55.66	7.51
7	1602	H1	Duzce, Turkey	Bolu	0.74	55.93	7.14
8	1602	H2	Duzce, Turkey	Bolu	0.81	65.88	7.14
9	3749	H1	Cape Mendocino	Fortuna Fire Station	0.33	33.91	7.01
10	3749	H2	Cape Mendocino	Fortuna Fire Station	0.28	38.05	7.01

2.3. Incremental Dynamic Analysis

Incremental Dynamic Analysis (IDA) is a comprehensive analytical technique employed to assess structural seismic performance by subjecting buildings to a progressively scaled series of ground motion records. This method systematically applies increasing seismic intensity levels to the structure, typically measured in terms of spectral acceleration or peak ground acceleration, until it reaches a specified limit state or experiences collapse. With each increment, response parameters of peak displacement and inter-story drift ratios are meticulously recorded to capture the behaviour of the building under varying intensities. The time histories are scaled incrementally, ranging from 0.1g up to 4g, allowing for an extensive evaluation of the structure's performance across a broad spectrum of seismic demands.

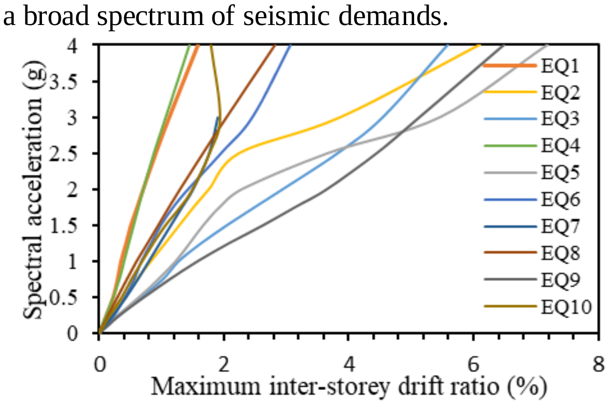

Fig. 2: Spectral acceleration vs inter-storey drift ratio generated by time history records.

The nonlinear hinge properties are assigned to understand nonlinear behaviour for concrete using the Mander model and steel using the Park strain hardening model [15]. Figure 2 demonstrates the variability in collapse behaviour between different ground motion records, highlighting the inherent uncertainties in earthquake shaking and their potential impact on building performance.

3. Results and Discussion

3.1. Development of Fragility Curve using Multi-Strip Analysis (MSA)

The multi-strip analysis needs a discrete set of ground motion intensity measures (IM) to obtain the curve (Palsanawala et al., 2024c). The number of IM for a particular ground motion depends on the response of the building observed at the initial level. The fragility curve from the various intensities of earthquake ground motion is generated using Eq. 1. The median (θ) and standard deviation (β) are derived by maximising the function shown in Eq. 2.

$$P(IM_i) = \Phi\left[\frac{1}{\beta}\ln\left(\frac{IM_i}{\theta}\right)\right] \tag{1}$$

$$\{\hat{\theta},\hat{\beta}\} = \underset{\theta,\beta}{\arg\max}\sum_{i=1}^{m}\left\{\ln\binom{n_k}{z_k} + z_i \ln\Phi\left[\frac{1}{\beta}\ln\left(\frac{IM_i}{\theta}\right)\right]\right\} + (n_k - z_k)\ln\left(1 - \Phi\left[\frac{1}{\beta}\ln\left(\frac{IM_i}{\theta}\right)\right]\right) \tag{2}$$

Where, P = conventional fragility function at IMi, n_k = total GMs, z_k = collapsed GMs, θ = median and β = standard deviation. Figure 3 represents the fragility curve of the studied building under considered earthquake loading conditions.

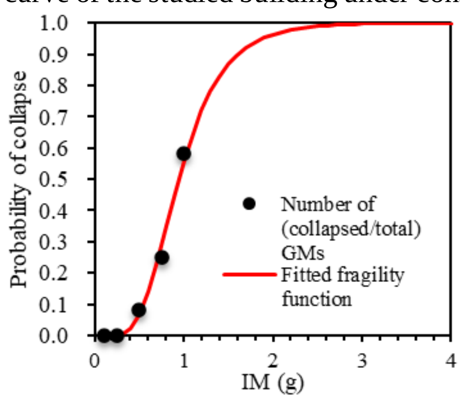

Fig. 3: Fragility curve of 10-storey RC frame building.

3.2. Development of Hazar Curve

A seismic hazard curve depicts the likelihood of different levels of ground shaking at a specific location. It shows that higher shaking intensities are less probable, with steeper curves indicating higher seismic risk. The procedure of hazard curve generation is used from FEMA 273 guidelines using Eqs. (3) – (5) below [16].

$$\ln(S_i) = \ln(S_{i10/50}) + \left[\ln(S_{iBSE-2}) - \ln(S_{i10/50})\right][0.606\ln(P_R) - 3.73] \tag{3}$$

$$P_R = \frac{1}{1 - e^{0.02\ln(1-P_{E50})}} \tag{4}$$

$$S_i = S_{i10/50}(P_R/475)^n \tag{5}$$

$\ln(S_i)$ represents the natural logarithm of the spectral acceleration parameter at a desired probability of exceedance, $\ln(S_{i10/50})$ represents the natural logarithm of the spectral acceleration parameter at 10% probability of exceedance in 50 years, $\ln(S_{iBSE-2})$ represents the natural logarithm of the spectral acceleration parameter at 2% probability of exceedance in 50 years, $\ln(P_R)$ represents the natural logarithm of the mean return period at the desired exceedance probability.

Figure 4 shows the hazard curve of the studied RC frame representing the probability of intensity exceeded in a given year.

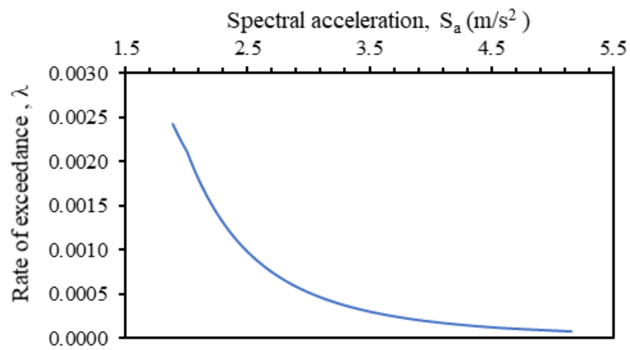

Fig. 4: Hazard curve showing annual rate of exceedance.

To assess the likelihood of building collapse during an earthquake, we need to combine information about the potential ground shaking at a specific location (seismic hazard) with the building's vulnerability to that shaking. This is achieved through a process called convolution, which is performed numerically using a discrete convolution approach. In this technique, the site-specific hazard curve, representing the probability of different earthquake intensities occurring, mathematically combines with the building's fragility curve, which depicts the probability of collapse at various shaking intensities. The Python Code is performed to determine a structure's optimal design hazard level, given a target collapse risk. Figure 5 shows the collapse risk obtained at 0.47g intensity when the target collapse risk is 1%. The building is redesigned for the earthquake intensity, and the design obtained for the considered target risk is shown in Figure 6.

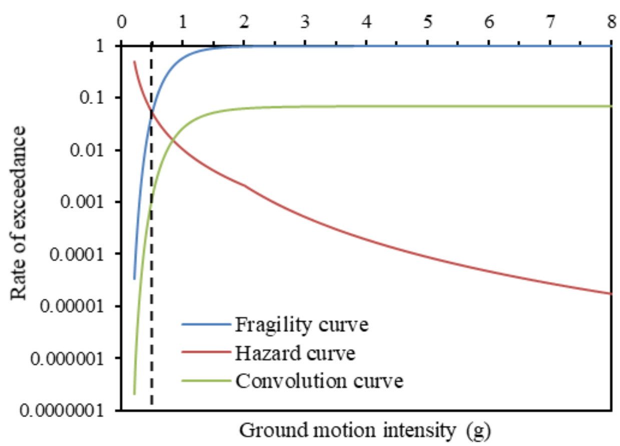

Fig. 5: Combination of Fragility and Hazard curve to evaluate collapse risk.

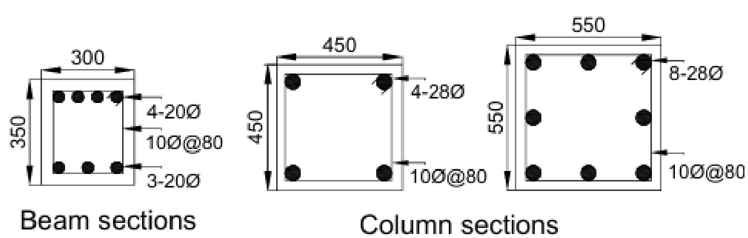

Fig. 6: Redesign of beam section and column sections from the risk-targeted approach.

4. Conclusion

The study focused on the methodology of risk-targeted seismic design on a 10-storey RC frame building designed for Zone III using the design hazard given in the Indian code. The incremental nonlinear dynamic analysis is conducted to understand the building's behaviour. The fragility and hazard curves are generated using statistical methods. The collapse risk value is determined for the studied building by convoluting fragility curves with respective hazard curves.

The findings of this study unequivocally demonstrate that designing buildings solely based on the generalised response spectrum outlined in the Indian code does not guarantee a uniform collapse probability across different locations, even within the same seismic zone. This inconsistency arises from the inherent variability in structural capacity and the distinct hazard profiles of different sites, factors often overlooked by traditional deterministic design methods. In conclusion, the risk-targeted design is observed to be 1.5 times heavier than the building initially designed using IS code, which is reflected in columns on lower floors, especially for 1% target risk.

The study is limited to 10-storey RC frame buildings as the methodology used to evaluate collapse risk is lengthy. However, the study can be extended further by taking more buildings with varying heights and locations.

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