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Original Article

Seismic Fragility Analysis Using the Capacity Spectrum Method (CSM) of a Modern Four-Storey Classroom Building

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Abstract *- The Philippines is no stranger to earthquakes, but the worry over the future movement in the West Valley Fault (WVF) proves that the next large-scale earthquake can happen as soon as within the next half-century. Hence, many structures, including commercial, institutional, and residential types within a considerable vicinity of the fault line, would not be spared from the effects of the projected tremor. It is therefore important that seismic fragility analyses of these structures, such as modern four-storey classroom buildings, are done to make the necessary preparation and mitigation steps before the tremor strikes. Researchers utilized Midas Gen in modelling the building from the obtained structural plans. Using data from 20 earthquake events covering local and international records, the overall performance of the structure was also determined. Based on national standards on seismic design, in correlation with a PGA vs Intensity scale, the study concluded that the study site was able to behave adequately in a 0.4g scenario, suffering slight to moderate damage at maximum. In line with this assessment, researchers see the potential of using the seismic fragility analysis for older buildings around the area and for other structures as preemptive measures before any quake strikes.*

Keywords *- Pushover Curves, Fragility Curves, Capacity Spectrum Method, Seismic Vulnerability, Probability of Exceedance.*

1. Introduction

General reference sources often highlight that the Philippines is among the nations situated along the infamous Pacific Ring of Fire. This geotectonic setting renders the archipelago highly vulnerable to seismic activity, ranging from minor tremors to major earthquakes. According to the United States Geological Survey (USGS) in their online publications, approximately 90% of the world's earthquakes and 81% of the most powerful events occur within the Ring of Fire, as reported. [1].

In addition, the USGS notes the significance of the Tethyan orogenic belt—commonly referred to as the Alpine-Himalayan orogenic belt—which accounts for 5–6% of global seismic occurrences and 17% of the largest recorded earthquakes.Since it sits in a very seismically active area, more precisely known as the Philippine Mobile Belt, it is inevitable for parts of the country to suffer the most horrendous of this natural phenomenon at some point in the future [2]. In a shortlist by the Philippine Institute of Volcanology and Seismology (PHIVOLCS) of the largest and deadliest earthquakes to hit the country in the modern era, three of which have occurred in the most populous island of Luzon: the infamous 1990 Luzon earthquake with its epicenter from Rizal, Nueva Ecija, the 1968 Casiguran earthquake that was notable for toppling the Ruby Tower in Manila, and the ensuing tsunami in the 1994 Mindoro earthquake [3]. Such proves that most of the Philippine population is susceptible and quite far from being safe in another event of the same or of greater intensity.

A closer examination of seismic risk highlights the West Valley Fault (WVF), one of the most studied and anticipated fault systems in the Philippines. Current models for the fault line expect it to generate an earthquake of at most a magnitude 7.7 [4] in the National Capital Region (NCR) and the surrounding provinces (Figure 1). Archaeological and geological evidence indicate that the Valley Fault System, an alternative designation for the WVF, is already primed for another high-intensity rupture anytime soon. The potential consequences of such an event would be catastrophic, with widespread disruption across major population centers in the nation directly affected by its movement. Historical records show that the WVF last ruptured in 1658 AD, producing a magnitude 5.7 earthquake, while the East Valley Fault last moved in 1771. Given the system's recurrence interval of approximately 200 to 400 years, the next large-scale earthquake that can rattle the capital can occur anytime within the next five decades or so from the time this research was written.

Fig. 1 A map tracing the West Valley Fault. The northern portion extends way up to eastern Bulacan, with Malolos within a considerable distance from the fault line.

Neighboring provinces like Bulacan would likewise experience the adverse impacts of a major tremor from the WVF. As part of the Metro Luzon Urban Beltway Super Region, Bulacan hosts critical infrastructure and key institutions that play essential roles in serving public interests. The vulnerability of these facilities underscores the broader regional risks associated with seismic activity along the Valley Fault System. In public higher education, for example, Bulacan State University (BulSU), a public university in the province, leads the list with over 40,000 students enrolled. Ever since it was founded during the American occupation period, the entire Main Campus (or Malolos Campus) itself has undergone a series of structural developments. Further, there are ongoing university programs for rehabilitation and/or refurbishment in many of the currently standing buildings on the campus as a response to both the growing student population and the demands of the environment. This adds to the fact that the campus already experienced some significant tremors in recent years, most noteworthy was the 2019 Luzon earthquake that was recorded with a magnitude of 6.1 and was just a hundred kilometers away from the campus. Among the new additions in the university's infrastructure is the university's new College of Business Education and Accountancy (CBEA) building, which currently houses thousands of students and faculty under its namesake. As such, any failure to place safeguards in these kinds of structures may well result in unnecessary fatalities once a massive earthquake strikes the region.

Local civil engineers and authorities are already aware of the necessity to conduct thorough preparation for all kinds of scenarios before, during, and after an earthquake. For the past years, seismic events that have rattled towns and provinces far from the busy metropolitan region of and around Manila have already posed a significant question of whether completed and newly built structures will be up for the main shock from the West Valley Fault. However, extensive studies on the post-tremor conditions from the affected areas, as well as technically the entire state of earthquake engineering in the Philippines, are few compared to other countries in the West, and data that might be significant for further analysis of structures are limited to previous studies or yet to be studied.

A deeper understanding of structural damage brought about by earthquakes can be achieved through the development and analysis of fragility curves, which are becoming indispensable tools for both preliminary preparations for seismic events and post-event response evaluation. Fragility curves, after all, express the likelihood that a structure will attain or surpass a particular damage state when subjected to ground shaking. Over time, there has been a wide variety of mathematical models and engineering approaches for constructing fragility curves, reflecting further their importance in forecasting the extent of potential damage during seismic events. They can also support even the most basic seismic risk assessments by showing how buildings may respond under various shaking intensities. In other approaches, they are also used to examine the influence of aftershocks and determine whether a structure remains safe for occupancy following the mainshock. Ultimately, fragility functions contribute to more informed decision-making aimed at reducing economic losses and, critically, minimizing casualties during earthquakes.

Despite growing interest in seismic vulnerability assessment in the Philippines, significant gaps remain in the application of fragility analysis to other public infrastructure. Considering the limited availability of in-depth Philippine strong-motion records and studies, this forces local researchers to rely on foreign ground-motion datasets and hampers the determination and study of outcomes that are more likely and more accurately reflect local seismic conditions. While recent hazard mapping efforts from government agencies already recognize this gap in the field, few investigations in the current decade have focused on evaluating the seismic performance of more recently built buildings, such as those in schools and universities, especially by using nonlinear procedures such as the Capacity Spectrum Method (CSM). These gaps alone underscore the need for a comprehensive fragility analysis of a modern four-storey classroom building to provide context-specific insights that can inform seismic design, suggest retrofitting strategies, and enforce relevant engineering policies in the Philippines.

For this study, soil–structure interaction effects were not incorporated due to the absence of site-specific geotechnical data and the logistical constraints imposed by the COVID-19 pandemic prevailing during the conduct of the research. Architectural recommendations are likewise excluded, except in instances where such considerations emerge as critical factors influencing the structural stability or integrity of the building under investigation, and which shall be reflected as a recommendation. Retrofitting strategies are also omitted, as the development of intervention measures falls outside the intended scope of this work.

Furthermore, the extraction of in-situ material properties was not feasible because of pandemic-related restrictions on site access, resulting in certain analytical components being necessarily theoretical. The unavailability of specialized engineering equipment typically required for detailed structural characterization may also introduce deviations between computed and actual structural parameters when future research is conducted. Finally, the study does not undertake analyses related to progressive stiffness degradation, energy dissipation mechanisms, or ultimate failure modes, as these aspects extend beyond the defined objectives of the present investigation.

2. Literature Review

For a long time, it has been established that earthquakes themselves are not directly attributable to most fatalities when they occur. Approximately 50,000 earthquakes occur around the world each year, and these earthquakes are recognizable without equipment. About 100 of these are large enough to cause severe damage when placed near densely populated areas. Over the centuries, earthquakes have caused millions of deaths and immense damage [6].

It should be an established idea that sometimes, the worst earthquakes are not the most powerful. The number of people killed or injured is generally a function of earthquake depth (shallow quakes do greater damage), population density, and the level of punishment buildings and other structures can take before failing. Even prior to the onset of the 21st century, 75% of the fatalities in earthquakes come from structural collapse [7] - which is why buildings should be designed properly to avoid being susceptible to damage. Tsunamis were generated by some earthquakes, such as the 2004 Indian Ocean earthquake and the 2011 Great Sendai Earthquake in Japan, causing extra damage and loss of life. Two of the most powerful earthquakes ever recorded, the Chile earthquakes of 1960 and 2010, on the other hand, had comparatively low mortality tolls.

Considering urban development, the existence of design flaws, construction quality, and the absence of regular maintenance result in loss of lives and damage to property. [8]. These factors, therefore, can affect the number of casualties, injuries, and loss of assets in an earthquake, associated with what we call the vulnerability of the existing building. Khan et al. defined vulnerability in their 2019 study as the inability to resist a hazard, and seismic vulnerability is the probability of likely damage to buildings, services, infrastructures, etc., due to earthquakes [9]. Setting aside other variables directly proportional to the effect of an earthquake, like focal depth, epicentre distance, and local environmental circumstances, it is therefore important that there exists a system of checks and balances in earthquake engineering. Therefore, building components, especially their structural supports, require an extensive and complete understanding and evaluation. Further, public infrastructure, regardless of its time, needs to undergo routine and regular inspection, maintenance, and monitoring to ensure both visible and non-visible aspects of its integrity are considered for its overall health.

Considering public infrastructure, it is therefore important that there is a system for Structural Health Monitoring (SHM). While it is true that the engineering and construction industries are subjected to a thorough and rigorous process before even moving ahead, and in the belief that there is diligence on the part of the designer and the worker, SHM connects all the pre-construction to the post-construction conditions. As such, it helps in identifying areas to focus on during analysis and provides adequate reasoning for resource allocation on retrofitting and repairing the building systems as soon as possible. This is important as poor execution of retrofitting may also contribute to the seismic vulnerability of a building. After all, refurbishment or retrofitting can have a role in the increase of seismic vulnerability of a building [10].

Any evaluation of existing structures requires a good understanding of the building's components and overall behavior as a system. As such, infrastructure and facilities serving public functions must undergo periodic inspection, maintenance, and monitoring to ensure long-term safety, serviceability, and sustainability [11]. However, reliance on visual inspection as the primary assessment method is not without its limitations. Visual inspections can readily identify surface-level deterioration such as cracking or corrosion, but the approach remains inherently qualitative. As such, it may likely fail to detect any subsurface or early-stage damage that develops from long-term material degradation, fatigue, or seismic loading. This constraint alone underscores the need for more advanced approaches or supplementary work beyond visual inspection alone to ensure a reliable understanding of structural condition and performance.

Structural evaluation methods generally fall into either linear or nonlinear analytical frameworks, each offering insights into how a system responds to different loads. The choice of analytical approach, however, can significantly influence the accuracy and realism of simulated structural behavior, particularly under seismic demands. Among nonlinear procedures, pushover analysis, also known as nonlinear static analysis, is a common process employed in the field. Given its relative simplicity, especially in the use of ground motion data, it can be used in structural and earthquake engineering [12] to get an idea of the inelastic structural response of a structure. Another preferred approach is nonlinear time history analysis, a more realistic method and detailed approach to generate seismic demand predictions and evaluate the performance of structures under seismic duress [13]. However, considering the capacity spectrum method (CSM), this would require extensive ground-motion datasets, sophisticated modeling, and significant computational resources compared to a dataset that can be readily connected with seismic demand spectra. Further, CSM is an easier approach when there is a need to characterize overall seismic vulnerability rather than simulate every possible dynamic interaction that may happen.

On that note, it is important to be mindful that while recent earthquakes showed that older buildings missing out on modern seismic codes are more damaged in the end, this emphasizes the need for seismic evaluation of existing buildings. In Egypt, for example, reinforced concrete framed buildings are the most popular type of existing structures, but they were mainly built to withstand gravity loads only, which would contribute to seismic deficiencies [14]. As such, this scenario already leads to the idea that it would be detrimental in the long run, considering the potential effects of earthquakes in the area.

Countries situated along active tectonic boundaries, such as the Philippines, are routinely exposed to earthquakes of varying intensities. Although low-magnitude events are often disregarded due to their minimal visible impact on typical structures, existing buildings remain susceptible to the cumulative and sometimes imperceptible effects of repeated ground shaking. One of the most serious recent major tremors to strike the heavily populated Greater Manila Area, which comprises the provinces of Bulacan, Cavite, Laguna, and Rizal together with the National Capital Region, was in 2019, when a tectonic earthquake of magnitude 6.1 occurred near Castillejos, Zambales. Intensity V was felt in Bulacan's provincial capital, Malolos, especially considering the 10-kilometer depth of the earthquake [15].

In line with the mentioned events, the Philippine Institute of Volcanology and Seismology (PHIVOLCS) continues to predict a 7.2 magnitude earthquake, like the 2013 Bohol quake, along the 100-kilometer West Valley Fault, which runs through six Metro Manila cities. Projections indicate that such an event could result in extensive structural collapse affecting roughly 40% of residential and commercial buildings and could lead to significant casualties, the majority of which would stem from the failure of critical facilities such as schools, hospitals, shopping malls, and places of assembly. [16].

Economic loss is one of the effects of seismic vulnerability in buildings. In areas with medium to high seismic activity, human and economic losses stem from the severe physical damage sustained by buildings, as well as the partial or complete collapse of structures that were not originally designed or adequately strengthened to resist earthquakes [17]. Further, the cost of rebuilding and reconstructing structures may vary depending on the damage the structure suffers. According to a study in 2018, earthquakes cause a 1.6% reduction in GDP per capita. It also stated that low- and middle-income countries suffer more economic damage than high-income countries [18]. On the other hand, the age of the structure can be one of the factors that make it susceptible to seismic hazards. In the Philippines, public spaces such as schools and educational facilities have often served as evacuation centers and community shelters during disasters, which makes them important in the neighborhood. However, most of the infrastructure for longstanding schools in the nation is already decades old, so their structural resilience is a matter of public safety and social stability.

One local research study that was conducted at Adamson University [19] analyzed and modeled five university buildings on the campus that are aged 10 to 86 years old. The analysis was performed by acquiring structural performance using nonlinear analysis (pushover analysis and time course analysis). The parameters needed to derive the vulnerability curve, such as ductility factor, damage index factor, and damage rank, were obtained using a variety of software. From the generated vulnerability curve at the end, only one structure, the Francis Regis Clet Building, met the requirement of the National Structural Code of the Philippines that structures must withstand up to about 40% ground acceleration. The researchers recommended further tests to determine whether the buildings are suitable for any retrofitting measures that would allow them to withstand the level of ground motion.

In another research in 2018, school buildings in Cagayan de Oro in Mindanao were surveyed. The majority of the surveyed school facilities, which were built between the 1980s and 2010s, fell under reinforced concrete, while there remains a significant number of other buildings with timber frames **(**Figure 2).

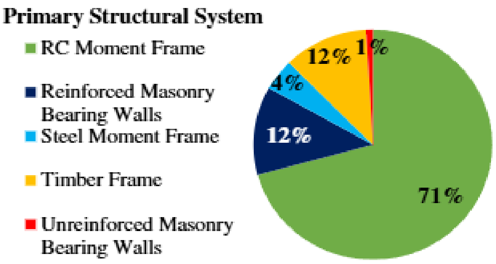


Fig. 2 Statistics on primary structural systems of surveyed schools in Cagayan de Oro, Philippines. [20]

The findings of that study revealed that many existing school buildings are structurally inadequate, with a high probability of sustaining moderate to severe damage during strong earthquakes [20]. It also demonstrates that structural retrofitting—such as strengthening columns, adding shear walls, or improving load paths—significantly reduces vulnerability and enhances resilience. Retrofitted schools show improved performance, lower expected losses, and reduced casualty risks compared to their unmodified counterparts. Importantly, the study underscores that retrofitting is more cost-effective than post-disaster reconstruction, especially when applied strategically to schools located near active faults or in densely populated areas.

3. Objectives of the Study

The researchers' primary objective is centered on determining the seismic susceptibility and performance of the study site based on significant earthquake data from the past years. Hence, this paper was designed to achieve these specific objectives along the way:

- Use the as-built plan of the building to generate a working three-dimensional (3D) model of the structure.
- Use pushover analysis to determine the performance points for each peak ground acceleration (PGA).
- Generate fragility curves showing the probabilities of each of the various damage levels, considering the chance of its occurrence and exceeding certain seismic requirements.
- Interpret the fragility curves to provide insights for further structural evaluation in terms of the local situation and for future studies.

4. Materials and Methods

The process will be a mix of evaluation and experimental methods to present a more accurate and detailed result in the end. Researchers also note in this paper that the latest National Structure Code of the Philippines (NSCP) will be used to bring any analysis up to date with nationally recognized standards and laws.

This paper has followed a specific paradigm to properly process the data acquired. First, a model of the building, the ground motion data from 20 earthquakes, will be obtained prior to the generation of the pushover curve and response spectra, with respect to shear being the only mode of failure considered.

Once these are determined, the performance points per response spectra data will be gathered, of which the displacement value will be utilized for the utilization of damage indices and ranks, and identification of the probability of occurrences per rank. Finally, a log-normal equation will be used to generate the final output: the seismic fragility curves of the building. The process discussed is laid out in the following flow chart methodology (Figure 3).

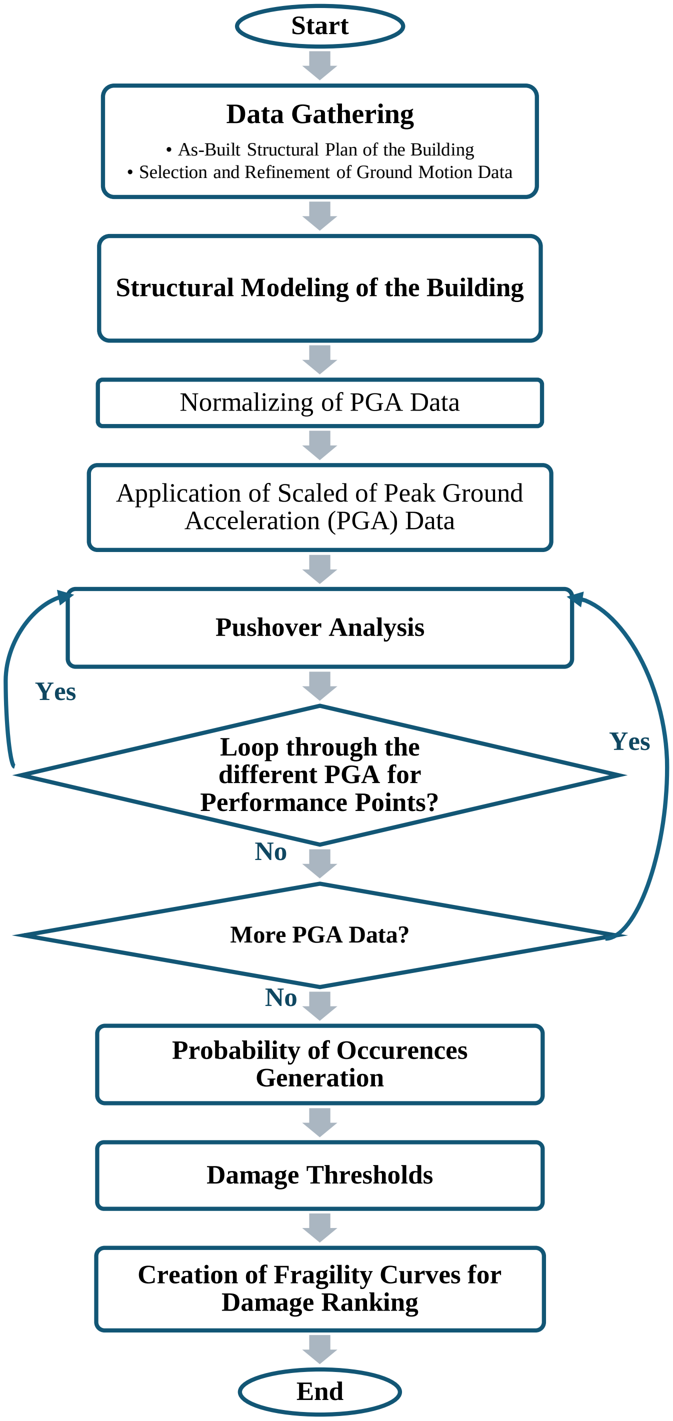


Fig. 3 Flowchart for the entire analysis.

4.1. Ground Motion Data

The study employed a set of twenty earthquake ground-motion records, comprising ten internationally recorded events and ten locally sourced Philippine motions. The inclusion of international records provides a broader range of spectral shapes, intensity measures, and frequency content consistent with global strong-motion databases, which reduces bias associated with limited local recordings. At the same time, the inclusion of Philippine ground motion data allowed researchers to counter the extremes of the international records and balance the likely outcomes with region-specific seismic characteristics. That way, any characterization of the structure's behavior will be as close as possible to the prevailing site conditions and faulting styles expected out of the Valley Fault System's movement. For CSM, this mixed-record strategy would support the development of fragility curves that are both statistically reliable and contextually appropriate for the Philippines.

At the time of the writing, the researchers gathered what was available from the IRIS Wilber 3 Data Services website and then cross-checked with existing records from the United States Geological Service (USGS) to exclude any potential artificial events. Hence, the list (Tables 1 and 2) that was implemented was not strictly in the definition of the top ten largest earthquakes in history.

Table 1. Reference International Ground Motion Data

Reference Earthquakes since 1970 (International)		
Event/Region	**Magnitude**	**Date**
2011 Great Tohoku Earthquake, Japan	9.1	2011 Mar 3
2004 Sumatra - Andaman Islands Earthquake	9.1	2004 Dec 26
Offshore Bio-Bio, Chile	8.8	2010 Feb 27
Off the west coast of northern Sumatra	8.6	2012 Apr 11
Northern Sumatra, Indonesia	8.6	2005 Mar 28
Southern Sumatra, Indonesia	8.4	2007 Sept 12
Near the coast of southern Peru	8.4	2001 Jun 23
Sea of Okhotsk	8.3	2013 May 24
Kuril Islands	8.3	2006 Nov 15
2017 Chiapas Earthquake, 101km SSW of Tres Picos, Mexico	8.2	2017 Sept 8

Table 2. Reference Local Ground Motion Data

Reference Earthquakes since 1970 (International)		
Event/Region	**Magnitude**	**Date**
Luzon, Philippines	7.7	1990 July 16
Philippine Islands region	7.6	2012 Aug 31
Luzon, Philippines	7.3	1999 Dec 11
Mindanao, Philippines	7.3	1992 May 17
Catanduanes, Philippines	7.3	1988 Feb 24
Samar, Philippines	7.2	1995 Apr 21
60 km SE of Bobon, Philippines	7.1	2021 Aug 11
4 km SE of Sagbayan, Philippines	7.1	2013 Oct 15
1994 Mindoro earthquake	7.1	1994 Nov 14
4 km SE of Sagbayan, Philippines	7.1	2013 Oct 15

For the corresponding technical data of the local seismic events, they were adapted from the Incorporated Research Institutions for Seismology (IRIS) Earthquake Browser's sortable table of the top 20 earthquakes within the borders of the Philippines. Maximum boundary set at 18.98 degrees latitude, 127.56 degrees longitude, minimum boundaries at 5.29 98 degrees latitude, 116.56 degrees longitude.

Damage rank and indices will be based on a 2016 study by Vasavada & Patel. The thresholds that will be identified – ranging from no damage to complete damage- will be based on the researchers' gathered yield and ultimate displacement from the pushover curve [21]. Each spectral displacement value has an assigned damage rank for which all obtained and projected displacement values have been identified.

Table 3. Damage State Threshold (Vasavada & Patel, 2016)

Damage States	**Spectral Displacement**	**Damage Rank**
No Damage	*0*	D
Slight Damage	*0.7Dy*	C
Moderate Damage	*Dy*	B
Extensive Damage	*Dy + 0.25(Du-Dy)*	A
Collapse	*Du*	As

Researchers have also set the percentage drift needed for the application of the loads in the model. The maximum interstorey drift was determined using Equation (1):

$$\%drift = \frac{Roof\ displacement}{Building\ height} \times 100\% \qquad (1)$$

4.2. Development of Fragility Curves

Constructing the fragility curve will require the use of Equation (2) as shown below. The equation will require both the mean value of the data μ and the standard deviation value σ of the logarithm of the PGA as essential parameters to determine and characterize the probabilities per the damage ranks mentioned in the previous section.

$$P[D/PGA] = \Phi\ \frac{\ln(PGA) - \mu}{\sigma} \qquad (2)$$

Other variables in the equation are the D as the damage state, and Φ as the standard normal cumulative distribution function.

Some values after the pushover analysis were computed to arrive at the fragility curve output of the research. While it was expected that all displacement values from a performance point in the capacity spectrum curve would be determined by the software, the researchers will be using an extrapolation method in the case of the remaining values becoming unobtainable due to limitations.

5. Results and Discussion

This section focuses on the results and outcomes for the specific objectives laid out in the paper.

5.1. Study Site and Building Model

The CBEA Building of the Bulacan State University Main Campus was opened around 2019. It is four stories tall and is bounded by a small campus park in the east, the College of Science's extension building on its West, the Laboratory High School Building on its south, a vacant lot on its north, and the Federizo Hall building and its spaces on its northeast. The area was formerly occupied by a building associated with the College of Industrial Technology (CIT) before being demolished some years ago to pave the way for its construction. On the PHIVOLCS Fault Finder web application, the building and its vicinity are approximately 35.8 km away from the nearest fault line in the area – the West Valley Fault system.

The model of the building (Figure 4) was then designed in Midas Gen according to the retrieved architectural details and structural plans of the building. No other considerations (e.g., actual strengths or material conditions) were included, considering the limitations discussed in the earlier chapters. The as-built structural model of the building contained its key characteristics as it was completed. As an additional note, the structure falls under Occupancy Category III of the National Structural Code of the Philippines (NSCP).

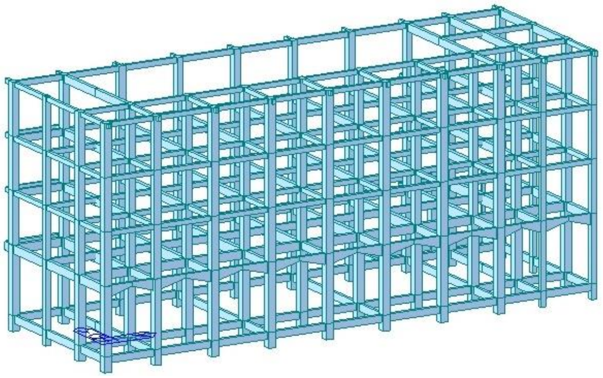


Fig. 4 Working model of the four-storey classroom building based on the as-built plan.

5.2. Pushover Curves

The shape and identified critical points in the pushover curve allowed researchers to observe how the structure balances strength and ductility under increasing seismic demand. On the pushover curves for the X and Y-directions (Figures 5 and 6), researchers looked at displacements and shear base forces as calculated by the software as a basis for the next phase of the study.

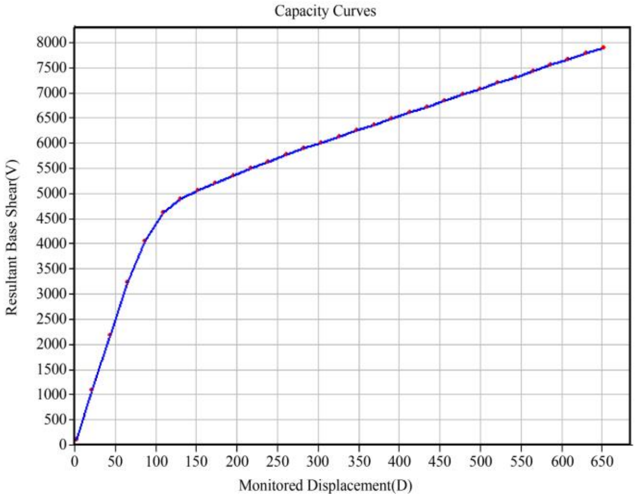


Fig. 5 Pushover curve for the X-axis of the Building

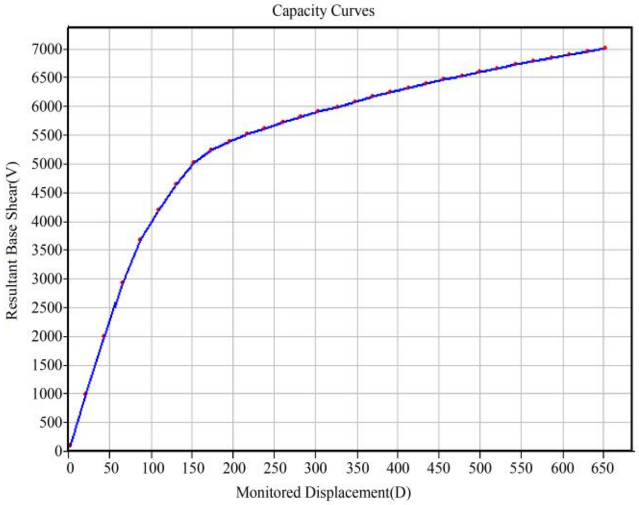
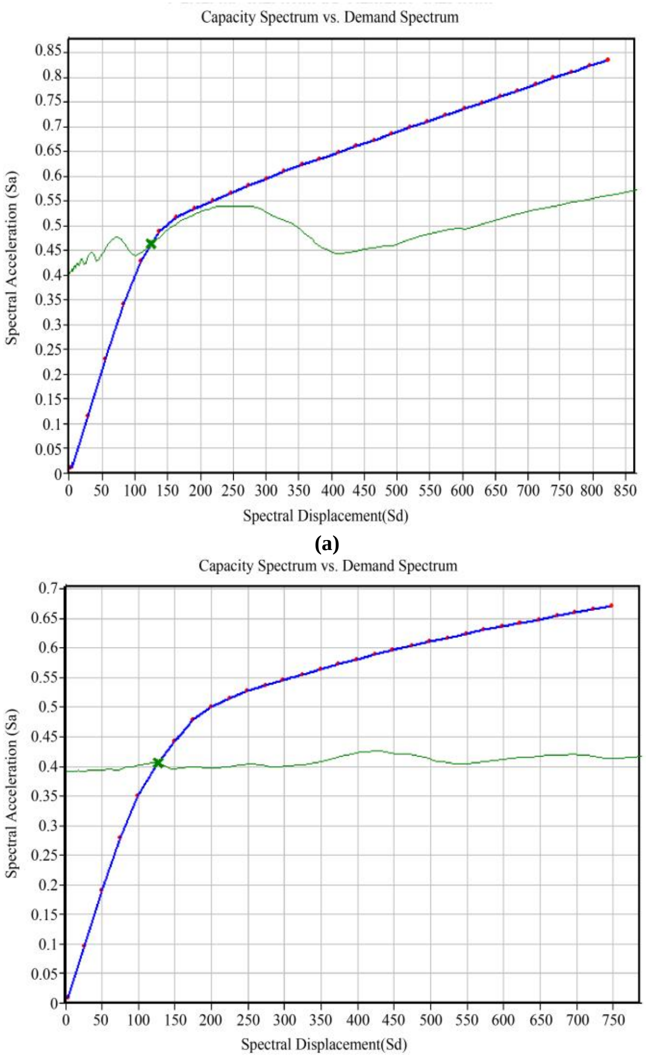


Fig. 6 Pushover curve for the Y-axis of the building

5.3. Capacity Spectrum Curves

Afterwards, researchers would be using the ATC-40 Capacity Spectrum curve available in the application. The curve utilizes the values generated from the pushover and the response spectra loaded in the static analysis. The response spectra loads were set on Seismic Zone 4 as per the National Structural Code of the Philippines, with Seismic Source Type A set owing to the considerations of the proximity of the study site to the West Valley Fault.

The Capacity Spectrum Method (CSM) would then be used to determine the performance points – the exact point where the capacity curve intersects the response spectra curve.



(a)

(b)

Fig. 7 Capacity Spectrum vs Demand Spectrum curves for the (a) X-axis and (b) Y-axes of the classroom building

5.4. *Fragility Curves*

Within the National Structural Code of the Philippines (NSCP), the seismic design basis for structures is anchored on a prescribed Peak Ground Acceleration (PGA) of 0.4g, corresponding to the code's adopted 10% probability of exceedance in 50 years for sites classified under Seismic Zone 4.

This baseline value aligns with probabilistic seismic hazard data developed for the country and reflects the expected ground-shaking environment associated with major tectonic sources in the Philippine archipelago.

A comprehensive probabilistic seismic hazard model released in 2020, which accounts for regional tectonics and active fault systems, further supports this design threshold. The model (Figure 8) evaluated hazard levels based on exceedance probabilities over 10- and 50-year periods and indicates that areas proximal to Metro Manila, including the study site, may be subjected to strong ground motions within the approximate range of 0.3g to 0.5g, or approximately up to 50% of the standard acceleration due to Earth's gravity. These values represent a substantial fraction of gravitational acceleration and underscore the necessity of adopting a conservative design PGA to ensure structural safety under credible seismic scenarios.

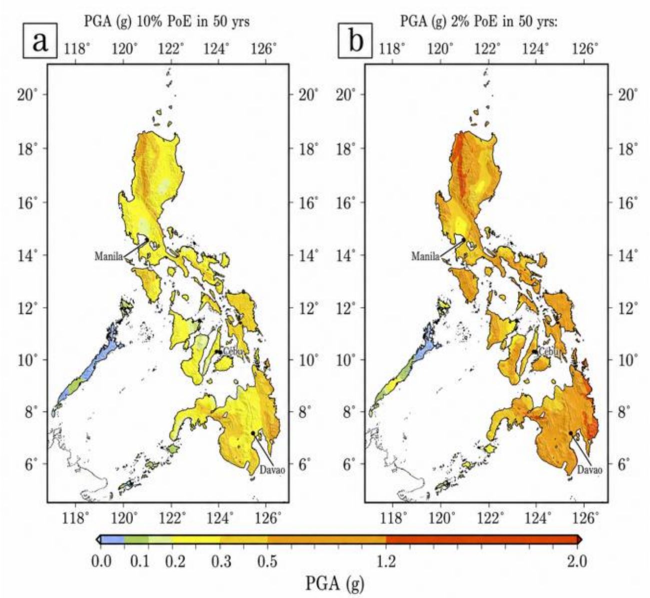
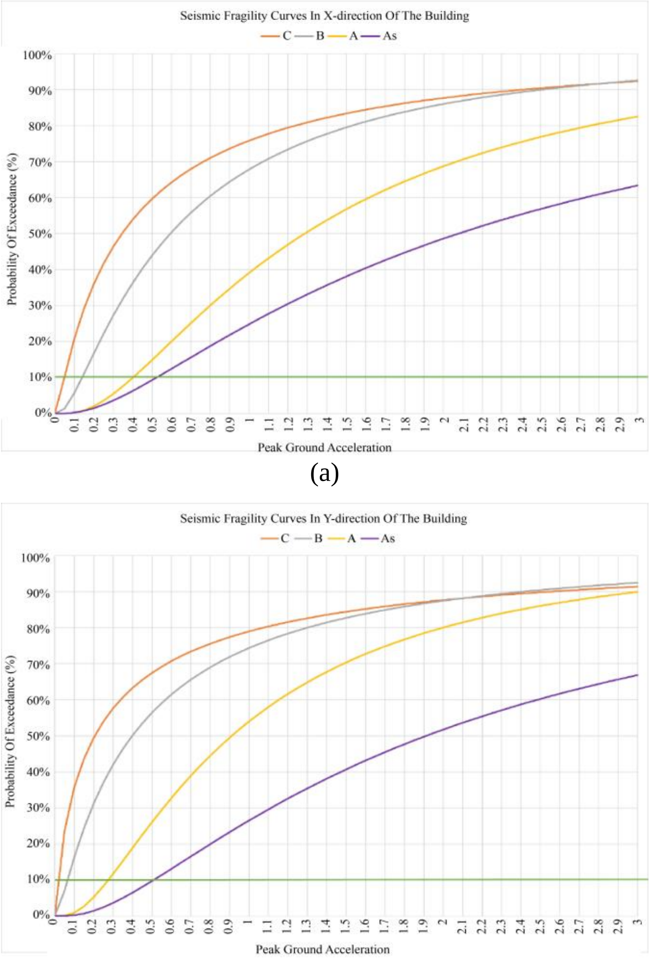


Fig. 8 Peak ground acceleration (PGA) map for the Philippines with (a) 10% probability of exceedance and (b) 2% probability of exceedance in 50 years. [22]

The generated building model was subjected to different ground motions from international and local records – including the largest in the data available, which are the 9.1 Mw earthquake in 2011 (Japan) and 2004 (in the Indian Ocean), plus the 7.7 Mw earthquake in Luzon in 1990.

The seismic fragility curves, therefore, gave the researchers the possibility of determining the probability of exceedance at 10%, or the basic design PGA. As discussed in earlier sections, the decision to maximize and widen the dataset on ground motion data for the generation of fragility curves was to reduce any potential bias arising from the limited number of records available in the Philippines and allow all potential scenarios to reduce uncertainty in the building's structural response.

The following charts are the generated fragility curves for the X and Y-directions of the building, where each damage rank can be compared. Damage rank "D" (no damage) must not be included in the fragility curve presentation. A line was also made visible to denote the 10% probability of exceedance threshold for each curve/damage rank.



(a)

(b)

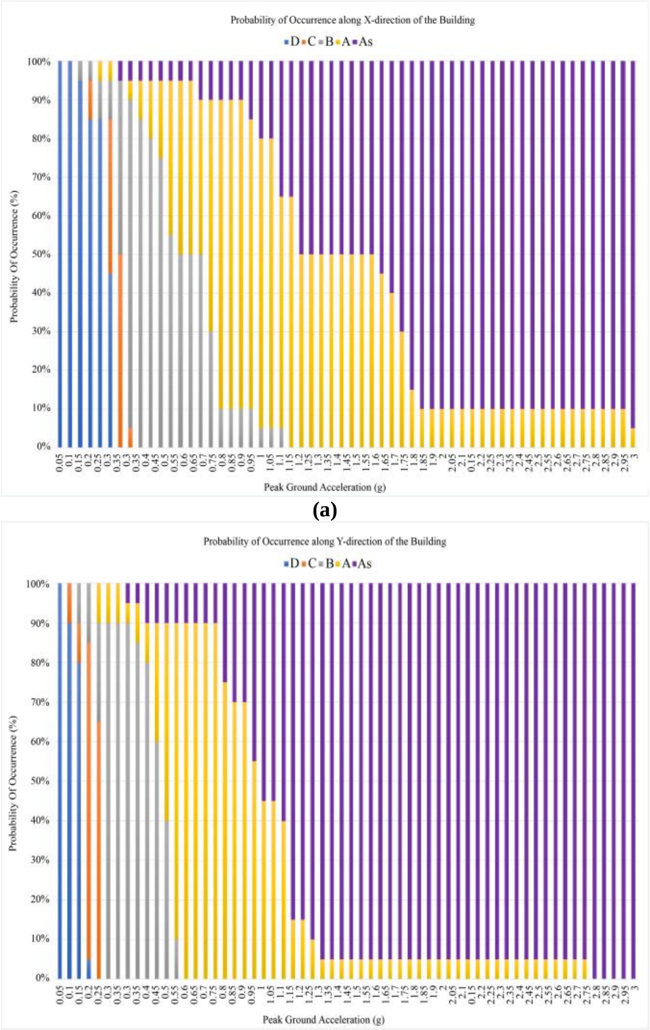
Fig. 9 Fragility curves for: (a) the X-axis of the structure; (b) for the Y-axis of the structure

5.5. *Probability of Occurrence and Exceedance (PoE)*

In this study, exceedance probabilities are used to relate structural demand to damage states, allowing the fragility curves to express the probability that the building will reach or surpass a defined damage threshold under varying seismic intensities.

Each earthquake record, in both the East-West (EW) direction and the North-South (NS) direction, had its performance points with respect to its shear and displacement for each peak ground acceleration (which was refined at an interval of 0.05) collected. As some PGAs returned a failure to generate a performance point from the fragility curve in the software, researchers used extrapolation using the polynomial equation generated by at least four points to project the rest of the values and complete the entire table up to 3.0g.

With all displacements gathered, the number of occurrences of an earthquake meeting a specific damage ratio was plotted in a 100% stacked column graph.



(a)

(b)

Fig. 10 Probability of occurrence curves for: (a) the X-axis of the structure; (b) the Y-axis of the structure

At 0.4g on the calculations, the following are the probability of exceedance thresholds for the classroom building:

Table 4. Probability of Exceedance (PoE) per Damage Rank

Motion of the Earthquake	**Axis of the Building**	**PoE for Rank "C"**	**PoE for Rank "B"**	**PoE for Rank "A"**	**PoE for Rank "As"**
East-West	X	54%	36%	10%	6%
North-South	Y	63%	50%	19%	6%

Furthermore, based on the graph estimates, the following are the PGA thresholds at 10% probability of exceedance for the same building.

Table 5. PGA at 10% Probability of Exceedance per Damage Rank

Motion of the Earthquake	Axis of the Building	PGA (g) at 10% PoE for Rank "C."	PGA (g) at 10% PoE for Rank "B."	PGA (g) at 10% PoE for Rank "A."	PGA (g) at 10% PoE for Rank "As."
East-West	X	0.05	0.14	0.41	0.53
North-South	Y	0.03	0.07	0.27	0.51

The Probability of Exceedance (PoE) was then determined in accordance with the mean, standard deviation, and probability of exceedance equations. Based on the National Structural Code of the Philippines, structures in the Philippines should be able to withstand a peak ground acceleration of 0.4g. The PGAs per 10% probability of exceedance also gives us the idea that, in most cases, a West Valley Fault movement with an Intensity VIII tremor felt in the area will not cause the building to collapse entirely.

5.6. Correlation to Seismic Magnitude Scales

The researchers utilized the PHIVOLCS Earthquake Intensity Scale (PEIS), which was crafted and used since 1996 in the Philippines, replacing the Rossi-Forel Scale. The PEIS measures an earthquake event based on the expected effects of the tremor in an area. This allows the study to be in a more localized context.

The PEIS deviates slightly from the Modified Mercalli scale, which uses 12 scales based on the last recognized revision made by Adolfo Cancani in 1904 and Harry O. Wood and Frank Neumann in 1931. The Modified Mercalli Intensity scale is used in the United States and most of Southern Europe, with the United States Geological Service usually grouping the last two with Intensity X as Intensity X+.

In the interest of showing the difference for the basis of comparison, a 2004 report by Japan International Cooperation Agency (JICA), Metropolitan Manila Development Authority (MMDA), and the PHIVOLCS for an earthquake impact reduction study for Metropolitan Manila gives us the comparative Modified Mercalli and even the Japan Meteorological Agency (JMA) intensity scale on each of the designated PEIS intensity scale. It can be noted that the PEIS Scale generally does not deviate from the intended assumptions provided by the Mercalli scale nor by the JMA scale (which focuses more on moment magnitude) used in Japan.

Table 6. PEIS vs Modified Mercalli vs JMA Scales

PEIS Scale	Condition	Modified Mercalli Intensity Equivalent	Japan Meteorological Agency (JMA) Intensity Equivalent
I	Scarcely Perceptible	I	0
II	Slightly Felt	II	1
III	Weak	III	2
IV	Moderately Strong	IV	2-3
V	Strong	V	3
VI	Very Strong	VI	4
VII	Destructive	VII	4
VIII	Very Destructive	VIII, IX	5-6
IX	Devastating	X, XI	7
X	Completely Devastating	XII	7

Given the presented calculations and these tables, we could use a 2014 table **(**Table 7) on the correlation of the PGA and the instrumental intensity scale and magnitude scale in Richter:

Table 7. PGA Correlation to Intensity and Richter Scales [23]

Moment Magnitude (Richter)	Instrumental Intensity	Acceleration (g)
Under 2.0	I	< 0.0017
2.0 – 2.9	II - III	0.0017 – 0.014
3.0 – 3.9	IV	0.014 – 0.039
4.0 – 4.9	V	0.039 – 0.092
5.0 – 5.9	VI	0.092 – 0.18
6.0 – 6.9	VII	0.18 – 0.34
7.0 – 7.9	VIII	0.34 – 0.65
8.0 or higher	IX	0.65 – 1.24
	X	> 1.24

A 7.2 magnitude earthquake from the West Valley Fault will most likely fall in the Richter magnitude range of 7.0-7.9. Assuming the seismic hazard assessment that Malolos City will be suffering an Intensity VIII tremor, and have a PGA range between 0.34 and 0.65, the potential damage rank will be placed between moderate and heavy. Further, from the resulting projected PGAs and the probability of occurrence and exceedance, it can be safely said that the building can generally withstand the tremor with slight to moderate damage on the x-axis and y-axis, respectively, but will not collapse even at the threshold PGA as set by the standard.

For reference, if we are to place the structure at the same distance of a tremor occurring at a 9.0 magnitude earthquake such as those seen in Japan and Indonesia before, the building will suffer at most at least a 0.65g PGA or even more than the 1.24g expected in the correlation table, which means in any case, the building will collapse – coinciding with the descriptive analysis of any earthquake generating at least an Intensity IX tremor.

6. Summary of Findings

The four-storey classroom building was modelled according to the obtained plans and details using Midas Gen. However, the researchers would like to point out ahead of time that by the end of the day, the overall accuracy of the model will also depend on these as-built plans. On that note, the accuracy of the instruments used, as well as factoring in human errors, can and will affect the output we have presented in this study.

On the damage ranks calculated, the researchers can say that, as per NSCP guidelines, the building should be able to withstand the projected earthquakes within the area, and according to the standard, given at around 0.4g. On the other hand, some specific earthquake scenarios may pose threats to the building if they were to happen in the Philippines. While the largest record of any earthquake in the Philippines is at 8.0, and most scientific sources would agree that the West Valley Fault may not exceed 7.2 magnitude, researchers did not limit themselves to this threshold and still used references such as the 9.0-9.1 M_w earthquake from 2011 in eastern Japan. In this situation, the Midas model of the building had already failed to generate a performance point exceeding 0.2g or 0.4g in other cases. Should a PGA of at least 1.0g occur in the area, the building would likely collapse based on the probabilities we have generated, despite its recently constructed status at the time of this writing.

Nonetheless, with the assumptions and the relevance of the anticipated events that the researchers explore, the results present us with the likelihood of the building sustaining slight to moderate damage at most as the peak ground acceleration increases accordingly with the expected maximum intensity.

It can also be noted that, based on the analysis done, the Y-axis of the building is slightly weaker than its counterpart, so future explorations on retrofitting or improvement of structural integrity may be focused on this axis of the structure. In line with these observations, however, researchers see there is no need to recommend immediate retrofitting for the building, but there is a need to continuously monitor and check the structure for any structural defects that might influence the overall integrity of the building.

However, everyone must be reminded that the accelerations projected in this study do not automatically equate to a particular intensity or magnitude when an earthquake occurs, and hence, further studies may be conducted to deliver a closer projection to the reality that may unfold in the study site. Researchers conclude that considerations of including non-destructive tests and using nonlinear dynamic methods would return a better view of what could transpire during the anticipated earthquake events within the area. The probabilistic ranges presented are limited only to the numbers obtained from fragility curves generated in this research, and other factors that might affect the eventual occurrence and state of the building are not considered in this paper. Future researchers are highly encouraged to explore these areas to increase the accuracy of the analysis.

7. Conclusion

Future research in this area, incorporating actual material properties of the concrete present in the structure, is recommended to establish the nonlinear behavior of the building in newer analyses.

Considering the limitations and gaps acknowledged for this work, checking and inclusion of Soil-Structure Interaction (SSI) principles may also be a new perspective to check the structure's behavior in a more realistic manner and relevant to the study site in a wider sense. This would also help in identifying whether the type of soil present in the area ultimately influences the structure under seismic events and can be connected to future studies anchored on foundation design, structural analysis, and earthquake engineering.

Given that the study focused on a recently built structure and well within the latest national structural codes, future researchers may explore whether there is a need for retrofitting in a couple of years, and what strengthening interventions and techniques are appropriate and practical for implementation in executing the building. Other studies should also look into whether there are ways to further reduce the effects of seismic loads on the structure without compromising the construction standards or involving destructive refurbishments. Future researchers can also take note of the following for additional areas of study:

- Inclusion of Non-Destructive Tests (NDTs) in the variables concerning the creation of the model to be analyzed. The researchers were unable to utilize these, given the concurrent situation prevalent at the time of the study, as well as the limitations, the unavailability, and the economics to get the necessary instruments (such as Schmidt's rebound hammer) at the time the research was conducted.
- Establishment of a seismic health monitoring system by the local authorities or institutional officials. This would require regular monitoring of buildings within the campus and ensuring the general integrity of structures in consideration of seismic events. Furthermore, researchers see this as necessary given the projections that the study area, in the case of the WVF moving, can suffer as high as an Intensity VIII tremor based on the PEIS.

Given that the Philippines is among the countries experiencing the significant impacts of climate change, future research may also explore how persistent and extreme environmental conditions influence the long-term performance of structural materials. Factors such as recurrent flooding and prolonged exposure to extreme heat during the dry season may be starting points to explore whether these contribute to changes in material behavior or accelerate deterioration processes. Investigating these environmental stressors would provide valuable insight into whether climate-related phenomena have a direct effect on the degradation of structural components and how such can alter a building's seismic fragility over time. This would also be highly relevant for studies focused on the conservation of aging infrastructure and for finding appropriate and practical retrofitting strategies that can lead to enhancing structural resilience under both seismic and environmental hazards.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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