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Development of Seismic Fragility Curves for Kinaadman Hall

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Abstract: *Kinaadman Hall, an educational facility at Caraga State University-Main Campus in Ampayon, Butuan City, Agusan del Norte, Caraga Region, is around 4 kilometers from the nearest active fault, making it more vulnerable to seismic events. This study aims to examine its seismic susceptibility by developing fragility curves to assess if the building would withstand a 0.4g peak ground acceleration (PGA) earthquake with a maximum likelihood of exceedance of 10%, as the National Structural Code of the Philippines (NSCP) requires. The study employed 40 earthquakes from the Incorporated Research Institutions for Seismology (IRIS). The researcher constructed the structural model using SAP2000, which was then utilized to perform Pushover Analysis and the Capacity Spectrum Method (CSM). Analysis revealed that the "Complete Damage" condition for the Kinaadman Hall had calculated the highest probability of exceedance along the Y-axis of 5.2 percent at a PGA of 0.4g. The results were within the 10% limit, indicating that the Kinaadman Hall complies with the NSCP.*

Keywords: Seismic Fragility Curve, Kinaadman Hall, Pushover Analysis, Capacity Spectrum Method, SAP2000

1. INTRODUCTION

Recently, on 02 December 2023, a major earthquake with magnitude 7.4 shook the Province of Surigao del Sur and a large portion of Mindanao [1]. Butuan City also felt the shaking, the strongest among the 3368 earthquakes near Butuan City in the past 10 years. The city is experiencing earthquakes, necessitating immediate measures to mitigate the loss of life caused by these destructive geological hazards. Seismic risks refer to the dangers connected with earthquakes, and earthquake engineering is a discipline of civil engineering focused on mitigating these hazards. During and right after an earthquake, the main factors determining seismic damage are the types of structures involved. To limit this danger, an effective tool must be adopted for seismic hazard assessment and risk evaluation [2]. Fragility curves are the best representation of risk assessment [3]. Because of this, many researchers are creating seismic fragility curves to estimate the potential damage to earthquake-prone structures.

Fragility curves demonstrate the likelihood that a structure will surpass a particular damage condition stage concerning a seismic intensity parameter. With the development of computational techniques and the availability of a sizable database of existing structures, researchers can develop fragility analysis to assess a building's hazards accurately.

The National Structural Code of the Philippines (NSCP 2015) states that buildings less than 10 kilometers from a fault are susceptible to earthquake damage. Kinaadman Hall, located approximately 4 kilometers from the nearest active fault, sustained visible cracks during the recent earthquake. While the building survived the damage, it raises questions about its capacity to withstand future seismic events. Designers and researchers must take action to evaluate how earthquakes affect structures and investigate ways to enhance design to prevent significant damage from happening in the future.

This study aims to develop analytical seismic fragility curves for the Kinaadman Hall at the Caraga State University Campus. Specifically, this study seeks to determine the actual structural geometry of the Kinaadman Hall and develop a model of the building using SAP2000, determine the performance points of the building by generating the capacity spectrum method and demand spectrum of the building using the ATC-40 Capacity Spectrum Method, determine the damage state thresholds as functions of the derived capacity spectrum, and develop analytical seismic fragility curve as a function of peak ground acceleration (PGA) for the building. The results of this seismic vulnerability and resilience research are used to inform policy and regulatory frameworks, enabling the development of rigorous safety standards and building regulations to increase community resilience [4].

2. METHODOLOGY

The study's purpose was to see how susceptible the Kinaadman Hall would be in the event of a large earthquake in the future. As a result, researchers developed new parameters to construct the fragility curves using analytical techniques such as Pushover Analysis (Nonlinear Static Analysis) and the Capacity Spectrum Method (CSM). Figure 1 displays the study design based on the Atendido study [5], which included the procedures used to generate fragility curves.

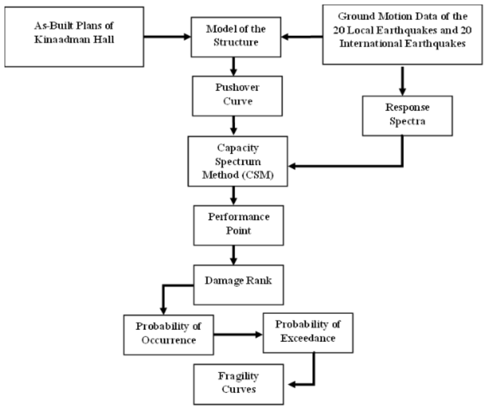

Fig. 1. Research Design in Developing Fragility Curves

2.1 Data Gathering

The As-Built Plan pertains to drawings with the dimensions and layout of the structure. The As-Built Plan of the Kinaadman Hall will be used in structural modeling. These plans are available at the Engineering and Construction Office of Caraga State University.
Twenty (20) strongest ground motion data in the Philippines (local) setting and Twenty (20) strongest ground motion data in an international setting will be used and gathered from the Incorporated Research Institutions for Seismology (IRIS). The earthquakes are selected based on the following criteria: local earthquakes with a magnitude of at least 6.0 and international earthquakes with a magnitude of at least 7.0, which occurred from 1980 to the present.

2.2 Capacity Spectrum Method

Using SAP2000, the structural model will be created in compliance with the As-Built Plan. The model will also be designed with the ground motion data gathered from the IRIS database. The Capacity Spectrum Method (CSM) will then be used to evaluate the structure. The CSM procedure compares the capacity of the structure with the demand of the structure. The critical performance point in the seismic analysis of the structure is where these two curves intersect [6].

2.3 Development of Seismic Fragility Curves

The yield displacement and ultimate displacement of the Pushover Analysis and the performance points of the Capacity Spectrum Method (CSM) would result in the seismic fragility curves of the Kinaadman Hall. The following were the detailed step-by-step process for developing these fragility curves that were adapted by the analytical approach [7,8]:

1. Compute the damage state threshold using Table 3 to determine each damage state's spectral displacement range.

Table 1. Damage State Threshold Values [4]

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

Where:
d_{pp} = displacement of the performance points
d_y = yield displacement
d_u = ultimate displacement

2. Evaluate the damage state of all the displacement of the Capacity Curve and Response Spectra performance points.
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. Calculate the damage ratio by getting the cumulative sum of the probability of occurrence.
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 using Equations (1) and Equation (2).

$$\lambda = \frac{\Sigma x}{N} \qquad \text{Eq. (1)}$$

$$\xi = \frac{\sqrt{\Sigma\,(x-\lambda)^2}}{N-1} \qquad \text{Eq. (2)}$$

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

7. Compute the probability of exceedance (Pr) using Equation (3) formulated by [4]

$$Pr = \Phi\left[\frac{\{ln(x) - \lambda\}}{\xi}\right] \qquad \text{Eq. (3)}$$

Where:
Φ = standard normal distribution
X = peak ground acceleration
λ = mean of the ground motion data
ξ = standard deviation

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 Kinaadman Hall due to East-West and North-South directions of earthquakes.

3. RESULTS AND DISCUSSION

3.1 Kinaadman Hall Structural Modeling

This study utilized SAP2000 to model the As-Built Plan of the Kinaadman Hall of Caraga State University, obtained from the campus Engineering and Construction Office. SAP2000 was also used for the Nonlinear Static "Pushover" Analysis and the Capacity Spectrum Method to extract the fragility function parameters.

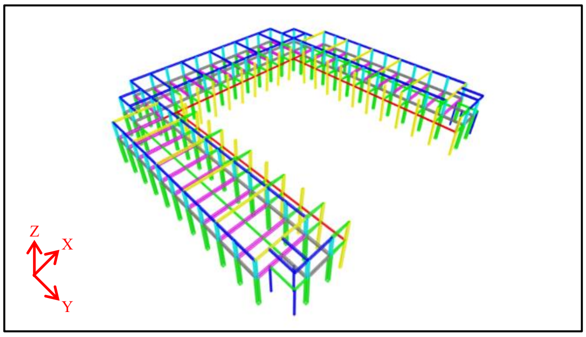

Fig. 2. Structural Model of Kinaadman Hall

3.2 Pushover Analysis and Capacity Spectrum Method

The pushover curve of the structure in the x and y axes, which shows the relationship between displacement and base shear force, was obtained using a Nonlinear Pushover Analysis after Kinaadman Hall's structural modeling. The yield and final displacement of the structure were identified using the curve. The collected ground motion data was then used to calculate performance points using the ATC-40 Capacity Spectrum Method.

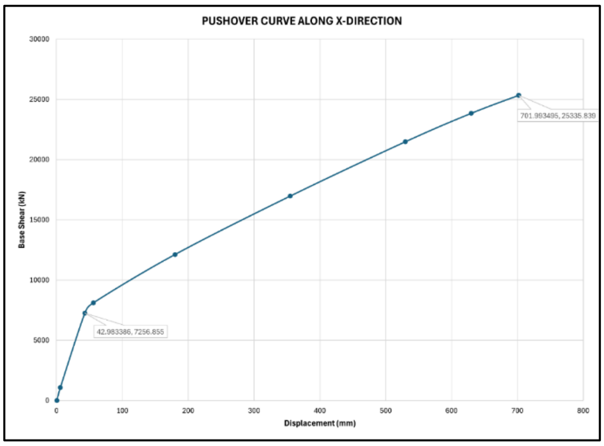

Fig. 3. Pushover Curve along the X-direction of the Kinaadman Hall

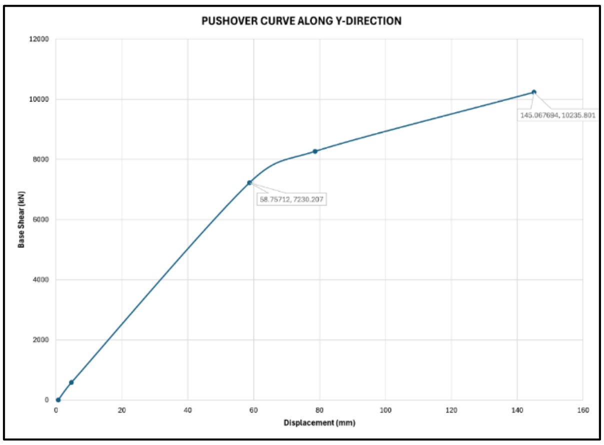

Fig. 4. Pushover Curve along the Y-direction of the Kinaadman Hall

Figures 3 and 4 show the curves obtained from the pushover analysis along the X and Y directions, respectively. The corresponding base shear force of the yield displacement along the y-direction Figure 4, which is 7230.207 kN, is lower than that of the base shear force corresponding to the yield displacement along the x-direction Figure 3, which is 7256.855 kN. This means the Kinaadman Hall can resist a greater base shear force on the x-direction. Hence, the X-direction is the structure's stronger axis in comparison to the Y-direction.

The recorded yield and ultimate displacements of the pushover curves in both directions will be the values to be entered to establish the damage threshold of the structure. Using the Damage State Threshold [3], the researchers have calculated the damage state with its equivalent spectral displacement for both the structure's X-axis- and Y-axis. The tabulated data shown in Tables 4 and 5 below are the damaged state limits of the Kinaadman Hall.

Table 2. Damage State Thresholds of Kinaadman Hall in the X-Direction

Description	Threshold Values	Lower Limit (mm)	Upper Limit (mm)
No Damage (D)	$0 < d_{pp} \leq 0.7d_y$	0	30.0883702
Slight Damage (C)	$0.7d_y < d_{pp} \leq d_y$	30.0883702	42.983386
Moderate Damage (B)	$d_y < d_{pp} \leq [d_y + 0.25\ (d_u - d_y)]$	42.983386	207.7359133
Extensive Damage (A)	$[d_y + 0.25\ (d_u - d_y)] < d_{pp} \leq d_u$	207.7359133	701.9934950
Complete Damage (As)	$d_{pp} > d_u$	701.9934950	701.9934950<

Table 3. Damage State Thresholds of Kinaadman Hall in the Y-Direction

Description	Threshold Values	Lower Limit (mm)	Upper Limit (mm)
No Damage (D)	$0 < d_{pp} \leq 0.7d_y$	0	41.129984
Slight Damage (C)	$0.7d_y < d_{pp} \leq d_y$	41.129984	58.75712
Moderate Damage (B)	$d_y < d_{pp} \leq [d_y + 0.25\ (d_u - d_y)]$	58.75712	80.3347635

Extensive Damage (A)	$[d_y + 0.25\,(d_u - d_y)] < d_{pp} \leq d_u$	80.3347635	145.0676940
Complete Damage (As)	$d_{pp} > d_u$	145.0676940	145.0676940<

The pushover curves obtained from the analysis were translated into capacity curves, where the pushover curve's displacement is translated into spectral displacement, and the base shear is translated into spectral acceleration. Figures 5 and 6 show the capacity curve in the X-Direction and Y-Direction, respectively, with 3.0g PGA based on the East-West direction of the earthquake event in Mindanao, Philippines, on 03 December 2023, with a magnitude of 6.9. The said earthquake event was one of the eighty sets of earthquake ground motion data obtained from the SAGE Database. It is used to tabulate the summary of performance points obtained from the Capacity Spectrum Method. The green plot represents the capacity curve, while the red plot represents the family of demand spectra.

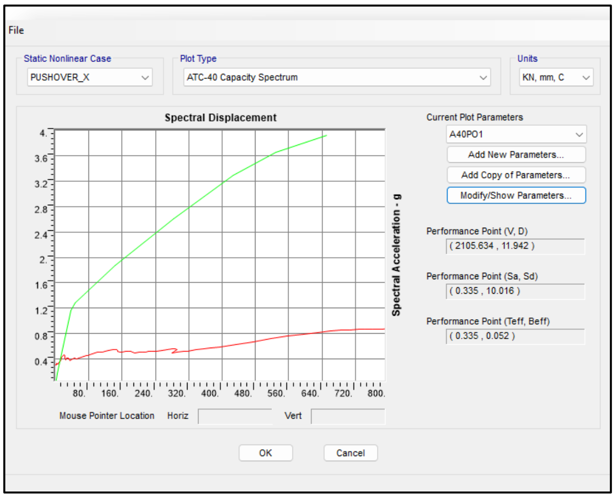

Fig. 5. Capacity Curve in X-Direction of the Kinaadman Hall based on the East-West direction of the earthquake event in Mindanao, Philippines, on 03 December 2023, with a magnitude of 6.9

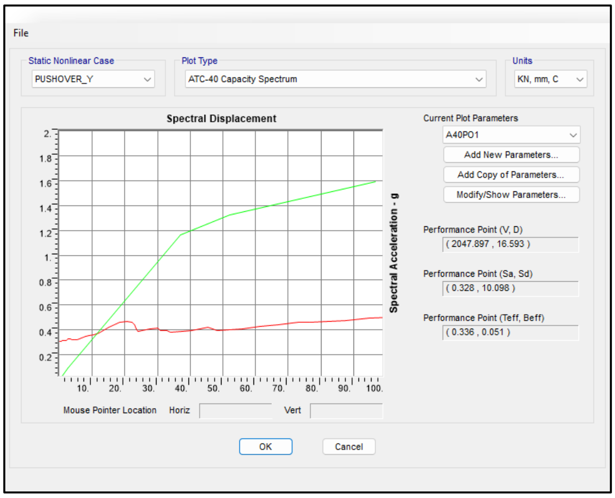

Fig. 6. Capacity Curve in Y-Direction of the Kinaadman Hall based on the East-West direction of the earthquake event in Mindanao, Philippines, on 03 December 2023, with a magnitude of 6.9

Table 4. Performance Points Displacement Summary along the X-Axis and Y-Axis of the Kinaadman Hall when subjected to the East-West Direction of the Earthquake Event in Mindanao, Philippines, on 03 December 2023, with a magnitude of 6.9

PGA (g)	X-Axis (mm)	Y-Axis (mm)
0.1	0.829	1.201
0.2	1.201	1.715
0.3	1.572	2.23
0.4	1.944	2.744
0.5	2.316	3.258
0.6	2.676944	3.762564
0.7	3.048206	4.277731
0.8	3.420736	4.794576
0.9	3.794534	5.313099
1.0	4.176	5.835
1.1	4.545934	6.355179
1.2	4.923536	6.878736
1,3	5.302406	7.403971
1.4	5.682544	7.930884
1.5	6.06395	8.459475
1.6	6.446624	8.989744
1.7	6.830566	9.521691
1.8	7.215776	10.055316
1.9	7.602254	10.590619
2.0	7.977	11.118
2.1	8.379014	11.666259
2.2	8.769296	12.206596
2.3	9.160846	12.748611
2.4	9.553664	13.292304
2.5	9.94775	13.837675
2.6	10.343104	14.384724
2.7	10.739726	14.933451
2.8	11.137616	15.483856
2.9	11.536774	16.035939
3.0	11.942	16.593

The damage rank was then derived using the collected performance points. The cumulative damage and rankings were then utilized to calculate statistical parameters and the damage ratio. These data for East-West and North-South on both the X-Axis and Y-Axis were plotted to create a seismic fragility curve and determine the threshold at a 10% likelihood of exceedance.

3.3 Seismic Fragility Curves

Seismic Fragility Curves provide a probabilistic framework for assessing structures' vulnerability to earthquake-induced damage. These curves represent the potential of a structure surpassing a specific damage condition given a degree of ground shaking intensity.
The X-axis of the curve shows the shaking intensity of an earthquake, which is often measured by peak ground acceleration. The Y-axis represents the probability of a particular damage level that the building would reach. The steeper the curve, the more vulnerable a building is. If the curve is shifted to the left, it would concur that the

building has a higher risk of damage at a certain damage level. On the other hand, a curve shifted to the right indicates that the building is stronger and can withstand more vigorous shaking before damage. The charts presented are the Seismic Fragility Curves of the Caraga State University's Kinaadman Hall (Figures 7 to 10). The researchers compared each damage rank in the fragility curves. Damage Rank D was excluded from the fragility study since it indicates no structural damage. With this, the researchers have observed that the Kinaadman Hall is expected to attain the following damages at a 10% probability of exceedance with specific PGA. In the X-Axis of the building along the East-West earthquake direction, at damage rank "C", the black curve or the "Slight Damage" rank, at the 10% Probability of Exceedance, a PGA of 0.285g was determined. occurs. At damage rank "B", the green curve or the "Moderate Damage" rank, at the 10% Probability of Exceedance, a PGA of 0.550g was determined.

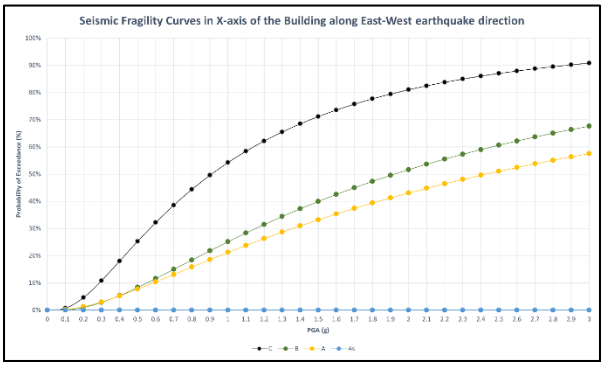

Fig. 7. Seismic Fragility Curves in East-West Earthquake Direction along X-Axis

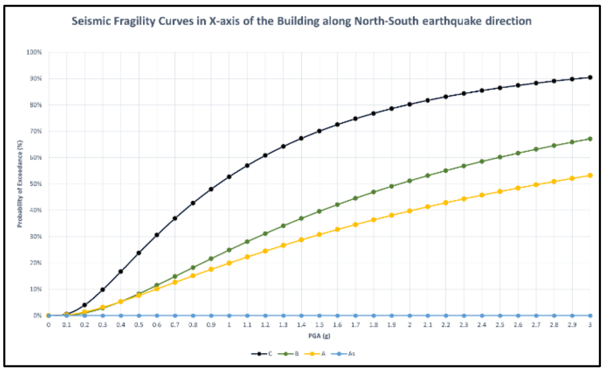

Fig. 8. Seismic Fragility Curves in North-South Earthquake Direction along X-Axis

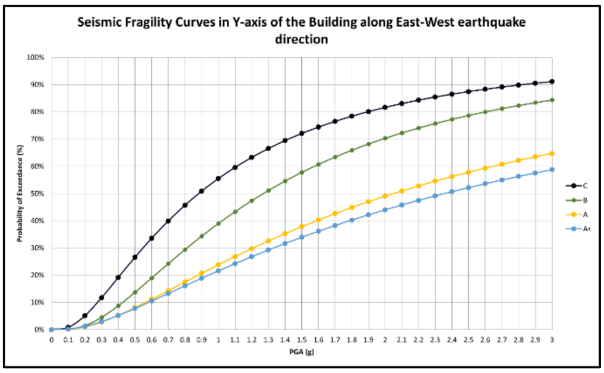

Fig. 9. Seismic Fragility Curves in East-West Earthquake Direction along Y-Axis

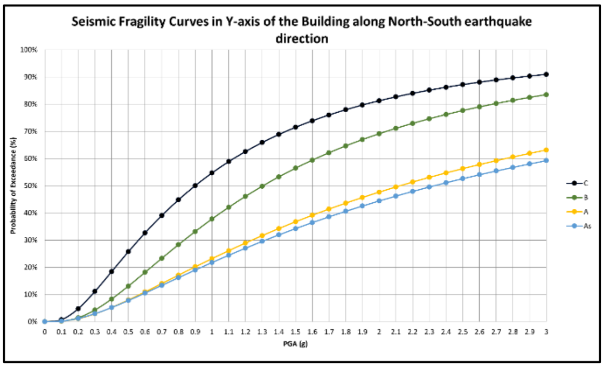

Fig. 10. Seismic Fragility Curves in North-South Earthquake Direction along Y-Axis

The building is expected to be slightly damaged when a peak ground acceleration of 0.285g ground motion The building is expected to be moderately damaged when a peak ground acceleration of 0.550g ground motion occurs. At damage rank "A", the yellow curve or the "Extensive Damage" rank, at the 10% Probability of Exceedance, a PGA of 0.585g was determined. The building is expected to be extensively damaged when a peak ground acceleration of 0.585g ground motion occurs. In Figure 11, the seismic fragility curves illustrate the value of PGA at 10% Probability of Exceedance for each damage rank.

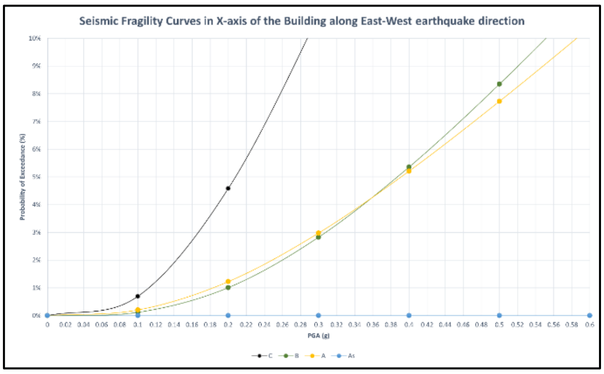

Fig. 11. Seismic Fragility Curves in East-West Direction along X-Axis at 10% Probability of Exceedance

In the X-Axis of the building along the North-South earthquake direction, at damage rank "C", the black curve or the "Slight Damage" rank, at the 10% Probability of

Exceedance, a PGA of 0.300g was determined. The building is expected to be slightly damaged when a peak ground acceleration of 0.300g ground motion occurs. At damage rank "B", the green curve or the "Moderate Damage" rank, at the 10% Probability of Exceedance, a PGA of 0.555g was determined. The building is expected to be moderately damaged when a peak ground acceleration of 0.555g ground motion occurs. At damage rank "A", the yellow curve or the "Extensive Damage" rank, at the 10% Probability of Exceedance, a PGA of 0.595g was determined. The building is expected to be extensively damaged when a peak ground acceleration of 0.595g ground motion occurs. In Figure 12, the seismic fragility curves illustrate the value of PGA at 10% Probability of Exceedance for each damage rank.

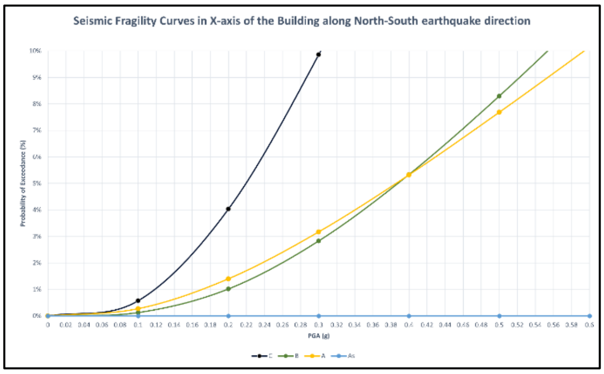

Fig. 12. Seismic Fragility Curves in North-South Direction along X-Axis at 10% Probability of Exceedance

In the Y-Axis of the building along the East-West earthquake direction, at damage rank "C," the black curve or the "Slight Damage" rank, at the 10% Probability of Exceedance, a PGA of 0.275g was determined. The building is expected to be slightly damaged when a peak ground acceleration of 0.275g ground motion occurs. At damage rank "B", the green curve or the "Moderate Damage" rank, at the 10% Probability of Exceedance, a PGA of 0.425g was determined. The building is expected to be moderately damaged when a peak ground acceleration of 0.425g ground motion occurs. At damage rank "A", the yellow curve or the "Extensive Damage" rank, at the 10% Probability of Exceedance, a PGA of 0.560g was determined. The building is expected to be extensively damaged when a peak ground acceleration of 0.560g ground motion occurs. At damage rank "As", the blue curve or the "Complete Damage" rank, at the 10% Probability of Exceedance, a PGA of 0.580g was determined. The building is expected to be completely damaged when a peak ground acceleration of 0.580g ground motion occurs. In Figure 13, the seismic fragility curves illustrate the value of PGA at 10% Probability of Exceedance for each damage rank.

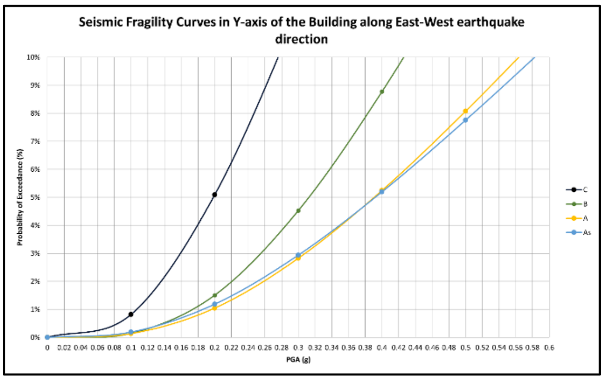

Fig. 13. Seismic Fragility Curves in East-West Direction along Y-Axis at 10% Probability of Exceedance

In the Y-Axis of the building along the North-South earthquake direction, at damage rank "C," the black curve or the "Slight Damage" rank, at the 10% Probability of Exceedance, a PGA of 0.285g was determined. The building is expected to be slightly damaged when a peak ground acceleration of 0.285g ground motion occurs. At damage rank "B", the green curve or the "Moderate Damage" rank, at the 10% Probability of Exceedance, a PGA of 0.435g was determined. The building is expected to be moderately damaged when a peak ground acceleration of 0.435g ground motion occurs. At damage rank "A", the yellow curve or the "Extensive Damage" rank, at the 10% Probability of Exceedance, a PGA of 0.570g was determined. The building is expected to be extensively damaged when a peak ground acceleration of 0.570g ground motion occurs. At damage rank "As", the blue curve or the "Complete Damage" rank, at the 10% Probability of Exceedance, a PGA of 0.580g was determined. The building is expected to be completely damaged when a peak ground acceleration of 0.580g ground motion occurs. In Figure 14, the seismic fragility curves illustrate the value of PGA at 10% Probability of Exceedance for each damage rank.

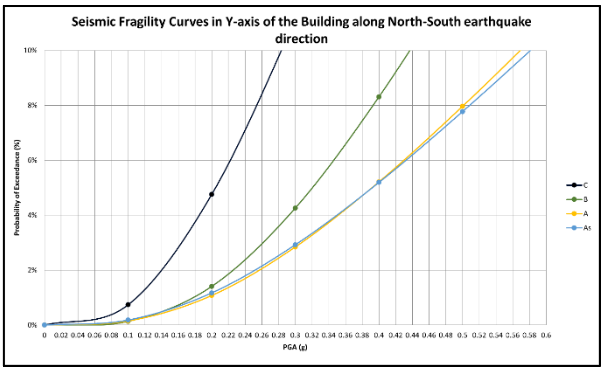

Fig. 14. Seismic Fragility Curves in North-South Direction along Y-Axis at 10% Probability of Exceedance.

Furthermore, Table 5 shows that the Kinaadman Hall's X-Axis had a larger peak ground acceleration. This is because either the building's X-Axis is regarded as stronger or ground motion data are more noticeable and experienced in the Y-Axis than in the X-Axis. Given this, the structural components of the Kinaadman Hall's Y-Axis were deemed more important.

Table 5. Minimum Peak Ground Acceleration (PGA) at 10% Probability of Exceedance of Each Damage State

		East-West	North-South
X-Axis	C	0.285g	0.300g
	B	0.550g	0.555g
	A	0.585g	0.595g
	As	N/A	N/A
Y-Axis	C	0.275g	0.285g
	B	0.425g	0.435g
	A	0.560g	0.570g
	As	0.580g	0.580g

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

After doing the Nonlinear Static Pushover Analysis with SAP2000, the pushover curves were generated in both the X and Y directions, where the structure's base shear was plotted against its displacement. The yield and ultimate displacements in the X-direction are 42.983386 mm and 701.993495 mm, respectively. On the other hand, the yield and ultimate displacements along the Y-direction are 58.75712 mm and 145.067694 mm, respectively. The corresponding base shear force of the yield displacement along the Y-direction, 7230.207 kN, is lower than that of the base shear force corresponding to the yield displacement along the X-direction, which is 7256.855 kN. This means the Kinaadman Hall can resist a greater base shear force on the X-direction. Hence, the X-direction is the structure's stronger axis in comparison to the y-direction. Based on the plotted fragility curves, the minimum/critical peak ground acceleration (PGA) for each damage state at 10% Probability of Exceedance (Pr) was then determined. The Kinaadman Hall was expected to attain "Slight Damage (C)" at PGA=0.275g earthquake. However, a "Moderate Damage (B)" would be sustained if the building was subjected to a PGA=0.425g earthquake. Meanwhile, the building would attain "Extensive Damage (A)" if subjected to a PGA=0.560g earthquake. Finally, the building was expected to reach "Complete Damage (As)" if subjected to a PGA=0.580g earthquake. Considering that the Kinaadman Hall has the capacity to endure a minimum PGA of 0.580g, which corresponds to "Complete damage (As)" as per the NSCP 2015 and surpasses the minimum demand of PGA=0.4g, the researchers deemed it safe for occupancy. Notably, a PGA of 0.580g is equivalent to Intensity VIII. Furthermore, the generated fragility curves showed that at 0.4g, the greatest Probability of Exceedance (Pr) under the condition of "Complete Damage (As)" was 5.20%, with no values exceeding 10%. The Kinaadman Hall of Caraga State University-Main Campus complies with the requirements for buildings located under Seismic Zone No. 4.

4.2 Recommendations

Using the data and findings obtained from the study, the researchers highly recommend that future researchers do the following:

- The study is only limited to the data indicated in the as-built plans of the building; therefore, the researchers recommend performing validation tests, such as the Rebound Hammer Test, Penetration Resistance Test, and Rapid Visual Inspection, to determine the current properties and strength of the structure.
- For greater accuracy, future researchers should evaluate more ground motion data than was employed in this study.
- Future researchers should explore other structural analysis and design software, such as ETABS and STAAD, to be applied to the analyses to extract the parameters for the fragility function.
- Since the study only focused on a particular building in Caraga State University, the Kinaadman Hall, broadening the project structure scope is recommended for more applications and significance. Investigating more buildings and structures inside the Caraga State University vicinity could also expand the scope of the future study.
- Future researchers should consider conducting a cost-benefit analysis to determine the retrofitting cost for the structure after it has sustained damage during a seismic event.
- Furthermore, future researchers could study other structures such as schools, residential buildings, industrial buildings, dams, bridges, and others to compare the fragility curves of these structures as they have distinct usage.

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