Physics-Based Simulation of Seismic Collapse in Heritage Masonry Churches of Bohol, Philippines

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Physics-Based Simulation of Seismic Collapse in Heritage Masonry Churches of Bohol, Philippines

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Abstract: *The 2013 Bohol earthquake exposed the seismic vulnerability of unreinforced masonry heritage churches in the Philippines, many of which suffered extensive damage or collapse. This study demonstrates a simplified, physics-based approach to simulate the seismic response of three surviving Baroque churches in Bohol—Santa Monica in Alburquerque, San Nicolas de Tolentino in Dimiao, and San Agustin in Panglao. Using the open-source Blender software and the Bullet Constraints Builder (BCB) add-on, the simulations replicate collapse scenarios with significantly reduced data input and computational demands compared to traditional finite element modeling. Results show that the churches remain intact under an Intensity VIII earthquake but experience progressive collapse at Intensities IX and X, aligning with observations from the 2013 event. The use of Blender and BCB supports rapid assessment of structural behavior and offers valuable insight into failure mechanisms, promoting disaster risk reduction and the preservation of historically significant masonry structures in seismic regions.*

Keywords: Earthquake simulation; Unreinforced masonry; Heritage churches; Blender; Bullet Constraints Builder.

1. INTRODUCTION

Masonry churches are among the most iconic architectural features of the Philippine landscape, particularly in the province of Bohol, where Spanish colonial influence is deeply embedded in the region's cultural and spiritual identity. These heritage structures, which serve as both sacred spaces and communal landmarks, are invaluable not only for their historical and architectural significance but also for their role in fostering communal harmony. However, their continued existence is increasingly threatened by natural hazards, most notably, earthquakes—due to Bohol's location along the seismically active Pacific Ring of Fire. Earthquakes can cause extensive structural damage, leading to cracks, deformation, or complete collapse of buildings and infrastructure [1,2].

The devastating 7.2-magnitude earthquake that struck Bohol in 2013 underscored the seismic vulnerability of these heritage churches [3,4]. Many collapsed or sustained irreparable damage, revealing the structural fragility of centuries-old buildings constructed long before the advent of modern seismic design codes. While some churches remarkably remained standing, their resilience cannot be taken for granted given the looming threat posed by the active Bohol fault system comprised of the East and North Bohol faults [5]. The need to preserve these remaining structures is urgent, especially considering their official recognition as culturally significant structures by the National Historical Commission of the Philippines (NHCP) and the National Museum. Despite ongoing conservation efforts, comprehensive and proactive measures are still needed to protect these landmarks from future seismic events.

Conventional approaches to structural assessment, such as finite element modeling (FEM), provide high-fidelity insights into structural response under seismic loading [6,7]. However, these methods are often time-consuming, resource-intensive, and require detailed material and geometric data—conditions not always feasible in heritage conservation contexts [8]. In response to these challenges, this study explores the use of an alternative physics-based simulation technique utilizing an open-source software: Blender in combination with the Bullet Constraints Builder (BCB) add-on. This platform enables real-time visualization of collapse mechanisms by modeling structures as assemblies of rigid bodies governed by Newtonian mechanics [9-11]. These simulations quickly identify failure modes and support assessments of heritage churches in data-scarce scenarios.

Unlike traditional FEM-based approaches, the Blender–BCB framework simplifies the modeling process while still capturing essential aspects of structural behavior and failure modes [12,13]. This makes it particularly suitable for preliminary investigations and decision-making in heritage conservation planning. Moreover, the resulting debris patterns from the simulations could aid in emergency preparedness and rescue operations by predicting potential entrapment zones [9].

This paper aims to simulate the seismic response and collapse scenarios of three surviving masonry churches in Bohol using the Blender–BCB platform. Through this approach, the study seeks to contribute to the ongoing discourse on accessible, efficient, and scalable tools for seismic vulnerability assessment of cultural heritage structures. The findings aim to support risk screening, heritage conservation planning, and the development of simplified modeling tools for resource-limited regions.

2. MATERIALS AND METHODS

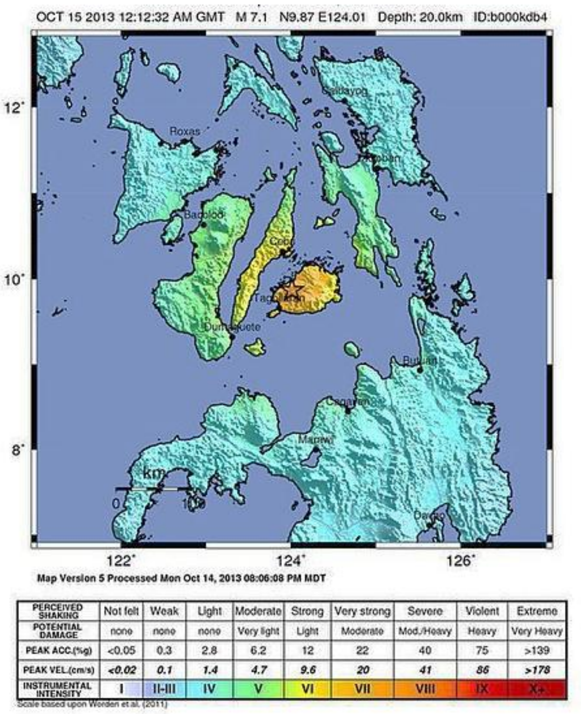
2.1 Blender and BCB

The Bullet Constraints Builder (BCB) is an open-source add-on for Blender that enables efficient collapse simulations of masonry structures based on the idea of Discrete Element Method (DEM) [9]. By integrating Blender's 3D environment with the Bullet Physics Engine, BCB models buildings as assemblies of rigid bodies connected by force-based constraints, replicating contact, friction, and cohesive forces at joints [9].

DEM applies Newtonian mechanics to discrete elements, making it well suited for scenarios where failure initiates at block or mortar interfaces [9]. Compared to continuum approaches such as finite element modeling, the BCB workflow dramatically reduces input requirements and computational effort, enabling near real-time visualization of collapse mechanisms [10,11] without sacrificing essential collapse behavior. Blender and BCB offer a practical, accessible tool for collapse visualization, rapid seismic risk assessment and heritage preservation planning.

2.2 Description of the Bohol Churches

The selected churches in Bohol, chosen primarily for their availability of engineering plans and common post-earthquake intact status, are representative of 19th-century Spanish colonial ecclesiastical architecture in the Philippines, featuring cruciform layouts, unreinforced masonry construction, and ornamental baroque details. All three churches are in the southern part of Bohol, share similar construction typologies, and withstood the 2013 earthquake without collapse, sustaining only cracks. According to the ShakeMap (Fig. 1) generated by United States Geological Survey (USGS) for the 2013 Bohol earthquake [14], the island province experienced high ground shaking intensities (Intensity VII–VIII), underscoring the seismic risk of such heritage structures despite their apparent robustness. These churches serve as case studies for simulating structural collapse under seismic loading using the Blender-BCB framework.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

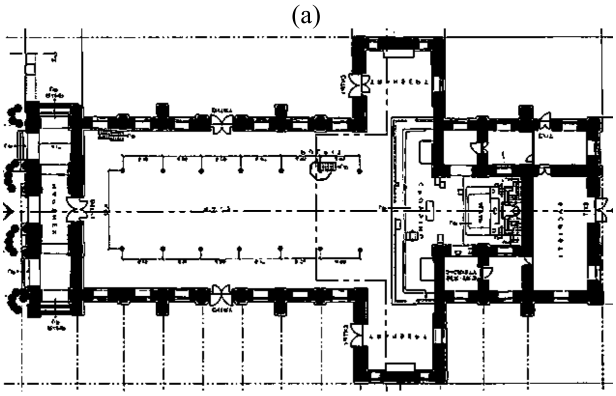
Fig. 1. USGS ShakeMap of Bohol 2013 earthquake [14]

Each church is characterized by thick load-bearing walls, high vaulted ceilings, and the use of *mamposteria,* i.e., stone masonry constructed using individual stones that are bonded together with mortar, cladded with coralline limestone bonded with lime mortar [15]. Their continued function today as places of worship and cultural heritage is a testament to both their robust construction and ongoing conservation efforts [16].

2.2.1 Parish Church of Santa Monica – Alburquerque, Bohol

- **Coordinates:** 9°36'40" N, 123°57'28" E
- **Wall Thickness:** 1.0 m
- **Wall Height:** 7.7 m
- **Total Floor Area:** 1815 m^2
- **Designation:** Important Cultural Property (National Museum of the Philippines); Marked Structure (National Historical Commission of the Philippines) [17]

(a)



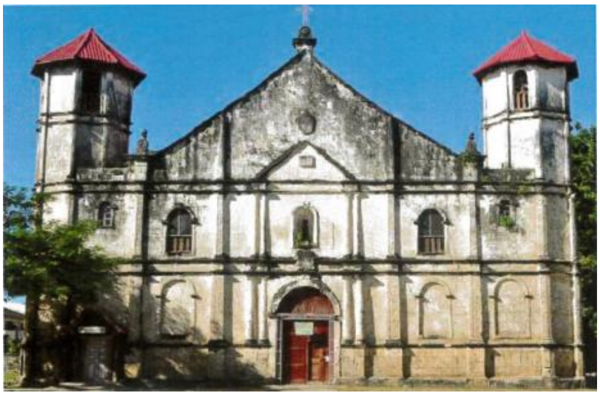
(b)

Fig. 2. (a) Façade and (b) floor plan of the Parish Church of Santa Monica – Alburquerque, Bohol (Courtesy of National Museum of the Philippines).

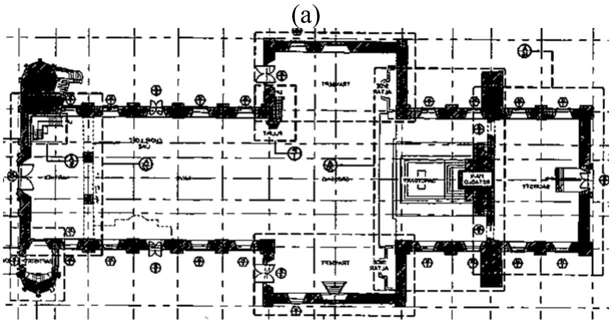
The Parish Church of Santa Monica in Alburquerque, completed in the late 19th century, is a significant example of Spanish colonial ecclesiastical architecture in the Philippines. According to the archives of the National Museum of the Philippines, it was built during a period of parish expansion under Spanish friars, reflecting both religious and administrative functions in the local community. The church features a cruciform plan (Fig. 2(b)) with wide transepts, thick unreinforced coral stone masonry walls, and a neoclassical façade embellished with classical pilasters and cornices. The bell tower, integrated into the front façade, was designed to serve as both a visual focal point and a functional element for liturgical and communal use (Fig. 2(a)). During the 2013 Bohol earthquake, the structure sustained only minor damage and was subsequently restored in compliance with national heritage conservation standards [16].

2.2.2 Parish Church of San Nicolas de Tolentino – Dimiao, Bohol

- **Coordinates:** 9°36’18” N, 124°9’41” E
- **Wall Thickness:** 1.8 m
- **Wall Height:** 12 m
- **Total Floor Area:** 1641 m^2
- **Designation:** National Cultural Treasure (National Museum of the Philippines) [17]



(a)



(b)

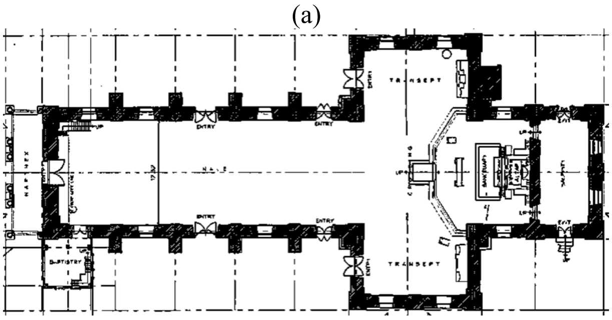
Fig. 3. (a) Façade and (b) floor plan of the Parish Church of San Nicolas de Tolentino – Dimiao, Bohol (Courtesy of National Museum of the Philippines).

Located in the municipality of Dimiao, the Parish Church of San Nicolas de Tolentino stands as a well-preserved example of Baroque-inspired colonial architecture, reflecting the artistic and religious sensibilities of the Spanish missionary period. It also features a cruciform layout, thick unreinforced masonry walls, side buttresses for lateral stability (Fig. 3), and intricately carved wooden altarpieces that exemplify local craftsmanship influenced by European styles. Despite its antiquity, the church sustained only minor damage during the 2013 Bohol earthquake and was subsequently restored in accordance with national heritage conservation protocols [16].

2.2.3 Parish Church of San Agustin – Panglao, Bohol

- **Coordinates:** 9°34’42” N, 123°44’44” E
- **Wall Thickness:** 1.8 m
- **Wall Height:** 7.64 m
- **Total Floor Area:** 1319 m^2
- **Designation:** Important Cultural Property (National Museum of the Philippines) [17]

(a)



(b)

Fig. 4. (a) Façade and (b) floor plan of the Parish Church of San Agustin – Panglao, Bohol (Courtesy of National Museum of the Philippines).

The San Agustin Church in Panglao Island, Bohol also adopts a cruciform layout (Fig. 4) and is constructed primarily from locally sourced coralline limestone, consistent with Spanish colonial building practices in coastal Bohol. Architecturally, it is distinguished by its prominent portico façade and elaborately frescoed ceilings that reflect a fusion of European religious motifs and Filipino artistry. The church sustained moderate structural damage during the 2013 Bohol earthquake, including cracking in masonry walls and the detachment of several architectural elements. Comprehensive restoration and retrofitting efforts were subsequently undertaken to strengthen the structure and preserve its cultural and historical significance [16].

These case study churches are not only vital to the religious life of their communities but also valuable in understanding the behavior of unreinforced masonry structures under seismic loading conditions. Their inclusion in this study allows for the evaluation of collapse mechanisms and potential loss scenarios using computationally efficient simulation techniques.

2.3 Modelling and assumptions

The three churches were modeled based on the engineering plans (Figs. 2–4) provided by the National Museum of the Philippines, supplemented by data obtained from on-site inspections. Three-dimensional representations of the structures were developed using

Blender to reconstruct the architectural geometry and facilitate subsequent structural analyses. The buildings and their constituent materials were modeled as homogeneous unreinforced masonry (URM), with material properties summarized in Table 1. These properties were adopted from prior investigations into the mechanical strength parameters of URM walls in Philippine heritage churches in Bohol [15].

To capture the discrete nature of masonry behavior under seismic loading, the models employed the BCB framework, which conceptualizes the structure as an assembly of discrete blocks interacting through contact surfaces, thereby enabling simulation of fracture initiation and progressive collapse mechanisms [9]. Consistent with established methodologies [18–21], the roofs were assumed to be non-interacting with the masonry walls and were represented as uniform pressure loads of 204 kg/m² [22,23]. This simplification is justified by two primary considerations: (1) the limited level of detail available in the architectural documentation provided by the National Museum, and (2) restricted access to the roof structural components for detailed inspection and material testing.

Table 1. Parameters and values employed for the seismic analysis of the three coralline limestone churches [15]

Parameter	Unit	Value
Compressive	*MPa*	8.36
Tensile	*MPa*	0.92
Shear	*MPa*	1.45
Bend	*MPa*	0.92
Density	*kg/m³*	1366

To simulate ground motion within the BCB framework, earthquake inputs are defined by specifying both the amplitude and frequency of horizontal ground vibrations. The vibration frequency is set to approximate the natural frequency of each structure to capture potential resonance effects, which are critical in assessing seismic vulnerability [24,25]. The natural frequency f (in Hz) is estimated using an empirical formula commonly applied to unreinforced masonry buildings [26]:

$$f = \frac{1}{0.05H^{0.75}}$$

where H is the wall height in meters. As this relationship indicates, taller buildings correspond to lower natural frequencies, making them more responsive to long-period ground motions.

Table 2 presents the wall heights of the selected churches along with their corresponding resonance frequencies computed using the above expression. This method allows for a simplified yet representative estimation of dynamic response within the BCB simulations, particularly in the absence of detailed modal data for heritage structures.

Table 2. Heights and corresponding vibration (natural) frequency of the churches

Church	Height (m)	Frequency (Hz)
Santa Monica	7.70	4.326
San Nicolas	12.0	3.102
San Agustin	7.64	4.352

For the amplitude of vibration, varying seismic intensity is characterized by peak ground velocity (PGV), as illustrated in Fig. 1. Since BCB accepts ground displacement instead of velocity as the primary input for dynamic loading, a sinusoidal ground motion is assumed to approximate the displacement from the velocity. Under this assumption, the peak ground displacement d can be derived from the PGV v and the vibration frequency f using the following basic mathematical relationship :

$$d = \frac{v}{\pi f}$$

where d is in meters, v is in m/s, f is in Hz, and π is approximately 3.1416. This expression provides a simplified yet consistent means of converting velocity-based seismic inputs into displacement amplitudes suitable for use in the BCB framework.

Table 3 shows the corresponding peak ground displacement for the three churches across various intensities of earthquake. In this study, the simulation started from the highest intensities down to the lower ones until no structural collapse was observed, which is during Intensity VIII. The duration of the ground motion is assumed to be 30 seconds, consistent with typical strong-motion phases of moderate to large earthquakes like the 2013 Bohol scenario.

Table 3. Simulated intensity of earthquake and the corresponding ground motion parameters [14]

Intensity	Peak Velocity (m/s)	Peak Displacement (m)		
		Santa Monica	San Nicolas	San Agustin
X	1.78	0.131	0.183	0.130
IX	0.86	0.063	0.088	0.063
VIII	0.41	0.030	0.042	0.030

It is important to note that within the BCB framework, the ground motion parameters are not strictly deterministic; instead, a built-in noise function is applied to introduce random variations in the ground motion over time. This incorporation of randomness aims to reflect the irregular and non-uniform nature of actual seismic events, thereby enhancing the realism of the simulation.

3. RESULTS AND DISCUSSION

This section presents the simulation results obtained using Blender integrated with the BCB add-on, focusing on the structural behavior of the three selected heritage churches. For ground motions up to Intensity VIII, all three structures remained intact with no signs of structural collapse, i.e., without fallen debris. This is consistent with post-earthquake field reports from the 2013 Bohol earthquake. Nevertheless, minor damage, primarily in the form of superficial cracking, could not be ruled out because of the observable displacements of structural components during the simulated shaking. Despite these large motions, the absence of debris formation affirms the robustness of the churches under moderate earthquake.

However, as seismic intensity was increased to levels IX and X, the models began to exhibit progressive and localized failures. Collapse mechanisms were commonly initiated at structurally sensitive areas such as the façade walls and apse—zones typically prone to out-of-plane and in-plane shear failure in unreinforced masonry buildings [27,28]. These observations not only validate known seismic vulnerabilities of heritage structures but also raise critical questions regarding the churches' current safety margins and resilience thresholds. The following subsections examine each church individually, analyzing the onset and progression of failure.

3.1 Santa Monica Church (Alburquerque) Collapse Analysis

As illustrated in Fig. 5, the collapse sequence of the Santa Monica Church in Alburquerque under Intensity X ground motion was initiated by out-of-plane failures at two critical architectural features: the portico of the façade and the gable of the apse. These elements, which lack substantial lateral support, detached early in the simulation, initiating a cascading failure mechanism. The collapse subsequently progressed along the longitudinal masonry walls of the nave, culminating in complete structural failure. This pattern is consistent with known vulnerabilities in unreinforced masonry systems, where slender or poorly connected walls with low in-plane stiffness are prone to seismic-induced out-of-plane instability [29,30]. The limited lateral resistance of the façade and apse walls rendered these zones particularly susceptible under strong ground excitation [31].

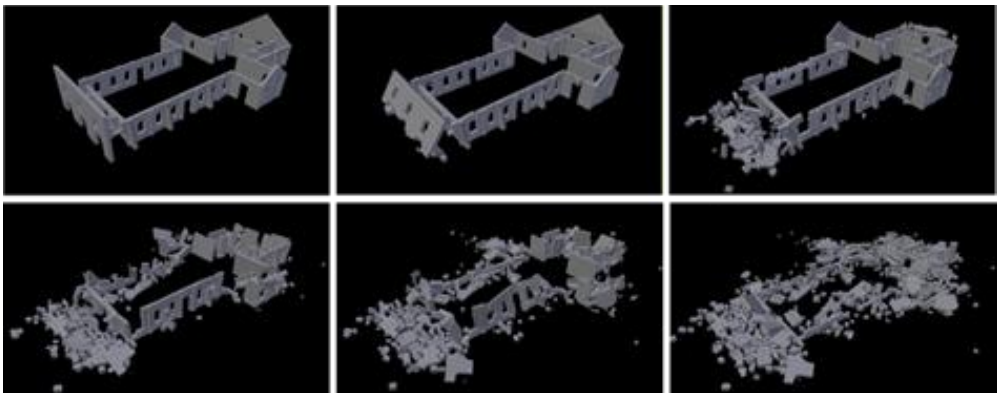


Fig. 5. Simulated structural response of the Parish Church of Santa Monica at Intensity X using Blender.

Building upon this collapse pattern, it is noteworthy that even under Intensity IX ground motion, significant localized damage was still observed in the same vulnerable regions, namely, the façade and apse, as illustrated in Fig. 6. Although complete structural collapse did not occur, the early onset of failure in these areas reinforces their role as critical initiation points for seismic damage. This recurring vulnerability can be attributed to their limited lateral stiffness, poor structural integration, and inherent geometric discontinuities, which make them particularly susceptible to out-of-plane failure [29-31]. Consequently, these findings highlight the urgent need for targeted retrofitting interventions in these architectural components to improve seismic performance and prevent progressive damage during future events.

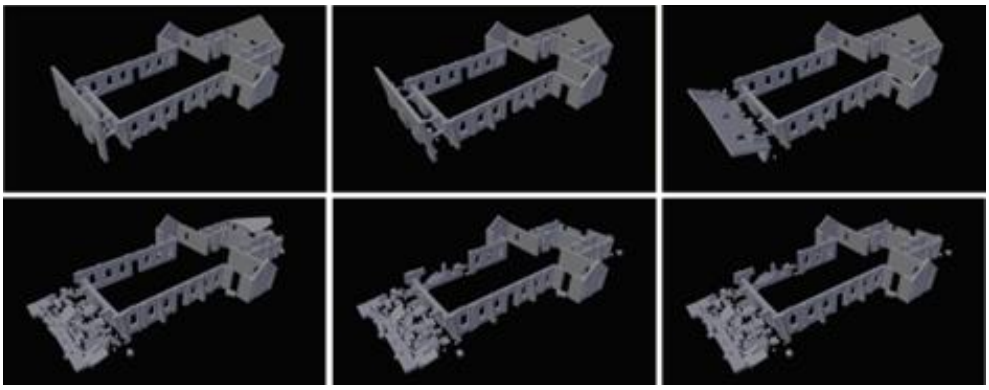


Fig. 6. Simulated structural response of the Parish Church of Santa Monica at Intensity IX using Blender.

3.2 San Nicolas de Tolentino Church (Dimiao) Collapse Analysis

Figure 7 illustrates that the structural collapse of the Dimiao Church was initiated by out-of-plane failures in the nave walls and apse region, with the failure sequence subsequently propagating to the transept walls. This pattern contrasts with that of the Alburquerque Church, where the collapse was triggered at the façade. The difference in failure mechanisms between the two churches is likely due to the presence of twin bell towers in Dimiao, which provided additional lateral confinement and stiffness to the façade, effectively delaying its failure. Furthermore, the bell towers could have influenced the global dynamic response of heritage masonry churches by altering load paths and increasing out-of-plane resistance in adjacent interacting walls [32,33]. As such, the collapse sequence observed in Dimiao underscores the significant impact of architectural configuration on seismic vulnerability.

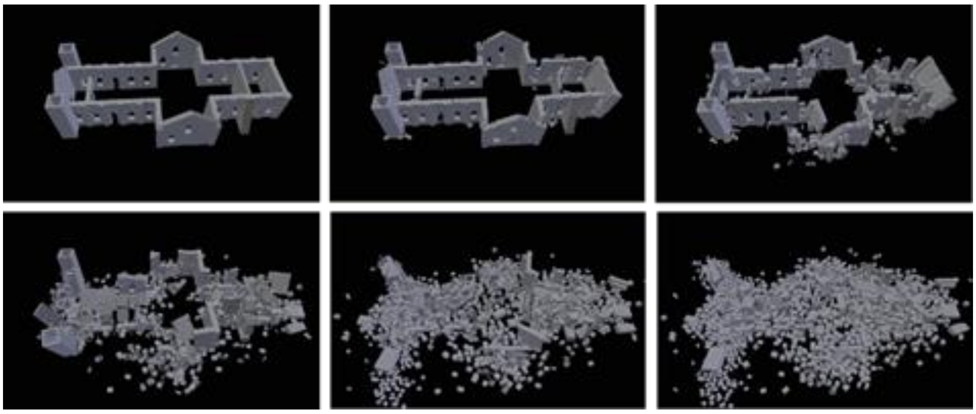


Fig. 7. Simulated structural response of the Parish Church of San Nicolas de Tolentino at Intensity X using Blender.

At earthquake Intensity IX, the Dimiao Church exhibited partial collapse, primarily affecting one of the nave walls. This localized failure aligns with the noted vulnerability of slender masonry walls to out-of-plane instability under seismic loads [29,30]. The additional lateral support provided by the bell towers likely delayed failure in the façade, concentrating damage in the nave walls instead. This behavior further emphasizes the critical role of architectural features in shaping seismic response and highlights the need for targeted reinforcement of vulnerable wall sections to prevent progressive collapse under stronger seismic events.

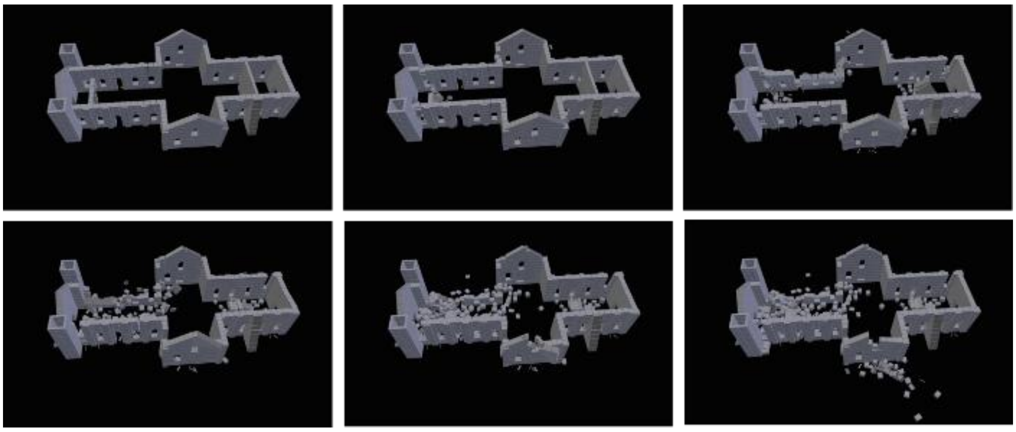


Fig. 8. Simulated structural response of the Parish Church of San Nicolas de Tolentino at Intensity IX using Blender.

3.3 San Agustin Church (Panglao) Collapse Analysis

The simulation results for the Intensity X earthquake on the Panglao Church are shown on Fig. 9. The structure experienced total collapse, with failure initiating at the apse and subsequently propagating to the nave and portico façade. This collapse sequence highlights the apse as a critical weak point, likely due to its limited lateral support and structural discontinuities, making it particularly vulnerable to out-of-plane failure under strong seismic excitation [29,30]. Similar behavior has been observed in other heritage churches such as Santa Monica and San Nicolas de Tolentino, where failure often begins in regions with reduced lateral stiffness before progressing to global collapse. These findings emphasize the need for targeted reinforcement of such vulnerable architectural elements to improve the seismic resilience of heritage masonry structures.

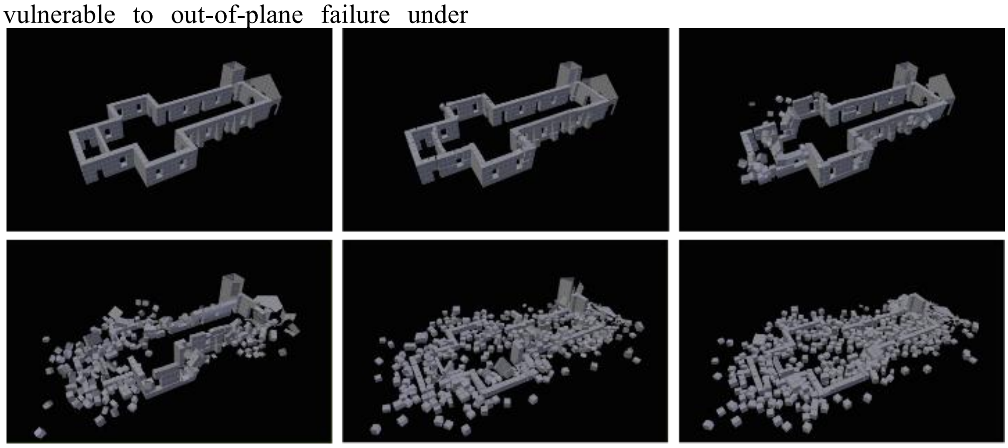


Fig. 9. Simulation in Blender of the Parish Church of San Agustin at Intensity X.

At Intensity IX, the church experienced near-total collapse, with damage extending from half of the apse to one of the nave walls, leaving only portions of the bell tower intact (Fig. 10). The partial survival of the bell tower may be attributed to its partial structural independence, allowing it to resist collapse separately from the main building.

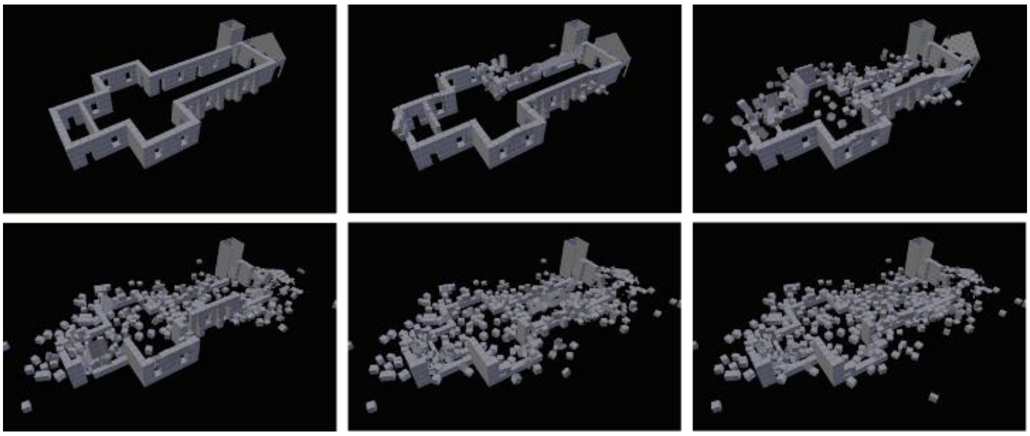


Fig. 10. Simulation in Blender of the Parish Church of San Agustin at Intensity IX.

In summary, the simulation results across all three heritage churches reveal a consistent pattern of seismic vulnerability concentrated in structurally discontinuous and weakly supported architectural elements such as the apse, nave walls, and façade. While moderate ground motions (up to Intensity VIII) did not result in collapse, higher intensities (IX and X) triggered progressive failures originating from these critical zones, ultimately leading to partial or total structural failure. These outcomes not only validate known failure mechanisms in unreinforced masonry buildings but also underscore the urgent need for targeted retrofitting strategies to strengthen these high-risk components and enhance seismic resilience. Moreover, the use of Blender integrated with the BCB add-on proved to be an effective and accessible tool for visualizing complex collapse mechanisms, offering valuable insights into the dynamic response of heritage structures. Its ability to simulate and animate progressive structural failure in detail makes it a promising platform for seismic risk assessment and structural diagnostics in heritage conservation efforts.

4. CONCLUSIONS

This study demonstrated the practical application of Blender integrated with the Bullet Constraints Builder (BCB) add-on in simulating the seismic response of unreinforced masonry heritage churches in Bohol. By combining physics-based modeling with architectural data, the simulation framework effectively demonstrated collapse patterns observed during strong ground motions. The case study churches—Santa Monica, San Nicolas de Tolentino, and San Agustin—remained intact under moderate seismic loading (Intensity VIII), consistent with historical records. However, simulations under higher intensities (IX and X) revealed progressive failure, particularly at structurally sensitive areas such as façade walls and apses. These findings affirm the method's value for visualizing collapse mechanisms, assessing seismic vulnerability, and informing conservation and retrofitting strategies for heritage structures in seismic zones.

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