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Seismic Fragility Assessment of Hiraya Building Using Fragility Curves

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Abstract: *The Hiraya Building, a three-story educational facility at Caraga State University-Main Campus in Ampayon, Butuan City, Agusan del Norte, Caraga Region, is situated near the Surigao segment of the Philippine Fault, making it highly susceptible to seismic activity due to the country's location within the Pacific Ring of Fire. This study developed seismic fragility curves by combining on-site inspections and advanced software tools such as SAP2000 for structural modeling and Processing and Review Interface for Strong-Motion Data (PRISM) for data processing. The structural model was subjected to 40 ground motion records from the Incorporated Research Institutions for Seismology (IRIS) database to simulate earthquake effects. Using the Capacity Spectrum Method, researchers analyzed the building's seismic performance and found a 10% probability of complete damage occurring at a peak ground acceleration (PGA) of 0.585g along the east-west (X) direction. These findings highlight the building's vulnerability and provide valuable insights for improving seismic resilience in this high-risk region.*

Keywords: Fragility Curves, Hiraya Building, SAP2000, Peak Ground Acceleration (PGA), Capacity Spectrum Method

1. INTRODUCTION

Earthquakes are natural events triggered by the rapid release of energy that generates seismic waves that shake the ground within the Earth's crust. These typically arise when underground rock suddenly breaks, leading to rapid movement along a fault [1]. According to Tan and Aniñon [2], earthquakes are responsible for approximately 20% of the total yearly economic damage caused by natural hazards, resulting in around 25,000 deaths each year, as assessed by UNISDR. The Philippines is highly susceptible to seismic activity because it is situated along the Pacific Ring of Fire, a region known for frequent earthquakes and volcanic eruptions. Approximately 90% of the world's earthquakes occur in this area [3]. Thousands of earthquakes happen yearly in the country, though the majority are too weak to be felt. However, powerful seismic events can have devastating effects, leading to significant loss of life and severe property damage [4]. For instance, the recent earthquake that struck Surigao del Sur on 02 December 2023, with a magnitude of 7.4, resulted in widespread structural damage and raised concerns about the safety of buildings in the region. The earthquake produced an intensity level VII on the Modified Mercalli Intensity (MMI) scale near the epicenter, indicating very strong shaking capable of causing moderate structural damage [5].

Butuan City, located 107 km from the epicenter, an intensity level VI was recorded, characterized by strong shaking that could compromise the integrity of buildings [6]. Educational facilities, such as the Hiraya Building, a three-story structure at Caraga State University, Ampayon, Butuan City, which houses the College of Computing and Information Sciences, experienced significant shaking, resulting in minor damage, including visible cracks and falling plaster in several areas. A joint inspection assessment concluded that the structure was still safe by the CSU Engineering and Construction Office (ECO) and the Office of the City Building Official (OCBO) in Butuan.

However, conducting a seismic assessment of this building is crucial for identifying its vulnerabilities through the development of fragility curves. Fragility curves provide a statistical representation of a structure's ability to withstand seismic forces and help assess the likelihood of damage at various levels of ground shaking [7]. The website from HazardHunterPH indicates that the building is located approximately 3.8 km west of the Surigao segment of the Philippine Fault. The effects of seismic activity can be detected from several kilometers away, showing that being near an active fault heightens the risk of damage from ground shaking and possible fault movement. Given the recent strong earthquakes, this risk is particularly concerning; it is crucial to evaluate the Hiraya Building to ensure it can endure future seismic activity and protect its occupants [8].

This study aims to assess the seismic fragility of the Hiraya Building at Caraga State University. This analysis is essential for identifying any vulnerabilities that may have emerged due to the recent earthquake, ensuring the safety of its occupants, and maintaining a resilient environment within the university.

2. METHODOLOGY

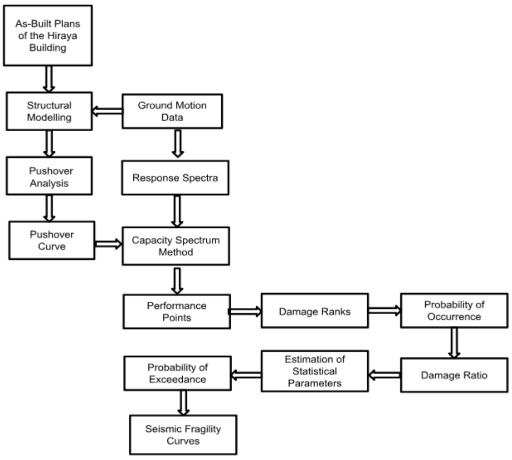

Fig. 1. Research Framework

2.1 Data Collection

The researchers carefully selected the data collection and analysis procedures to support the seismic fragility assessment of the Hiraya Building:

1. The As-Built Plan that will be used as the basis for the modeling of the structure of the Hiraya Building at Caraga State University-Main Campus will be obtained through a request from the campus Engineering and Construction Office (ECO), which will serve as the foundational reference for their analysis.
2. Forty (40) selected earthquakes will be obtained from the Incorporated Research Institutions for Seismology (IRIS) based on specific criteria: twenty (20) local earthquakes with a magnitude of 6.1 or higher and twenty (20) international earthquakes with a magnitude of 7.4 or higher which took place in different countries close to the Philippines.
3. The Processing and Review Interface for Strong-Motion Data (PRISM) software will enable the automated analysis of strong-motion acceleration records by generating compatible corresponding response spectra.

2.2 Structural Modelling

In this study, structural modeling will be performed using SAP2000 to establish the model units and grid system, creating a three-dimensional grid for the locations of columns and beams. Concrete will be used as the primary material, with specified properties such as unit weight and compressive strength, to ensure accurate analysis results. The model will be based on the As-Built Plan, and the applied loads will be calculated in accordance with the National Structural Code of the Philippines (NSCP 2015).

2.3 Nonlinear Static Pushover Analysis and Capacity Spectrum Method

2.3.1 Nonlinear Static Pushover Analysis

SAP2000 will be utilized for Nonlinear Static Analysis (Pushover Analysis), allowing for the examination of the relationship between force and displacement through the generation of a pushover curve. Once the structural model is completed, the following steps—based on the procedure cited in Baylon et al. [9]—will outline the process for conducting the nonlinear static analysis:

1. Load Case Definition – Establishing specific load cases required for nonlinear static analysis, including the modification of existing loads and the creation of new pushover load cases in both X and Y directions.
2. Assignment of Pushover Hinges – Incorporating nonlinear hinge properties into frame elements, either using default settings or defining custom parameters based on structural codes and empirical data.
3. Execution of Pushover Analysis – Running the configured model in SAP2000 to simulate the structure's performance under gradually increasing lateral loads, generating the pushover curves for further assessment.

2.3.2 Capacity Spectrum Method

The Capacity Spectrum Method (CSM) incorporates two distinct curves: the demand curve and the capacity curve. The demand curve will be generated by transforming ground motion data into response spectra using PRISM, which illustrates the relationship between the structural response period and peak ground acceleration (PGA). Peak ground acceleration represents the degree of ground motion based on the strength of a specific seismic activity [13]. The critical performance point of the seismic analysis is determined by the intersection of these two curves, indicating the structure's response under seismic loads [10]. The graphical intersection of these curves approximates the overall response of the structure, as highlighted by Atendido et al. [8]. This approach is essential for acquiring the performance points that will subsequently be utilized in creating the fragility curves. This method will be conducted through the following process:

1. Extraction of Pushover Curves – Obtaining nonlinear static pushover curves in both x and y directions using SAP2000.
2. Conversion to ATC-40 Capacity Spectrum – Transforming base shear-displacement data into capacity spectrum format to evaluate structural capacity.
3. Definition of Response Spectrum Functions – Uploading and defining spectral functions corresponding to different PGA levels and seismic directions.
4. Generation and Interpretation of Capacity and Demand Curves – Automatically generating and analyzing the intersection of curves to determine performance points.
5. Compilation of Performance Points – Summarizing results across all directional combinations and seismic records for use in fragility curve development.

2.4 Development of Fragility Curves

The ultimate and yield displacement obtained from the Nonlinear Static Analysis, along with the performance points provided, will be used to develop seismic fragility curves. The analytical method used by Shinozuka (2000), as presented in Gemoya et al. [10], will be followed in detail to develop the fragility curves, with the step-by-step procedure outlined as follows:

1. Calculate the threshold for the damage state by referring to Table 1, which provides the spectral displacement range for each damage state.

Table 1. Damage State Threshold (Vasavada & Patel, 2016 in Baylon et al. [10])

Damage State	Description	Threshold Values
D	No Damage	$0 < d_{pp} \leq 0.7d_y$
C	Slight Damage	$0.7d_y < d_{pp} \leq d_y$
B	Moderate Damage	$d_y < d_{pp} \leq [d_y + 0.25(d_u - d_y)]$
A	Extensive Damage	$[d_y + 0.25(d_u - d_y)] < d_{pp} < d_u$
As	Complete Damage	$d_{pp} > d_u$

Where;
dpp = displacement of the performance points;
dy = yield displacement;
du = ultimate displacement

2. Evaluate the damage state of all the displacement of the performance points of the Capacity Curve and Response Spectra.
3. Determine the number of occurrences of each damage state at each excitation level of peak ground acceleration (PGA).
4. Compute the probability of occurrence, in which the number of occurrences of each damage state at different PGA excitation levels was divided by the total number of occurrences of each damage state.
5. Determine the damage ratio

The formula for calculating the damage ratio:

$$DR = \frac{No.of\ Occurence}{Total\ number\ of\ records} \quad (1)$$

Where:

DR= Damage Ratio

6. Utilize the natural logarithmic (ln) of PGA to clearly visualize and validate the seismic curves of the damage ratio. The mean and standard deviation for each damage state were obtained by employing Equation (2) and Equation (3).

• Mean

$$\lambda = \frac{\Sigma x}{N} \tag{2}$$

Where:
λ = mean ground motion data
x = individual ground motion data obtained
N= the sample size of ground motion data obtained

• Standard Deviation

$$\xi = \sqrt{\frac{\Sigma (\chi - \lambda)^2}{N-1}} \tag{3}$$

Where:
λ = mean ground motion data obtained from Equation (2)
x = individual ground motion data obtained
N = the sample size of ground motion data obtained

7. Compute the probability of exceedance (Pr) using Equation (4) formulated by Shinozuka in Baylon et al. [11].

• Probability of Exceedance

$$PoE = \Phi \left[\frac{\{In(x) - \lambda\}}{\xi}\right] \tag{4}$$

Where:
PoE = Probability of Exceedance
Φ = Standard Normal Distribution
X = Peak Ground Acceleration (PGA)
λ = Mean
ξ = Standard Deviation

8. Plot the probability of exceedance against the peak ground acceleration (PGA) excitation level (i.e., 0.1g to 3.0g) to develop the seismic fragility curves in the x and y axes of the Hiraya Building due to East-West and North-South directions of earthquakes.

3. RESULTS AND DISCUSSION

3.1 Hiraya Building Modelling Using SAP2000

The researchers developed an accurate structural model of the Hiraya Building of Caraga State University-Main Campus using SAP2000 (Figure 2). This model was developed in accordance with the details provided in the structural plans, including all primary structural components such as columns, second-floor beams, third-floor beams, roof beams, and also the stair beams of the building, to ensure that all structural components were adequately considered. The researchers followed the guidelines and standards established by the National Structural Code of the Philippines (NSCP 2015) to ensure compliance and accuracy in load calculations.

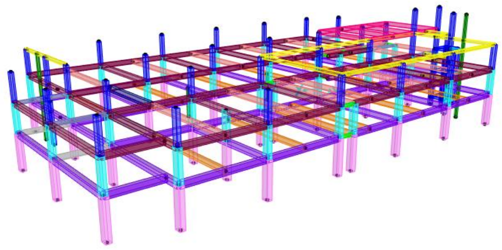

Fig. 2. Structural Model of Hiraya Building of Caraga State University- Main Campus.

3.2 Nonlinear Static Pushover Analysis and Capacity Spectrum Method

Following the development of the structural model, the researchers performed a nonlinear static pushover analysis to obtain the pushover curves in both the x-direction (Pushover X) and y-direction (Pushover Y). This analysis aimed to evaluate the building's sequence of damage states, taking into account not just its strength capacity but also its deformability, ductility, and the way seismic demand is distributed across the structure. These aspects are vital in pinpointing structural elements that are likely to reach their limit states when subjected to seismic forces [11]. The Capacity Spectrum Method (CSM), based on the analogous linearization approach, was built using the ATC-40 (Applied Technology Council, 1996). Therefore, a capacity spectrum that includes both a demand curve and a capacity curve will be created.
After that, the performance point—an intersection—will be obtained [12].

3.2.1 Pushover Curve

The pushover curve, which illustrates base shear on the y-axis and lateral displacement on the x-axis, is valuable in assessing the building's response to seismic events. It allows the identification of the (Du) ultimate displacement and determines which direction the structure offers greater resistance to base shear. Moreover, the curve provides the yield displacement (Dy), which marks the transition from elastic to inelastic behavior—represented by the point where the initially linear graph begins to curve. This is essential in understanding the initiation of nonlinear structural response.

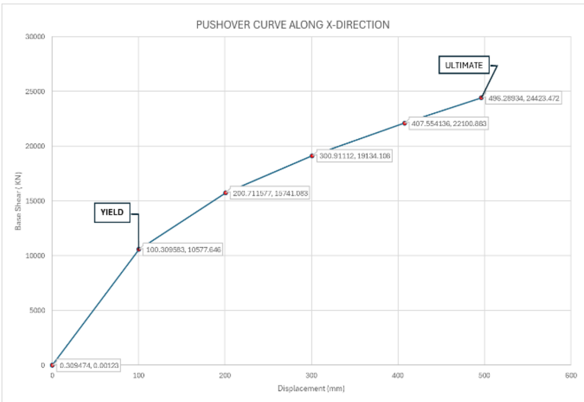

Fig. 3. Pushover Curve Along the X-direction of the Hiraya Building

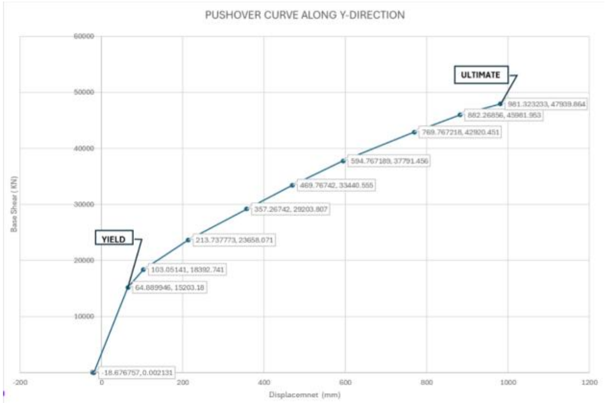

Fig. 4. Pushover Curve Along the Y-direction of the Hiraya Building

Figure 3 shows the Pushover Curve of the HIRAYA Building in the X-direction, with a yield displacement (dy) of 100.31 mm at a base shear of 10,577.65 kN and an ultimate displacement (du) of 496.29 mm at 24,423.47 kN. In the Y-direction (Figure 4), the yield displacement was 64.89 mm at 15,203.18 kN, and the ultimate displacement reached 981.32 mm at 47,939.86 kN.

3.2.2 Capacity Curve

Capacity curves in the East-West and North-South directions along the X-axis (Figures 5 and 6) were derived from pushover curves and transformed into capacity spectra by converting base shear and displacement into spectral parameters. Figures 5 and 6 show capacity curves based on the 11 March 2011 Honshu, Japan earthquake (Mw 9.1, 3.0g PGA) along the X-axis. Performance points using the Capacity Spectrum Method were obtained from 40 earthquake records, including this event. In structural reliability, the capacity curve represents the resistance function, and the response spectrum represents the load effect [11].

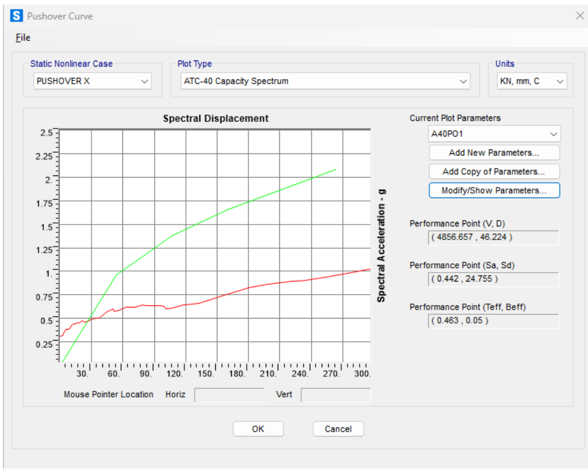

Fig. 5. Capacity Curve based on Near East Coast of Honshu, Japan Earthquake with a Magnitude of 9.1 in East-West direction at the x-axis of the building

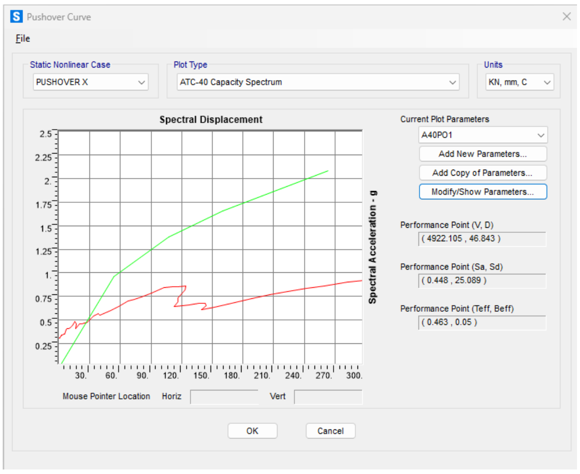

Fig 6. Capacity Curve based on Near East Coast of Honshu, Japan Earthquake with a Magnitude of 9.1 in North-South direction at x-axis of the building

3.2.3 Performance Points

Table 2. Performance Points Displacement Summary in the East-West Direction and North-South Direction along the X-axis and Y-axis when subjected to Near East Coast of Honshu, Japan Earthquake with a Magnitude of 9.1

Table 2. Performance Points Displacement Summary in the East-West Direction and North-South Direction along the X-axis and Y-axis when subjected to Near East Coast of Honshu, Japan Earthquake with a Magnitude of 9.1

EAST-WEST DIRECTION			NORTH-SOUTH DIRECTION		
PGA	X-AXIS D(mm)	Y-AXIS D(mm)	PGA	X-AXIS D(mm)	Y-AXIS D(mm)
0.1	1.757	0.669	0.1	1.776	0.634
0.2	3.21	1.342	0.2	3.248	1.273
0.3	4.668	2.019	0.3	4.726	1.916
0.4	6.132	2.7	0.4	6.21	2.563
0.5	7.601	3.384	0.5	7.698	3.215
0.6	9.2036	4.16502	0.6	9.323	3.97534
0.7	10.7339	4.89394	0.7	10.874	4.67738
0.8	12.2642	5.62286	0.8	12.425	5.37942
0.9	13.7945	6.35178	0.9	13.976	6.08146
1	15.031	6.867	1	15.229	6.54
1.1	16.8551	7.80962	1.1	17.078	7.48554
1.2	18.3854	8.53854	1.2	18.629	8.18758
1.3	19.9157	9.26746	1.3	20.18	8.88962
1.4	21.446	9.99638	1.4	21.731	9.59166
1.5	22.9763	10.7253	1.5	23.282	10.2937
1.6	24.5066	11.4542	1.6	24.833	10.9957
1.7	26.0369	12.1831	1.7	26.384	11.6978
1.8	27.5672	12.9121	1.8	27.935	12.3998
1.9	29.0975	13.641	1.9	29.486	13.1019
2	30.324	14.146	2	30.728	13.546
2.1	32.1581	15.0988	2.1	32.588	14.5059
2.2	33.6884	15.8277	2.2	34.139	15.208
2.3	35.2187	16.5567	2.3	35.69	15.91
2.4	36.749	17.2856	2.4	37.241	16.6121
2.5	38.2793	18.0145	2.5	38.792	17.3141
2.6	39.8096	18.7434	2.6	40.343	18.0161
2.7	41.3399	19.4723	2.7	41.894	18.7182
2.8	42.8702	20.2013	2.8	43.445	19.4202
2.9	44.4005	20.9302	2.9	44.996	20.1223
3	46.224	21.874	3	46.843	21.071

3.3 Seismic Fragility Curves of Hiraya Building

Seismic fragility curves were used to assess the probability of the Hiraya Building reaching or exceeding specific damage states under varying peak ground acceleration (PGA) levels from 0.1g to 3.0g. The x-axis represents PGA, while the y-axis shows the probability of exceedance. Steeper curves indicate higher vulnerability; curves shifted to the left suggest susceptibility to damage at lower PGAs, while those to the right indicate better seismic resistance. Figures 7-10 present the fragility curves for the Hiraya Building, comparing different damage states. As noted by Baylon & Marcos [8], the "No Damage" state (D) is typically excluded. The analysis showed expected damage levels at a 10% probability of exceedance for specific PGA values.

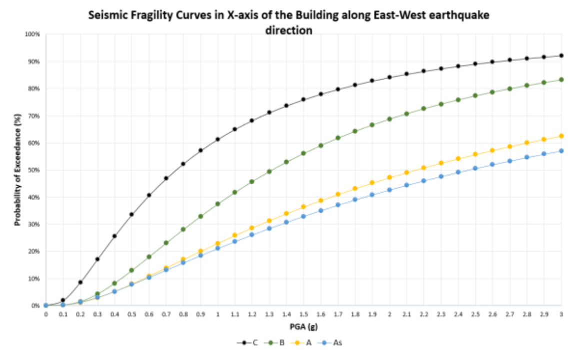

Fig. 7. Seismic Fragility Curves of Hiraya Building in East-West Earthquake Direction along X-axis

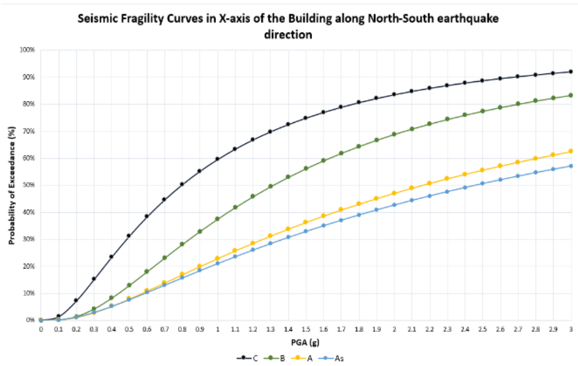

Fig. 8. Seismic Fragility Curves of Hiraya Building in North-South Earthquake Direction along X-axis

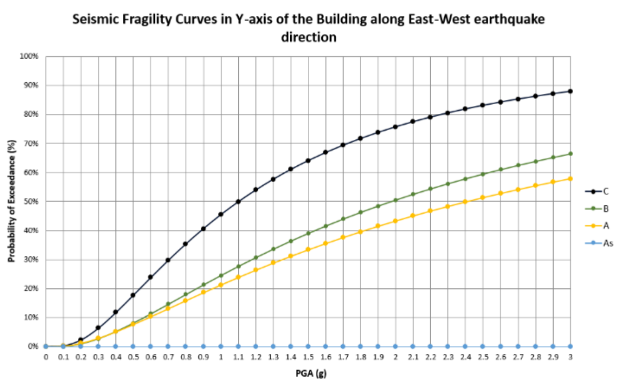

Fig. 9. Seismic Fragility Curves of Hiraya Building in East-West Earthquake Direction along Y-axis

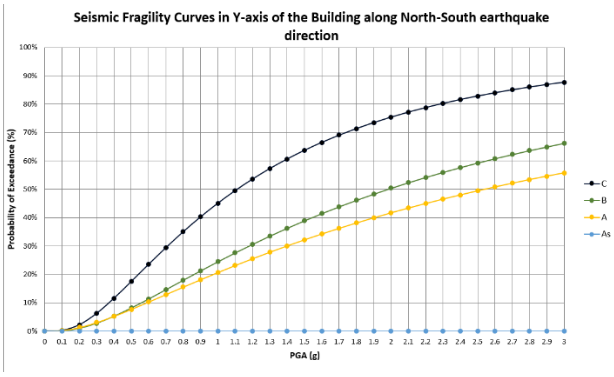

Fig. 10. Seismic Fragility Curves of Hiraya Building in North-South Earthquake Direction along Y-axis

In the East-West direction along the X-axis, fragility analysis showed that slight damage (State C) occurs at 0.219g PGA, moderate damage (State B) at 0.440g, extensive damage (State A) at 0.570g, and complete damage (State As) at 0.585g—all at a 10% probability of exceedance. Figure 11 presents the corresponding fragility curves, highlighting the building's increasing vulnerability with higher ground shaking intensity.

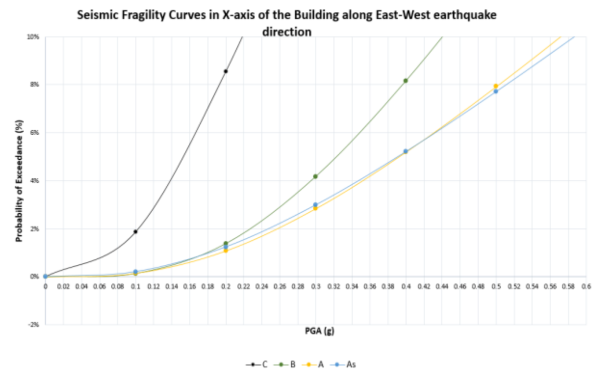

Fig. 11. Seismic Fragility Curves at a 10% Probability of Exceedance in the East-West Earthquake Direction Along the X-Axis of the Hiraya Building

Along the North-South direction of the Hiraya Building's X-axis, fragility analysis indicated slight damage (State C) at 0.216g PGA, moderate damage (State B) at 0.439g, extensive damage (State A) at 0.572g, and complete damage (State As) at 0.587g—all at a 10% probability of exceedance. These results suggest slightly higher fragility in this direction compared to East-West. Figure 12 shows the corresponding fragility curves.

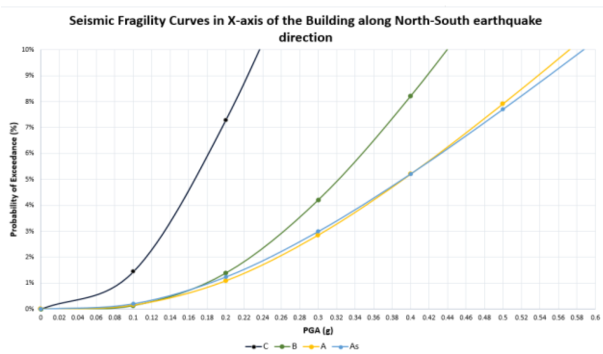

Fig. 12. Seismic Fragility Curves at a 10% Probability of Exceedance in the North-South Earthquake Direction Along the X-Axis of the Hiraya Building

Along the East-West direction of the Y-axis, the Hiraya Building showed greater seismic resistance. Slight damage (State C) occurred at 0.372g PGA, moderate damage (State B) at 0.557g, and extensive damage (State A) at 0.588g—all at a 10% probability of exceedance. No data was available for complete damage (State As). Figure 13 displays the corresponding fragility curves.

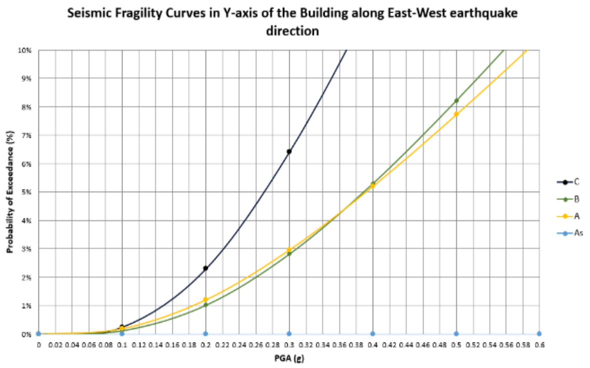

Fig. 13. Seismic Fragility Curves at a 10% Probability of Exceedance in the East-West Earthquake Direction Along the Y-Axis of the Hiraya Building

Along the North-South direction of the Y-axis, the Hiraya Building's seismic response was similar to the East-West direction. Slight damage (State C) occurred at 0.368g PGA, moderate damage (State B) at 0.556g, and extensive damage (State A) at 0.585g, all at a 10% probability of exceedance. No data were available for complete damage (State As). Figure 14 shows the fragility curves for this direction.

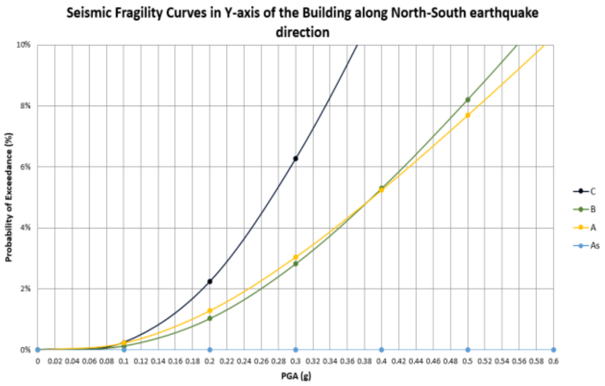

Fig. 14. Seismic Fragility Curves at a 10% Probability of Exceedance in the North-South Earthquake Direction Along the Y-Axis of the Hiraya Building

Table 3. Maximum PGA at 10% PoE of Each Damage State

Maximum Peak Ground Acceleration (PGA) at 10% Probability of Exceedance of Each Damage State				
Direction	Summary (g)			
	C	B	A	As
East-West (X-axis)	0.219	0.440	0.570	0.585
North-South (X-axis)	0.216	0.439	0.572	0.587
East-West (Y-axis)	0.372	0.557	0.588	N/A
North-South (Y-axis)	0.368	0.556	0.585	N/A

Table 3 presents the peak ground acceleration (PGA) values at a 10% probability of exceedance for each damage state—Slight (C), Moderate (B), Extensive (A), and Complete (As)—along both the x and y-axes. The data show that the y-axis (East-West and North-South) consistently has higher PGA values for damage states C, B, and A compared to the x-axis, suggesting greater structural resistance or stronger ground motion along the y-axis. For example, damage state A in the East-West direction records 0.588g on the y-axis versus 0.570g on the x-axis. Similarly, in the North-South direction, the y-axis shows 0.585g compared to 0.572g on the x-axis. Notably, complete damage (As) was recorded only along the x-axis, ranging from 0.585g to 0.587g, with no corresponding data for the y-axis—implying that the threshold for complete damage was not reached in that direction.

CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

The researchers developed a detailed structural model of the Hiraya Building at Caraga State University using SAP2000 (Figure 2), incorporating all primary components. A nonlinear static pushover analysis was performed along both X and Y directions. The X-direction showed a yield point at 10,577.65 kN base shear with 100.31 mm displacement and an ultimate point at 24,423.47 kN with 496.29 mm displacement. The Y-direction exhibited higher capacity, yielding at 15,203.18 kN and 64.89 mm displacement, reaching ultimate capacity at 47,939.86 kN and 981.32 mm displacement, indicating greater strength along the Y-axis. Seismic fragility curves assessed the building's damage probabilities at varying peak ground accelerations (PGA) with a 10% probability of exceedance. Slight damage (State C) occurs at 0.216g PGA, moderate (State B) at 0.439g, extensive (State A) at 0.570g, and complete damage (State As) at 0.585g to 0.587g in the East-West direction along the X-axis. The building withstands a minimum PGA of 0.4g, meeting seismic safety standards for occupancy. At 0.4g PGA, slight damage has a 20–30% exceedance probability, while moderate to complete damage remains below 10%. These results comply with the NSCP's seismic criteria for Zone 4, where a PGA of 0.4g is required. A PGA of 0.585g corresponds to Intensity VIII on the PHIVOLCS scale, indicating the building can endure strong shaking without collapse. The maximum probability of complete damage is 5.10%, under the 10% threshold, confirming the structure's compliance with national seismic safety standards.

4.2 Recommendations

The following recommendations are proposed to enhance future studies on the seismic fragility assessment of the Hiraya Building and similar structures:

1. Increase the Number of Ground Motion Records.
Utilize a larger dataset of earthquake ground motion records to enhance statistical reliability and produce smoother fragility curves.
2. Incorporate Geotechnical Information.
Include detailed geotechnical data, such as soil classification and shear wave velocity, to improve structural modeling and account for local site effects.
3. Explore Retrofitting and Cost-Benefit Analysis.
Investigate retrofitting strategies and perform cost-benefit analyses for practical methods to enhance structural resilience.
4. Utilize a Range of Structural Analysis Software.
Employing various structural analysis tools, such as ETABS, SAP2000, OpenSees, or Perform-3D, is encouraged. Comparing outputs from different tools can help validate results.
5. Expand Ground Motion Data Sources
Source records from additional databases like PEER, USGS, PHIVOLCS, or GEM for improved generalizability of the fragility analysis.
6. Conduct On-Site Structural Condition Assessments

This study is limited to the information provided in the building's structural plans. Therefore, it is recommended that tests, such as the Rebound Hammer Test, Penetration Resistance Test, and Rapid Visual Inspection, be conducted to assess the current condition and strength of the structure accurately.

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