Seismic Resilience Analysis of Vertical Geometrically Irregular RCC Building

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***Abstract*—Through the combination of fragility curve generation and nonlinear static analysis, this study seeks to provide a thorough evaluation of the seismic risk of vertically uneven buildings. The study examines how multi-story buildings with vertical irregularities function seismically, with a particular emphasis on determining how vulnerable they are to seismic loading. The main goals are to create fragility curves for different damage states on the seismic response of the building by doing nonlinear static (pushover) analysis. To comprehend the dynamic behavior and response, five distinct models of vertically irregular buildings have to be analyzed in SAP2000 under seismic stress. carrying out nonlinear static (pushover) analysis, which models how the structure would react to increasing lateral loads. By gradually applying seismic forces, the pushover analysis creates a capacity curve that aids in comprehending how well the building performs at various seismic intensity levels. Frailty curves are made to show the likelihood that a building may experience Slight Damage, Medium Damage, Extensive Damage, and Collapse Damage. With damage states determined by displacement, the fragility curves are built using the pushover analysis results. The study's findings will show Model 3 is 30% more vulnerable under seismic excitation than Model 1 for complete collapse.**

***Index Terms*— Fragility curves, Pushover Analysis, Seismic vulnerability, Vertical Irregularity**

I. INTRODUCTION

Urban infrastructure often includes irregular buildings with non-uniform mass, stiffness, strength, and height distributions, making them more vulnerable to seismic damage. Irregularities in earthquake-resistant systems result in abrupt changes in structural stiffness or strength, which are undesirable during seismic events. Researchers have identified vertical and horizontal structural irregularities as significant contributors to vulnerability. Horizontal irregularities occur when the center of mass and stiffness are misaligned, causing seismic loads to act unevenly. Vertical irregularities include varying story heights, setbacks in geometry, offset columns, and differing floor masses. Given the catastrophic damage caused by earthquakes, assessing seismic vulnerability has become crucial, with fragility curves being a key tool. Fragility curves estimate the probability of structural and nonstructural damage states being reached or exceeded. Represented as lognormal functions, these curves plot the likelihood of failure against peak ground acceleration, providing insights into the extent of potential damage

This study aims to improve understanding of the seismic behavior of highly irregular structures by addressing research gaps, analyzing structural performance, and evaluating design criteria. By focusing on these unique challenges, the study seeks to contribute to structural engineering, enhance seismic risk assessment, and support the development of earthquake-resistant designs for irregular buildings.

A. Non-Linear Static Analysis

The behaviour of the structure in the non-linear (pushover) analysis is represented by a capacity curve that shows the relationship between the base shear force and the roof displacement. Roof displacement was selected for the capacity curves due of its widespread application in practice.

B. Non-Linear Analysis Model

Nonlinear analysis involves a nonlinear relationship between applied forces and displacements, arising from geometric or material nonlinearities. Geometric nonlinearity occurs under large deformations that significantly alter a structure's shape, exemplified by the P-delta effect, where axial loads on lateral displacements generate additional moments. Material nonlinearity occurs when stress-strain behavior deviates from linearity and is modeled using the lumped plasticity approach, introducing plastic hinges at element ends. In nonlinear analysis, a structure's end stiffness evolves from its initial stiffness. Dead load cases are converted to nonlinear load cases to account for these effects, reflecting the structural behavior under combined nonlinear influences.

C. Seismic Vulnerability Analysis

Seismic fragility curves are crucial for assessing structural damage and seismic risk during earthquakes, indicating the probability of failure based on predefined damage states. These curves show the likelihood of failure against ground intensity variables like peak ground acceleration. Two main methods are used to create fragility curves. The first approach involves analytical functions based on limit states, where failure probabilities are calculated by comparing structural capacity with seismic demand. However, this method has limited application due to the complexity of closed-form limit state functions. The second, more commonly used method is simulation-based. Here, failure probabilities are derived by simulating numerous cases and dividing the number of failures by total simulations. This approach can accommodate advanced structural analysis techniques, such as dynamic response history analysis or inelastic pushover, allowing for a broader range of applications in determining seismic fragility.

Earthquake risk assessment estimates casualties, losses, and mitigates risks, considering hazard, vulnerability, and exposure. Vulnerability assessment determines a structure's susceptibility to earthquake damage. Two methods are used: empirical methods based on past earthquake damage and analytical methods using computer simulations to model structural response to seismic events.

D. Fragility Curve Development

Techniques for calculating losses from hurricanes, floods, and earthquakes are described in the HAZUS technical manual. Fragility curves, which plot the likelihood of achieving particular damage thresholds for specified earthquake magnitudes, are included. These curves, which are analytically specified for various building classes and damage states, are crucial for forecasting losses and mortality. It is believed that the damage function is a lognormal function. The median and standard deviation numbers are necessary in order to define a probability distribution. The conditional probability of reaching or surpassing a specific damage state ds is determined by a median spectral displacement Sd and standard deviation β. design level, and it is determined by,

$$P\left(\frac{DS}{Sd}\right) = \emptyset\left[\frac{\ln(Sd) - \ln(\lambda)}{\beta}\right]$$

∅ = Standard normal cumulative distribution function

Sd = Spectral displacement = Roof Displacement in First mode/ (First mode participation Factor + First mode modal displacement of roof)

λ = The Median spectral displacement value at which a building is considered damaged

β = The standard deviation of the damage state's natural logarithm of spectral displacement

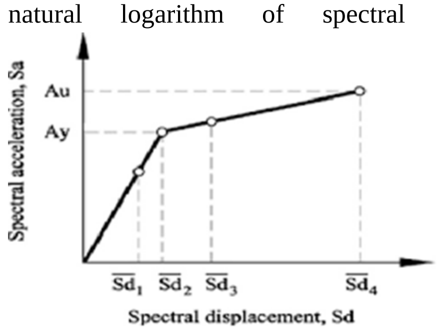

Fig -1: Damage Threshold graph

E. Discrete Damage Probability Calculation of Damage States

The discrete damage state probability ds are given below:

Collapse damage state Probability, P[C]=P[C/Sd]

Extensive damage state Probability, P[E]=P[C/Sd]-P[E/Sd]

Moderate damage state Probability, P[M]=P[E/Sd]-P[M/Sd]

Slight damage state Probability, P[S] =P[M/Sd]-P[S/Sd]

No damage state Probability, P[N]=1-P[S/Sd]

II. LITERATURE REVIEW

Research articles published by various authors in different papers have been studied and are summarized in the following section:

Ghosh, Ghosh and Chakraborty (2017) [1] integrated platform for the performance-based earthquake engineering (PBEE) context of seismic safety evaluation of structures in seismic scenarios. When assessing a structure's seismic susceptibility, this method is becoming more and more widely accepted. With regard to numerical simulation-based SFA inside the probabilistic PBEE framework, the current paper aims to give a general overview of the relevant advances. Considering the overall pattern of such SFA development, the relevant advancements are categorized into two subheadings: (1) the analytical SFA founded on probabilistic seismic demand and capacity models, and (2) the statistical simulation-based SFA utilizing random field theory and statistical simulation based on non-linear PBEE. This has also been examined separately, given the significance of using the Bayesian technique in SFA. Lastly, a summary of critical remarks regarding the advancements and field of research to advance the state-of-the-art is provided.

Gwalani, Singh and Varum (2019) [2] assesed the behavior and capacity at collapse of mid-rise RC frame-shear wall buildings that were designed in compliance with the most recent versions of the IS 1893 (Part 1) and BS EN 1998-1 codes, both with and without torsional irregularity. In order to achieve this, a set of far-field ground motion records is used to conduct bi-directional incremental dynamic analysis (BIDA) on three-dimensional building models. The non-linear behavior of beams is modeled using an experimentally calibrated lumped plasticity model to account for the cyclic deterioration of stiffness and strength, while the columns and shear walls are modeled using fiber-hinge models (ETABS-CSI, 2016) appropriately calibrated with the experimental results available in literature. The BIDA results are used to calculate seismic fragility curves in accordance with the FEMA P695 methodology and to evaluate collapse capacity. In the context of torsionally irregular buildings, the results are compared and analyzed, with a focus on the suitability and constraints of the design guidelines and recommendations in the two codes.

Shah, Davis and Kumar (2020) [3] derived fragility curves are using the inter-storey drift ratio and spectral acceleration at the fundamental period as the damage parameter and intensity measure, respectively. Every structure was designed in accordance with IS 1893 part 1 (2016) and IS 800 (2007). Time histories of several vertically irregularly structured structures were analyzed, and floor displacements were determined. The For mass vertical irregular buildings and typical stiffness buildings, probabilistic seismic demand models were created. Out of all the vertical buildings that were chosen, steel-framed structures with open ground floors were discovered to be the most dangerous vertically irregular construction.

Ghanem and Moon (2021) [4] addressed the computational difficulty in determining fragility curves by employing a novel structural reliability technique that integrates reliability and structural analysis to effectively and precisely compute the failure probability using the first-order reliability approach (FORM). This work investigates the seismic sensitivity of space-reinforced concrete frame buildings with varying degrees of vertical irregularity. More representative seismic fragility curves are created in addition to their three-dimensional analytical models. It is shown that the structure's vertical irregularity significantly affects seismic risk.

Mokashi and Jadhav (2024) [5] examined the possibility of using fragility curves to assess the effectiveness of structural systems, particularly those with a high degree of irregularity. In order to conduct a non-linear static analysis of a G+6 story irregular structural frame that was created in accordance with Indian Standards, the study uses SAP2000. It demonstrates how to use fragility curves to assess the structural performance of a G+6 irregular reinforced concrete structure under seismic pressures. This research emphasizes the importance of considering distinct damage probabilities and collapse threats in various directions in order to properly examine structural vulnerabilities. It suggests a greater vulnerability to damage under specific loading conditions by showing a larger probability of collapse in the push-y direction (44%) as opposed to the push x direction (5%). The results of the study show that fragility curves offer a reasonable and trustworthy method of assessing the seismic performance of very irregular structures. Additionally, it attests to the fact that buildings constructed in accordance with Indian regulations are robust enough to endure an earthquake.

III. OBJECTIVES

1. To analyse and study the multistorey vertically irregular building under seismic loading.
2. To perform the nonlinear static analysis (Pushover analysis) for irregular building in SAP 2000 for Fragility curves.
3. To create the fragility curves for the irregular building for different states of damage like Slight damage, Medium Damage, Extensive Damage, Collapse Damage.

IV. METHODOLOGY

1. Seismic analysis is carried for the RCC Buildings with and without irregularities.
2. The SAP2000 software is used to conduct the study through modeling and analysis utilizing the nonlinear static analysis (Pushover Analysis).
3. Plotting the Fragility Curves for the building for different Damage state.
4. Evaluate the Discrete damage probability for the building and comparing the results.

A. Structural Modelling of Buildings

Table 1 has Structural Data which has been used for the Modelling. Setback Irregularity is introduced to building according to IS 1893:2016 and other references.

Table -1: Structural Modelling Details

Structural Details	
No. of Stories	G+12
X Direction Width	25 m
Y Direction Width	25 m
Storey Height	3 m
Live Load	3 kN/m2
Floor Finish	1.5 kN/m2
Importance Factor	1
Wall Thickness	230 mm
Wall Height	2.7 m
Parapet Wall Height	1.5 m
Concrete Grade	M 25
Steel Grade	Fe 500
Slab Thickness	150 mm
Beam Size	230 x 450 mm
Column Size	500 x 500 mm

RCC Building is modeled is SAP2000 without any irregularities then different types of vertical geometric irregularities were introduced for other two model.

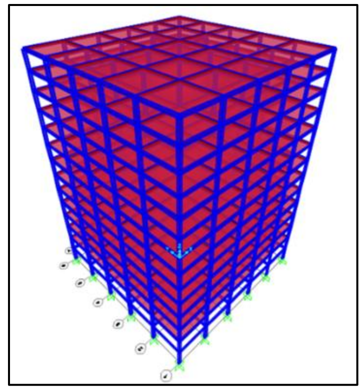

Fig -2: Isometric View for Model 1

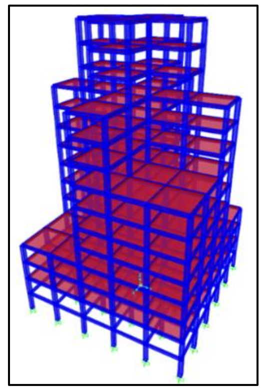

Fig -3: Isometric View for Model 2

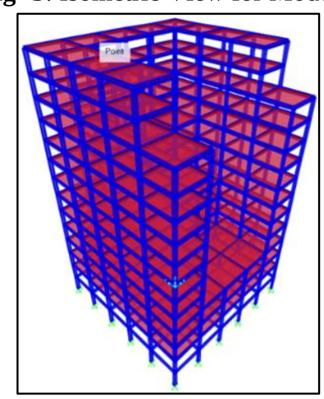

Fig -4: Isometric View for Model 3

V. RESULTS

Table -2: Base Shear due to Pushover Loading

Model	Base Shear in X Direction (KN)	Base Shear in Y Direction (KN)
Model 1	9231.042	9282.041
Model 2	8521.489	8517.324
Model 3	4516.992	3935.758

Table -3: Sd at yield point due to pushover loading

Model	Sd at Yield Point in X Direction (Meters)	Sd at Yield Point in Y Direction (Meters)
Model 1	0.180	0.181
Model 2	0.124	0.124
Model 3	0.091	0.086

Table -4: Sd at ultimate point due to pushover loading

Model	Sd at Ultimate Point in X Direction (Meters)	Sd at Ultimate Point in Y Direction (Meters)
Model 1	0.373	0.373
Model 2	0.39	0.391
Model 3	0.373	0.358

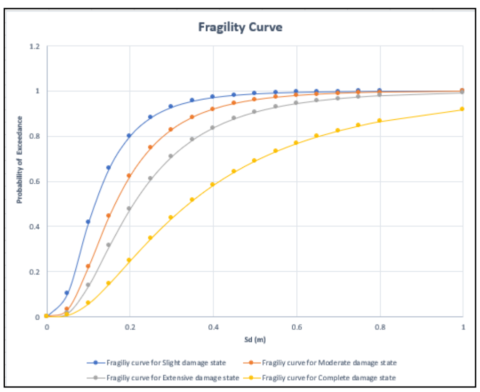

Fig. 5: Fragility Curve for Model 1 in X Direction

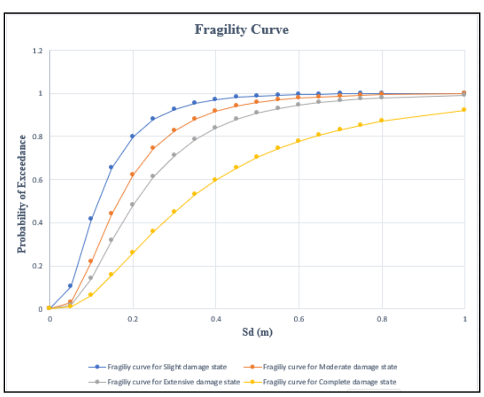

Fig. 6: Fragility Curve for Model 1 in Y Direction

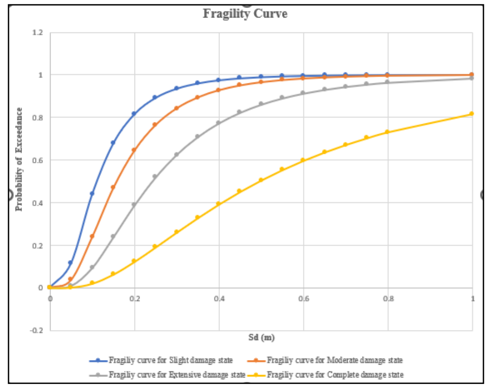

Fig. 7: Fragility Curve for Model 2 in X Direction

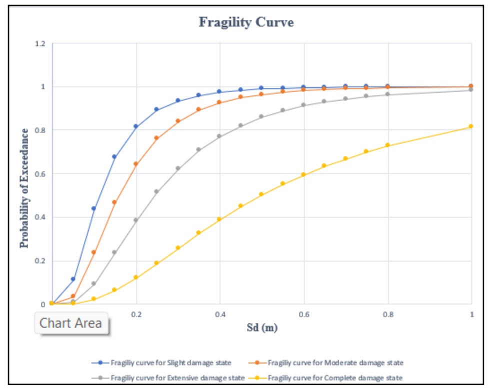

Fig. 8: Fragility Curve for Model 2 in Y Direction

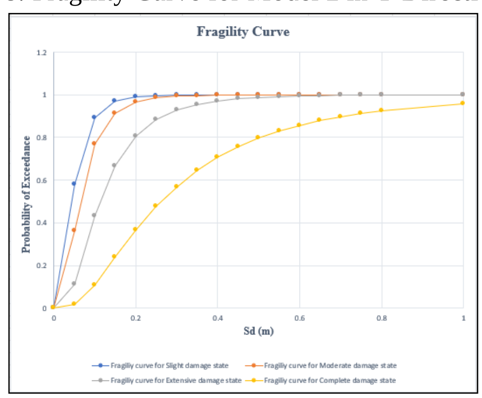

Fig. 9: Fragility Curve for Model 3 in X Direction

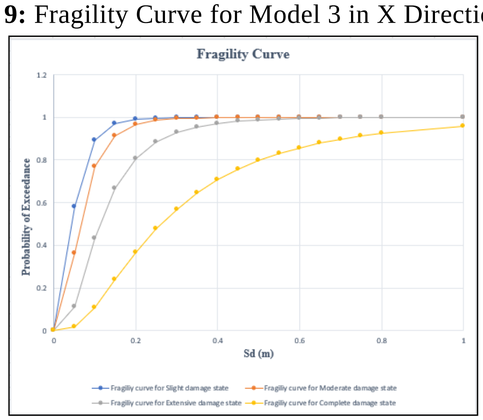

Fig. 10: Fragility Curve for Model 3 in Y Direction

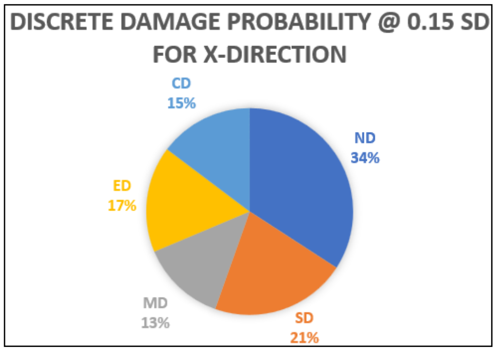

Fig -11: Damage Probability for Model 1 In X Direction

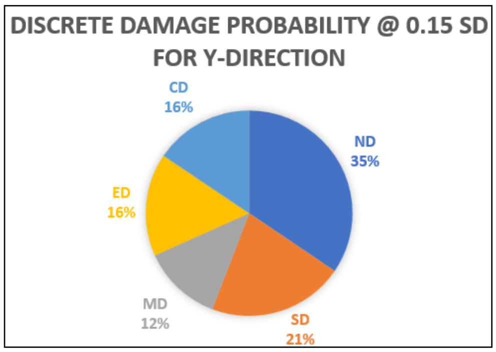

Fig -12: Damage Probability for Model 1 In Y Direction

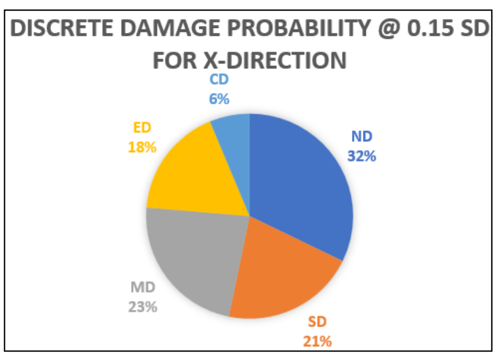

Fig -13: Damage Probability for Model 2 In X Direction

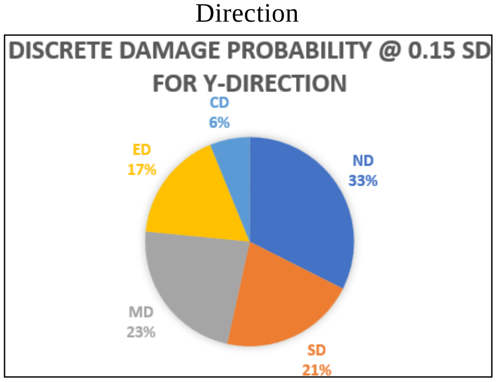

Fig -14: Damage Probability for Model 2 In Y Direction

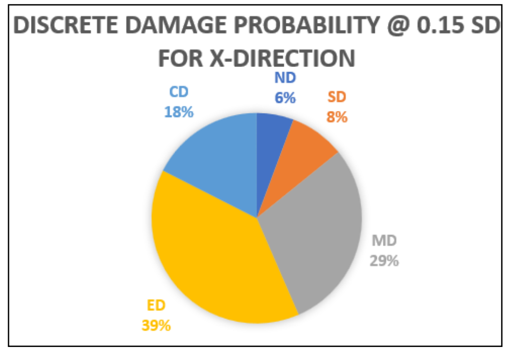

Fig -15: Damage Probability for Model 3 In X Direction

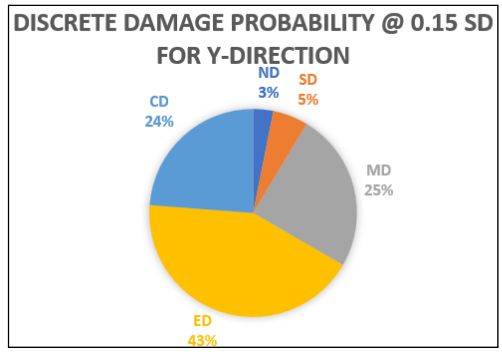

Fig -16: Damage Probability for Model 3 In Y Direction

From above tables and figures we found out that,

- For Seismic Analysis, Max. Displacement observed in Model 2 having 73.699 mm. Max. Base Shear observed in Model 1 and is 1939.536 kN.
- For Pushover Analysis, Max Base Shear is observed in Model 1 and is 5045.151 kN.
- Form Table 3, Max. Spectral Displacement at yield point in X direction is observed in Model 3 and is 0.091 m and in Y direction is observed in Model 3 and is 0.081 m. Min.
- Form Table 4, Spectral Displacement at ultimate point in X direction is observed in Model 2 and is 0.254 m and in Y direction is observed in Model 2 and is 0.263 m.
- Fig 5 to 8 shows the fragility curve for different Models, Fragility curve does not show in any noticeable changes except for moderate damage condition in Model 1 and 2. Model 3 curve slope increases for every damage condition. From this vulnerability of the models can be assumed.
- The No Damage probability in X and Y direction decreased by 3% and 2% respectively in Model 2. The No Damage

probability for Model 3 decreased by 28% and 32% in X direction and Y direction respectively.

- The Probability for slight damage remains same for the Model 1 and Model 2. Slight Damage Probability for Model 3 decreased by 13% and 16% in X and Y direction respectively.
- Medium Damage Probability is increased by 10% in both direction for Model 2. In Model 3 probability increased by 16% and 13% in X and Y Direction respectively.
- Extensive Damage Probability increased by only 1% in Model 2 in Both directions. However, in Model 3 it increased by 22% in X direction and 27% in Y direction.
- Collapse Damage Probability in Model 2 is decreased by 10% in both direction and Model 3 increased by 3% and 8% in X and Y direction respectively.

VII. CONCLUSION

From the above study, the conclusions can be made as follows:

- For Model 2, Vulnerability increases 10% in both Medium and Collapse condition. In other cases, shows similar results as Model 1.
- For Model 3, Vulnerability increases significantly for every damage condition.
- Model 2 shows the resilience as good as the model 1 because of the damage probability do not defer that much to the model 1 which can be related to the nature of the irregularity it has. In Model 2 setback has been given to the model is constant in both directions. Because of that, irregularity has been introduced but does not affect the buildings vulnerability that much.
- However, in model 3 damage probability increases in almost every cases. It can get related to the setback irregularity which has not been constant in both directions. Because of that, model 3 is not as resilient as model 1 and 2.
- The building's seismic vulnerability increases as the building's irregularity increases, meaning that the building's damage likelihood rises in proportion to its irregularity and also the nature of the irregularity.

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