FRAGILITY CURVES PREDICTION OF SELECT BUILDINGS WITH SOFT-STORY AND RE-ENTRANT CORNER IRREGULARITIES IN SAN JOSE, OCCIDENTAL MINDORO

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ABSTRACT

Since buildings are designed for different needs, this leads to significant irregularities. Predominantly, their response to ground motions concerned their resilience during seismic events. Considering different performance objectives, this research bridged the gap in determining the as-constructed irregular buildings' response against ground motions adapting ASCE provisions in a localized setting. The buildings first underwent finite element modeling considering the as-built plan, structural specifications, and spectral accelerations of Occidental Mindoro. Performing nonlinear static analysis resulted in the pushover curves and subsequently generated the fragility curves by the log-normal distributions of the spectral displacements. Polynomial curve fitting developed the best-fit fragility curves and produced mathematical models. The calibrated models resulted in a very strong correlation (R^2 = 0.9994 and RMSE = 0.0321) between the input and the output variables. In addition, a 0.3794 RMSE value resulted in the validation of the predicted models to the code-based fragility curves, giving a very high correlation. Further, for the Ms. 7.1 earthquake, the Hotel A and the Hotel B were expected to be 27.61% and 44.72% damaged, with 33.14% and 33.104% serviceable after the disaster. Thus, based on member checks, Hotel A (soft-story) and Hotel B (re-entrant) buildings were susceptible to magnitude five and beyond earthquakes.

Keywords: *Spectral Acceleration, Nonlinear Static Analysis, Pushover Curves, Fragility Curves, Prediction Model*

INTRODUCTION

Approximately 90 percent of the world's earthquakes occur along the Pacific Ocean's Pacific Ring of Fire perimeter, where the Philippines and other neighboring countries like Japan are renowned for their high volcanic activity (Roque et al., 2023). Large destructive earthquakes seldom occur, but undoubtedly, they occur without caution (Paton et al., 2015). The same higher magnitude earthquakes were recorded throughout the Philippine archipelago, including the Mindoro earthquake in 1994, which had 7.1 magnitude and was just as high as the formidable earthquake that struck Western Japan in January 2024 measuring 7.6 in magnitude, recording the epicenter in Ishikawa Prefecture (Shelly, 2024). Conversely, since Mindoro province is situated at the point where the Palawan Continental Block (PCB) intruded into the Philippine Mobile Belt (PMB) during the early Miocene, it has experienced various degrees of seismic events, with about 18 earthquakes occurring annually (DOST-PHILVOLCS, 2018). The most destructive Mindoro earthquake (Ms. 7.1) hit the province in November 1994 caused by tectonic movements along the Philippine Fault Zone and the newly identified Aglubang River Fault in Occidental Mindoro, which affected 22,452 families, with 77 confirmed casualties and 430 injured individuals and harmed 1,530 houses, with 6,036 being partially damaged. Subsequently, on December 5, 2023, Lubang, Occidental Mindoro, experienced a 5.9 magnitude earthquake. Similarly, on April 29, 2023, a 5.2 magnitude earthquake shook Looc town in the province, damaging a condemned building and a residential house (DOST-PHIVOLCS, 2023).

Thus, daily exposure to critical infrastructures impaired by earthquakes increases personal risk (Freddi et al., 2021). United Nations (UN) designed Sustainable Development Goals (SDGs), which served as the groundwork for this research to set up flexible infrastructure (SDG 9) and SDG 11 (build a safe and sustainable community for all) (United Nations, 2016). Given the history of past seismic events in Occidental Mindoro Province, it was evident that irregular structure, either in plan (re-entrant) or vertical elevation (soft-story), was recognized as the considerable cause of earthquake failure, especially in seismic zones (Siva, Abraham, & Kumari, 2019). Buildings with irregularities, predominantly vertical (Dya & Oreeta, 2015) or plan configurations (Krishnan & Thasleen, 2020) became susceptible to powerful earthquakes. Hence, systematically assessing the structural integrity of both regular and irregular buildings was crucial for effectively enhancing infrastructure resilience (SDG 9) and overall performance and safety (SDG 11).

While several related studies have focused on the seismic vulnerability of buildings with an irregular shape (Mouhine & Hilali, 2022), producing fragility curves (Smiroldo, Fasan, & Amadio, 2023) based on assumptions regarding building geometry (Mouhine & Hilali, 2022), these studies may not accurately reflect the actual behavior of buildings during earthquakes, as they lacked precise, as-constructed building data. Hence, this study was conducted to analyze the fragility curve since structures with soft-story (Hotel A) and re-entrant irregularities (Hotel B) have been identified as high-risk typologies in the event of an earthquake. Studies on fragility curves (Bsaylon, 2018), pushover-based fragility curves (Bhosale, Davis, & Sarkar, 2017), and code-based fragility curves (Biglari et al., 2023) played a direct role in minimizing economic losses and the risk of earthquake casualties. The researchers aimed to predict potential damage a structure might sustain during seismic events, and their utility extends to pre-earthquake scenarios, aiding in proactive measures for better preparedness and design considerations (Nazri, 2017). The study addressed the need for proactive risk assessment and mitigation strategies by developing fragility curves and a performance-based design simulation for Occidental Mindoro, analyzing physical condition of two buildings with soft-story and re-entrant irregularities using SeismoBuild software. It generates pushover curves aligned with performance objectives, predicts fragility curves through nonlinear static analysis, and validates results with polynomial curve fitting and code-based fragility curves. The goal is to estimate collapse probability, this study offers a roadmap for future developments, fostering a built environment that not only meet the needs of its residents but also safeguards their safety and well-being to support the province's aspirations for safer and more disaster resilient urbanization by understanding the vulnerability of buildings with soft stories and re-entrant irregularities.

MATERIALS AND METHODS

Research Design

The researchers used modeling and assessment procedures using quantitative approach to assess the building's performance against the set ground motions and generate the fragility curves. The seismic analyses were created using Seismobuild and examined and interpreted based on the results of the nonlinear static analysis (pushover analysis). Moreover, calibration and validation of the prediction models were assessed based on the R-squared and the root mean squared error (RMSE) values to interpret the correlation between the input variables (spectral displacements) and the output variables (probability of collapse).

Study Site

The study focused on San Jose, Occidental Mindoro, specifically the buildings of Hotel A located at Brgy. 6, Mabini St. and the Hotel B at Liboro St., which are prone to ground shaking due to three active faults within Occidental Mindoro's perimeter. The two buildings were selected based on the availability of the as-built plan, structural specifications, and access to the building perimeter.

Data Collection

To provide a clearer view of the performance-based design of a fragility curves prediction of buildings with soft-story and re-entrant irregularities in San Jose Occidental Mindoro, the researchers sought buildings with vertical and plan irregularities, particularly soft-story and re-entrant corners before gathering the ground motion data from the Spectral Acceleration Map of the Philippines (SAMPH) from DOST-PHIVOLCS. Data presents the input spectral acceleration of Occidental Mindoro. The researchers described the physical conditions of the select buildings (soft-story; Hotel A) and (re-entrant irregularities; Hotel B) through a rapid visual screening procedure (RSVP). The researchers adapted the process as provided in the FEMA P-154 manual and assessed building loads based on the building use, category, and floor area as referred to the National Structural Code of the Philippines (NSCP) 2015, the updated structural code of the country to determine the beam's uniformly distributed loads, the slabs' area load, and the building's self-weight (Table 1).

Table 1. Spectral acceleration table of short and long periods acceleration in terms of gravity considering its performance levels and return periods.

PERFORMANCE OBJECTIVES	SHORT PERIOD (Acceleration in g)	LONG PERIOD (Acceleration in g)	RETURN PERIOD (years)	REFERENCES	EQUIVALENT MAGNITUDE Booth, C. (2007)
Operational Level (OL)	0.40	0.20	72	NSCP 2015	<5.0M-5.5M
Immediate Occupancy (IO)	0.60	0.30	225	JICA-DPWH	5.5M-6.0 M
Life Safety (LS)	0.76	0.38	975	SAMPH	5.5M -6.5M
Collapse Prevention (CP)	1.9	0.70	2475	SAMPH	<6.5M – 8.5M

Ethical Consideration

The building owner of two selected buildings were informed about the sole purpose of seismic assessment and simulation, as well as its implication. The researchers provided them with clear information regarding the process and the pertinent findings relevant to them. Furthermore, the building plans collected are only utilized for this research, and the rights of the people whose irregular buildings were being simulated and evaluated are confidential.

Research Procedures

The researchers created the building models within the SeismoBuild software interface for simulation, considering the parameters for the reinforced concrete members. The researchers utilized the nonlinear static analysis based mainly on ASCE 41. The researchers developed pushover curves based on the set performance objectives. The researchers also identified the maximum base shear each select building could resist in each damage limit state: OL, IO, LS, and CP. Eight analyses of varying $\pm \mathrm{X} \pm \mathrm{eccY}$ and $\pm \mathrm{Y} \pm \mathrm{eccX}$ were considered in the study.

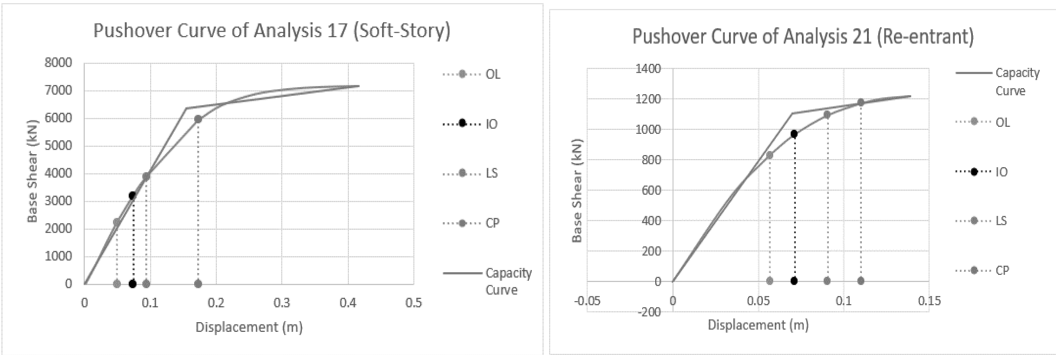
The researchers predicted the pushover-based fragility curves. The log-normal distribution of the spectral displacements was first done for each pushover curve to generate its equivalent fragility curve per damage level, making 64 curves for the two buildings. This aimed to predict the best-fit curves for each performance objective, giving four curves for the soft-story building and four for the re-entrant irregular building. The researchers considered the risk analysis for each select building based on member chord rotations and forces per nonlinear static analysis and predicted fragility curves.

Data Analysis

The nonlinear static analyses were conducted using the SeismoBuild software. The resulting pushover curves were interpolated using Microsoft Excel to obtain the maximum base shear. The same software generated one hundred and twenty-eight (128) fragility curves utilizing the log-normal distribution of the pushover curve data. From these curves, the best-fit polynomial models were calibrated. These prediction models were then assessed and validated with the resulting coefficient of determination, R^2, and root mean square error, RMSE. The calibration and validation were obtained using the MATLAB software.

RESULTS

Thirty-two (32) pushover curves were obtained from the nonlinear static analysis for each irregular building. Representative pushover curves depict the building's response to ground motions, dividing the building behavior into ductile and plastic. Figure 1a illustrates that the soft-story building displayed ductile behavior at OL, IO, and LS damage, while plastic behavior was observed at the CP damage level. In contrast, Figure 1b shows that the damage levels for the re-entrant building were divided such that at OL and IO levels, the building is ductile, while at LS and CP, the building displayed a plastic behavior (Figure 1).



(a) (b)

Figure 1. Representative pushover curves of irregular buildings: (a) soft-story and (b) re-entrant.

From the pushover curves, the maximum base shears were evaluated relative to the target displacements. The results show the governing maximum base shear at each corresponding target displacement per damage level. Analysis 19 (-X+eccY) governed the eight analyses of varying $\pm X \pm eccY$ and $\pm Y \pm eccX$ while Analysis 21 (+Y+eccX) governed the re-entrant building (Table 2).

Table 2. Target displacement and base shear from the pushover analysis.

PERFORMANCE OBJECTIVE/DAMAGE LEVEL	SOFT-STORY (ANALYSIS NO. 19)		RE-ENTRANT (ANALYSIS NO. 21)	
	Target Displacement (m)	Base shear (kN)	Target Displacement (m)	Base shear (kN)
Operational level	0.0485	2336.845	0.052	2518.961
Immediate occupancy	0.0727	3289.421	0.079	3545.200
Life safety	0.092	3953.620	0.099	4294.137
Collapse prevention	0.170	6034.104	0.183	6454.675

Since the pushover curves represent the building's behavior against earthquakes, it was prevalent that the fragility curves be generated to predict the probability of collapse of the select structures. A polynomial curve fitting governed the regression techniques as it gave higher correlations between variables. Result illustrates the data trends, the prediction models, and the validation data (Figure 2).

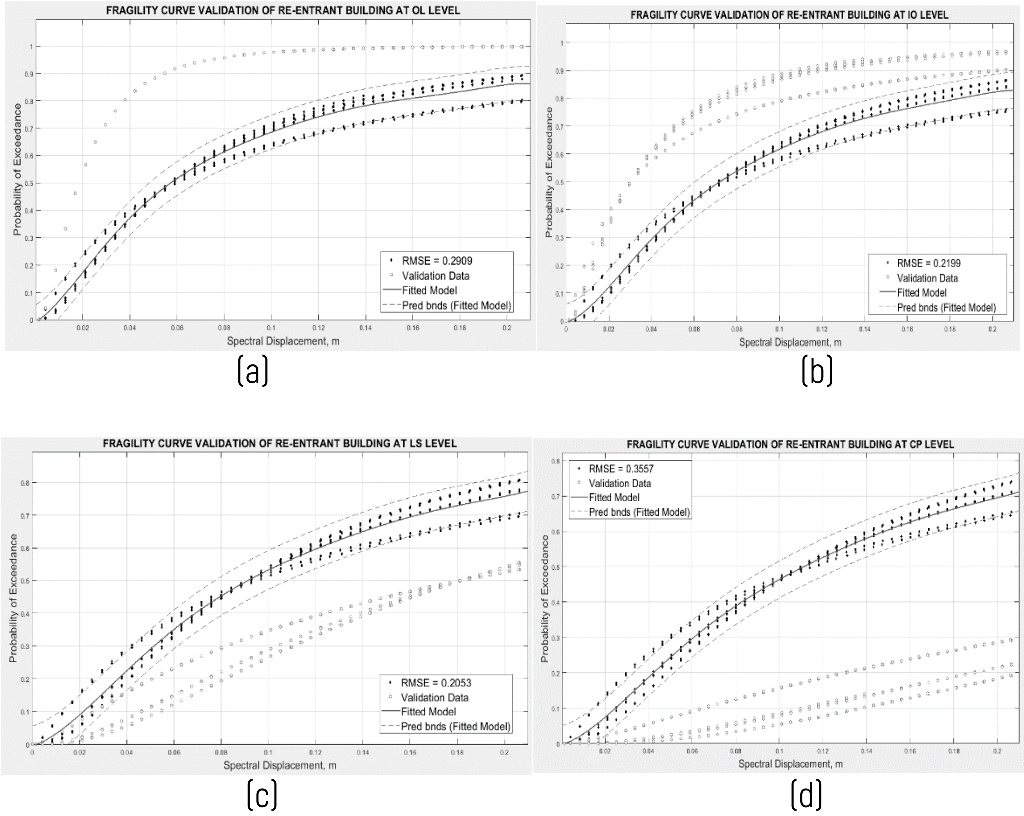


Figure 2. Fragility curves calibration and validation of re-entrant building at (a) OL, (b) IO, (c) LS, and (d) CP.

Conversely, the mathematical models were described by polynomial curves. The recursive equation is presented in Equation 1, where $P(S_d)$ signifies the probability of collapse, pn signifies the polynomial coefficients, and S_d signifies the spectral displacement. Result shows the coefficients of the mathematical model (Table 3).

$$P(S_d) = \sum_{0}^{n} p_n \, (S_d)^{n-1} \qquad (Eq. 1)$$

Table 3. Fragility curve recursive equation coefficients.

COEFFICIENT ID (pn)	SOFT-STORY BUILDING				RE-ENTRANT BUILDING			
	OL	IO	LS	CP	OL	IO	LS	CP
p10	57520							
p9	-163900	127600						
p8	194100	-226100			-2280000	-1651000		
p7	-126600	164800	2826		1822000	1350000	99440	74010
p6	5052	-63420	-3759		-586000	-449100	-72280	-54200
p5	-12910	13610	1875	59.34	96530	77690	20590	15630
p4	2152	-1525	-409.4	-49.37	-8402	-7318	-2843	-2203
p3	-237.3	50.41	23.85	8.766	316.5	326.2	172	138.9
p2	17.96	7.539	5.56	2.648	5.441	2.142	2.291	1.878
p1	-0.0094	-0.0141	-0.0244	-0.0298	-0.00887	-0.0041	-0.0055	-0.0041

Legend: OL - Operational Level Damage; IO - Immediate Occupancy Damage; LS – Life Safety Damage; CP - Collapse Prevention Damage

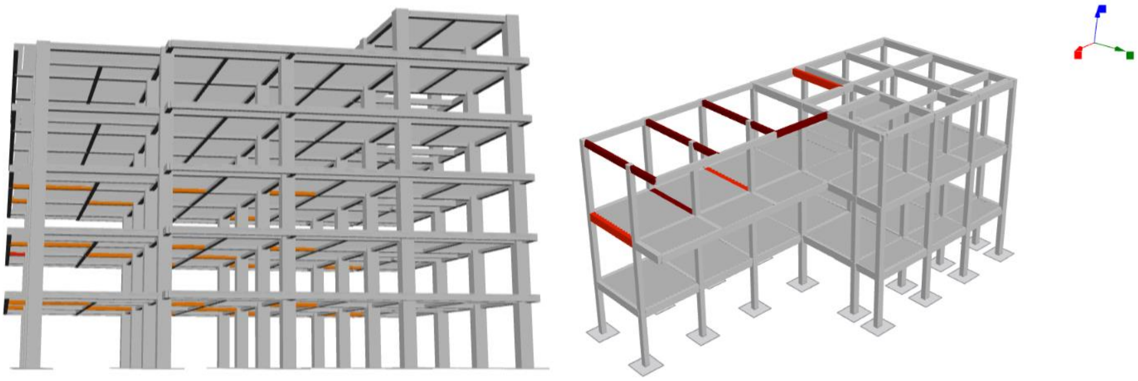
Predominantly, the prediction models were validated using the code-based fragility curves, and the validation data are shown in Figure 2 above. Measuring the coefficient of determination, $R^{2,}$ and the root mean squared error, RMSE, gave the interpretation of the mathematical models (Table 4).

Table 4. Coefficient of determination and RMSE values of the prediction models.

CRITERIA	SOFT-STORY BUILDING				RE-ENTRANT BUILDING			
	OL	IO	LS	CP	OL	IO	LS	CP
R^2	0.9994	0.9986	0.9968	0.9930	0.9854	0.9844	0.9848	0.9859
RMSE (Calibration)	0.0051	0.0092	0.0147	0.0215	0.0312	0.0322	0.0300	0.0266
RMSE (Validation)	0.0427	0.0111	0.2591	0.3793	0.2909	0.2199	0.2053	0.3557
Interpretation	VH	VH	VH	VH	VH	VH	VH	VH

Legend: OL - Operational Level Damage; IO - Immediate Occupancy Damage; LS – Life Safety Damage; CP - Collapse Prevention Damage, VH – Very High

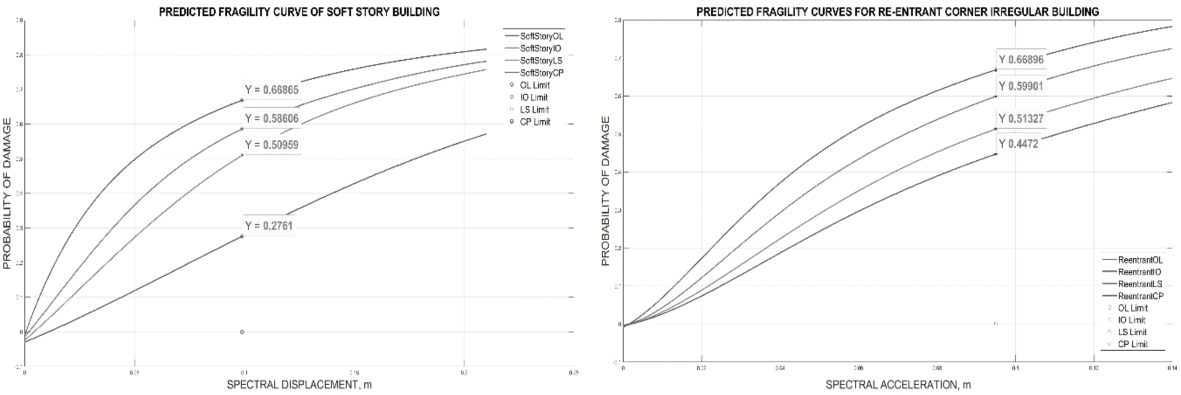
Subsequently, risk analyses of the select buildings were considered in the study. The risk assessment was based on two (2) categories: structural member response to the nonlinear static analysis and the probability of collapse based on the prediction models obtained. Figure 3 exemplifies the location of the structural member failure of the respective select buildings.



(a) (b)

Fig 3. Location of structural member failure per member shear forces of (a) soft-story building at OL and (b) re-entrant building at CP.

Conversely, a recorded 7.1 magnitude earthquake of equivalent spectral acceleration has been considered to quantify the probability of damage to the select buildings. Based on the results upon being subjected to ground motions, the building is expected to have a 27.61% complete collapse, with a 49.04% chance to evacuate the occupants to safety and a 33.14% chance of being operable after the event. At this point, there is a 58.61% chance that the structural frame of the soft-story building reached its yielding capacity. In comparison, there is a 50.959% probability that beams have larger cracks attributed to being flexural members. Bond failures of concrete and reinforcement are also expected at this level (Figure 4a). The results show from the predicted fragility curves that there is a 44.72% chance that the re-entrant building will collapse, where imminent danger should be avoided due to the unstable structural frame. A probability of 48.67% is the chance that the occupants can evacuate from the building, away from the danger of partial collapse of columns as expected. After the earthquake, there is a 33.104% probability that the re-entrant building is operable (Figure 4b).



(a) (b)

Figure 4. Predicted fragility curves of the irregular buildings reflecting the probability of damage at a 7.1 magnitude earthquake: (a) soft-story building and (b) re-entrant building.

DISCUSSION

The physical conditions of the components of the two select buildings were examined through a rapid visual screening. The study identified the Hotel A as the soft-story building, having a soft story at the ground floor level, while the Hotel B was the re-entrant corner irregular building. The evaluation found a rounding adjacency for re-entrant corner buildings and severe irregularity for soft-story buildings. Further, the assessment resulted in a level score of less than 2.0, requiring structural investigation (FEMA P-154). With this, building loads based on the structural codes were accounted for, providing a reasonable quantity of superimposed dead loads and live loads dependent on the materials reflected on the plans and the as-constructed structures (Costa & Beck, 2024).

Each subject building was then modeled using SeismoBuild software to account for the reinforcing bars, and the nonlinear static analysis was conducted. Subsequently, the pushover curves were obtained. The soft-story building attained a maximum base shears of 2518.961kN, 3545.2kN, 4294.137kN, and 6454.675kN for OL, IO, LS, and CP damage levels, with corresponding target displacements of 0.052m, 0.079m, 0.099m, and 0.183m, respectively. All these results were obtained from the governing modal analysis 21 out of all considered analyses. Analysis 21 accounted for the +Y + eccX earthquake loading, considering accidental torsions. Moreover, for the re-entrant building, analysis 19 (-X + eccY) provided maximum base shear of 1041.831kN, 1239.137kN, 1478.886kN, and 1653.481kN for slight, moderate, extensive, and collapse damage levels. The accidental torsion accounting for 15% of the lateral loads projected to the orthogonal axis provided significant rotations to the building during ground motions (Lazaris, 2019). The maximum base shears obtained are the limits the buildings can resist against ground motions (ASCE 41, 2017). Related literature suggested that at each performance objective OL, IO, LS, and CP, the building is expected to have slight, moderate, extensive, and complete damage (Dya & Oreta, 2015; Omidian & Khaji, 2022; Lazaris, 2019). This study's results implied that each base shear and target displacements were the limits to determine the intensity of the building damage.

Each pushover curve provided spectral displacements, the necessary data to generate the fragility curves. A series of fragility curves were obtained, accounting for all the modal analysis results using log-normal distributions. The number of generated fragility curves equates to the number of pushover curves resulting from the nonlinear static analysis. This generation gave necessary data to forecast the best-fit model to correlate the study buildings' spectral displacement and the probability of damage. Since many curves were made, a polynomial fitting was employed to predict the best-fit fragility curves (Choksi et al., 2017).

Moreover, MATLAB software was utilized to realize the results. The calibration resulted in R-squared values of 99.94%, 99.86%, 99.68%, and 99.30%, and values of RMSE of 0.005054, 0.009197, 0.01471, and 0.02146 for OL, IO, LS, and CP, respectively, for soft-story building. In contrast, R-squared values of 98.84%, 98.44%, 98.48%, and 98.59% and RMSE values of 0.03123, 0.03215, 0.03003, and 0.02661 for each respective increasing performance objectives were obtained for the re-entrant corner irregular building. Polynomial curve fitting proved to be the best-fit prediction model for data trends, giving a very high correlation between the input (spectral displacement) and the output (probability of collapse) variables (Choksi et al., 2017).

Code-based fragility curves were achieved and compared to the predicted models. The relationship between the predicted and code-based fragility curve was explained by the root mean squared error of the two data trends. The correlation provided an RMSE value of 0.0427 for the soft-story building at the operational level. At the subsequent damage levels, IO, LS, and CP, the correlation presented RMSE values of 0.0111, 0.2591, and 0.3793, respectively. In comparison, the re-entrant corner irregular building supplied RMSE values of 0.2909, 0.2199, 0.2053, and 0.3557 for each limit state.

Risk assessment for the subject buildings was primarily conducted using nonlinear static analysis and fragility curves. The assessments were divided into two methods: pushover-based and probability of exceedance. The pushover-based evaluation revealed that the soft-story building exhibited failures in terms of structural member shear force demand/capacity ratios. However, the building could resist member chord rotations during ground motions, passing the damage-capacity member checks. In contrast, both structural member checks showed beam failures in the re-entrant building at all damage levels. The progressive collapse in the re-entrant building was attributed to the excessive load capacity of its structural members (Fikri & Ingham, 2022). The fragility curves generated in this study align with findings from existing literature.

CONCLUSION

The study shows that the Hotel A was defined as a soft-story building. At the same time, the Hotel B was determined as a re-entrant corner irregular structure, and further structural investigation is needed, attributed to the evaluation cut-off score. The structural nonlinear static analysis showed that Analysis 21 (+Y +eccX) and Analysis 19 (-X + eccY) provided maximum base shears in all the modal analyses for soft-story and re-entrant buildings, respectively. From the log-normal distribution of the spectral displacements of the building, a polynomial fit governs the prediction of the fragility curves. Polynomial curve fitting proved to be the best-fit prediction model for data trends. Pearson's correlation coefficient and RMSE values provided a very high correlation between the spectral displacement and the probability of collapse in the prediction. Comparing these predicted fragility curves to the code-based generated curves provided the margin of error with RMSE values, giving a very high correlation. Therefore, these prediction models can be used for buildings with the same irregularities. The risk assessment per nonlinear analysis suggested that the subject buildings, Hotel A and Hotel B, are susceptible to earthquakes with magnitudes five and beyond. The predicted fragility curves can be used to quantify the probability of damage during the earthquake and the chance of operability after the disasters. From the study buildings, a spectral acceleration equivalent to a magnitude 7.1 earthquake was assessed, and it concluded that there is a 27.61% probability that the soft-story building would collapse, with 33.14% operability, while 44.72% chance that the re-entrant building would collapse and 33.104% chance of being serviceable.

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