MULTI –HAZARD RISK ASSESSMENT OF PRIORITY CULTURAL HERITAGE STRUCTURES IN THE PHILIPPINES[1]

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ABSTRACT: At the end of 2013 two catastrophic events occurred in the Philippines: the M 7.2 earthquake in Bohol and the strongest ever recorded Typhoon Haiyan, causing destruction across the islands of Cebu, Bohol and the Visayas region. These events raised the need to carry out a multi-hazard risk assessment of heritage buildings, many of which were irretrievably lost in the disasters. Philippines' Department of Tourism engaged ARS Progetti S.P.A., Rome, Italy, and the Center for Conservation of Cultural Property and Environment in the Tropics (CCCPET), University of Sto. Tomas, Manila, to undertake the "Assessment of the Multi-Hazard Vulnerability of Priority Cultural Heritage Structures in the Philippines", with experts from University College London, UK, and De La Salle University.
The main objective of the project was to reduce the vulnerability of cultural heritage structures to multiple natural hazards, including earthquake, typhoon, flood, by: (i) prioritizing of specific structures based on hazard maps and historical records; (ii) assessing their vulnerability; and (iii) recommending options to mitigate the impacts on them. The paper presents the methodology introduced to determine the seismic risk these heritage buildings are exposed to. All the selected cultural heritage structures are under the jurisdiction of the National Museum Commission of Philippines and of the National Commission for Culture and Arts.

KEYWORDS: *Multi-hazard vulnerability assessment, cultural heritage buildings, risk reduction, strengthening measures*

INGREDIENTS OF A MULTI RISK FRAMEWORK FOR HERITAGE STRUCTURES

Existing literature on multi-hazard vulnerability assessment is notably very sparse, especially in direct reference to historic buildings. While extensive seminal studies for the assessment of non-engineered structural typologies exposed to earthquakes are certainly available (D'Ayala, 2013),

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work in the field of vulnerability to wind and flood for cultural heritage structures is less advanced (Stephenson and D'Ayala, 2014). In particular, when more than one hazard is considered, such as in this study, there is a need for a consistent approach to assess the related vulnerability so that the calculation of the risk is commensurate across the hazards and decisions can be taken on the basis of multi-hazard risks ranked on a single common scale.

In this study, a first attempt to develop such a methodology for assessing the impact of earthquakes, typhoons and floods on priority cultural heritage buildings in the Philippines is presented. The proposed approach aims at balancing the relative simplicity of the analysis vis-à-vis the specific features and related variability in the building stock considered. Specifically, the adopted procedure consists of various steps. The first step pertains to the construction of a reliable inventory profile which characterizes the exposure of heritage assets in the region of interest and identifies the relevant building features affecting the multi-hazard structural performance. This leads to the selection of specific case-study compounds, each including a number of structures of different typology. Next, a performance-based assessment framework for historic buildings is introduced, including the definition of the hazard variables (and corresponding intensity) needed for such an assessment. In fact, for historic buildings and in case of assets of particular value, it might be more appropriate to consider the performance condition of damage limitation or significant damage associated to lower-intensity and shorter return period hazard levels. The proposed approach made extensive use of site-surveying to obtain the necessary data required for the performance-based assessment. Moreover, it combines quantitative state-of-the-art approaches for earthquake and typhoon vulnerability assessment, with a semi-quantitative approach for flood. Safety and conservation legislative frameworks and principles have been taken into account throughout the study, to tailor the assessment strategies and determine the performance criteria of reference. As a result, vulnerability and risk indicators can be quantified based on the collected data and developed tools. Rehabilitation strategies and mitigation measures for risk reduction can be suggested on the basis of the assessment results, together with the need for further investigations where appropriate.

The paper summarizes the multi hazard profile of the Philippines and the value of intensity reference chosen for this study. The rest of the manuscript concentrates on the seismic vulnerability assessment with a brief overview of methods applicable to historic buildings. Then, the detailed steps of the adopted methodology are presented and their application shown for the compound of St. Nicola da Tolentino Church and Convent in Dimiao, on the island of Bohol.

MULTI HAZARD PROFILE

The Philippines is one of the most hazard-prone countries in the world because of its geologic and geographic conditions. It is regularly subject to various hazard-events, inflicting loss of lives and costly damage to property in the country. In particular, the Philippines straddle a region of complex tectonics at the intersection of three major tectonic plates (the Philippine Sea, Sunda and Eurasia plates). As such, the country is exposed to large and damaging earthquakes. For example, the most recent earthquake, the M 7.2 Bohol earthquake (2013), damaged more than 73,000 structures, of which more than 14,500 were totally destroyed, including several heritage structures in Bohol and Cebu. According to official reports by the National Disaster Risk Reduction and Management Council (NDRRMC), 222 were reported dead, 8 were missing, and 976 people were injured. Similarly, several areas characterized by high wind and heavy rain exist along the northeast Philippine Sea coast. Because the southern half of the Philippines is relatively close to the equator, tropical cyclones are quite rare. While it is common for storms to maintain their intensity while crossing the Sibuyan Sea (separates the Visayas from the northern Philippine island of Luzon), storms tend to dissipate as they move from east to west and therefore the wind hazard along the South China Sea coast is lower. Typhoon Haiyan (2013), known as Super Typhoon Yolanda in the Philippines, was one of the strongest tropical cyclones ever recorded, which devastated several portions of the country, killing at least 6,300 people. The highest flood risk is in the mountainous regions of northern Luzon, due to the high frequency of events.

The Philippine Institute of Volcanology and Seismology (PHIVOLCS) is the Philippine national institution dedicated to monitor and provide information (including warnings) on the activities of volcanoes, earthquakes, and tsunamis; it is one of the service agencies of the Department of Science and Technology (DOST) of the Philippines. Similarly, the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) is the National Meteorological and Hydrological Services (NMHS) agency of the Philippines, also serving the DOST. The Nationwide Operational Assessment of Hazards (Project NOAH) was launched by the DOST to undertake disaster science research and development, advance the use of cutting edge technologies and recommend innovative information services in government's disaster prevention and mitigation efforts. These three agencies provide most of the information on seismic, wind and flood hazard in the country. Within the present study, the assessment of different hazard levels for the heritage sites has been carried out by using several state-of-the-art references, including data and studies from both PHIVOLCS and PAGASA as well as findings from other hazard assessment projects by national and international agencies and by individual researchers or local research groups. The summary of the hazard assessment for the heritage sites in Manila, Cebu and Bohol is shown in Table 1.

Table 1. Hazard Assessment for Heritage Structures Location

Site	PGA (g)*	Wind Speed (kph)**	Storm Surge (m)*** (advisory level 4)
Manila	0.4	200 (II)	5
Bohol	0.3	200 (II)	5
Cebu	0.3	200 (II)	5

* Corresponding to a return period of 475 years.
** Corresponding to a return period of 50 years (NSCP, 2010).
*** Corresponding to a return period of 100-150 years.

SEISMIC VULNERABILITY ASSESSMENT

For analytical seismic vulnerability assessment of large number of assets, guidance on suitable approaches can be obtained through Eurocode 8 or ASCE 41-13 (CEN 2005, ASCE. 2014). For cultural assets and heritage structures tailored guidelines are provided by DPCM (2008). These approaches rely on medium quality of the data and apply relatively simple analytical methods, based on a modest number of mechanical and geometric parameters, whereby mathematical model of index buildings representative of one or more typology are defined, and the response of such models to expected level of shaking intensities is computed. When considering unreinforced masonry building heritage, the "*Failure Mechanisms Identification and Vulnerability Evaluation"* (FaMIVE) method (D'Ayala D. 2005), results particularly suitable. Using a relatively modest set of data which can be collected from on-site observation and/or drawings, it enables the computation of the building response using limit state analysis. FaMIVE has the flexibility of either determine collapse load factors only or also equivalent capacity curves and performance points by intersection with demand spectra. The choice of either level depends on the way in which the demand is quantified. The following section provides a detailed account of the procedure.

METHODOLOGY ADOPTED FOR SEISMIC RISK ASSESSMENT FRAMEWORK

The FaMIVE approach (D'Ayala & Speranza 2003) has been developed in the last 15 years, evolving from a procedure to identify possible and most probable collapse mechanisms for masonry façades with diverse level of lateral constraint and determine their lateral acceleration capacity, to a method to derive capacity curves (D'Ayala 2005) and compute fragility functions for populations of buildings of similar typology or collapse modes (D'Ayala 2013). The method has been applied in several locations worldwide in pre- and post-earthquake situations.

In the application to the Philippines heritage, the use of FaMIVE benefited from direct access to most of the buildings and from availability of full sets of drawings. A first phase of the data collection requires the identification of recurring construction details, fabric of load bearing masonry, floors/roof layout and construction. This observation phase allows to identify recurring typology and to modify the survey data sheet to suit local construction practice. The second phase is based on completing survey datasheets containing geometric and structural information related to external bearing walls. Irregular and complex buildings are subdivided in simpler subunits. For each of them the most important or critical elevations are identified and one form (D'Ayala, Putrino, 2016) is filled in for each elevation or homogeneous portion of elevation in the building. Given the way in which FaMIVE is coded the procedure, and hence the form, can be tailored to best suit the sample, by adding or removing parameters that are relevant to the seismic behaviour of the buildings analysed. The form used for the application in the Philippines is accompanied by the FaMIVE Manual (D'Ayala, Putrino, 2016, annex to the "Multi-hazard risk assessment manual of the Philippines' built heritage assets", ARS Progetti et al., 2016) which also contains detailed explanation and coding of each of the form entries. The datasheet includes 11 sections: 1) Urban Data – related to the general description of the surveyed compound and its urban context; 2) Plan Characteristics of the Building - data to identify the geometry of the building and its typology, the relative position of the facade within the building, plan layout and vertical layout, type of loadbearing structures present; 3) Geometric Characteristics of the Façade - data on the geometric characteristics of the façade and its relationship with other walls. Consider also the presence of gable and towers; 4) Openings Layout - layout of openings, details of their number, width, height, dimension of edge piers, height of upper horizontal spandrel and type and material of lintels; 5) Structural Characteristics - data on the structural properties of the floor structures bearing on the façade; on the presence and type of elements restraining the façade; on characteristics of buttresses; 6) Load Bearing Structures Data - data on the structural characteristics of the façade including materials and size of the masonry units and the preservation condition; 7) Further Vulnerability Elements - data on presence and dimensions of construction elements that might generate actions that reduce the capacity of the facade and increase its vulnerability; 8) Tower System - section specifically dedicated to the tower system, when this is above/adjacent to the analysed façade; 9) Roof-Truss System – data on complex roof-truss system present in many of the surveyed churches and convents; 10) Damage Record and Crack Pattern - requires the identification of seismic damage, for each structural element of the façade and for any artistic asset attached to the façade; 11) Mechanism Identification - it requires the surveyor to indicate the mechanism/s that the surveyor is able to identify on the basis of the in situ observation and crack pattern recorded. For each section a reliability index is also scored, to provide a measure of the uncertainty associated with the input data.

Each failure mechanism corresponds to different constraint conditions between the façade analysed and the rest of the structure, hence a collapse mechanism can be univocally defined and its collapse load factor computed using an algorithm based on limit analysis. Specifically, the procedure implemented in FaMIVE, (Figure 1) first calculates the collapse load factor for each of the possible mechanisms for each façade in a building, then, using a set of structural criteria, identifies the one which is most likely to occur considering the combination of the largest portion mobilised with the lowest collapse load factor at building level. The version developed for the Philippines is based on a suite of 15 possible failure mechanisms, as shown in Figure 2 specialised to churches, towers and ordinary buildings.

The Italian seismic code for existing masonry structures OPCM 3274/03 (2003) & modifications OPCM 3431 (2005), Chapter 11 and Appendix C, codifies an approach that is based on the same assumption as the FaMIVE procedure, specifically a linear and a nonlinear kinematic approach to estimate the lateral capacity of the structure. It also indicates how to compute the factor of safety given the ultimate damage limit state. This can be used to define the relative risk that similar structures are exposed to given their inherent vulnerability and a given level of seismic hazard. This involves the use of the so-called structural behaviour factor, *q*, which is provided, for different structural types, by most capacity-based seismic codes standards, worldwide, such as Eurocode 8 (CEN, 2005).

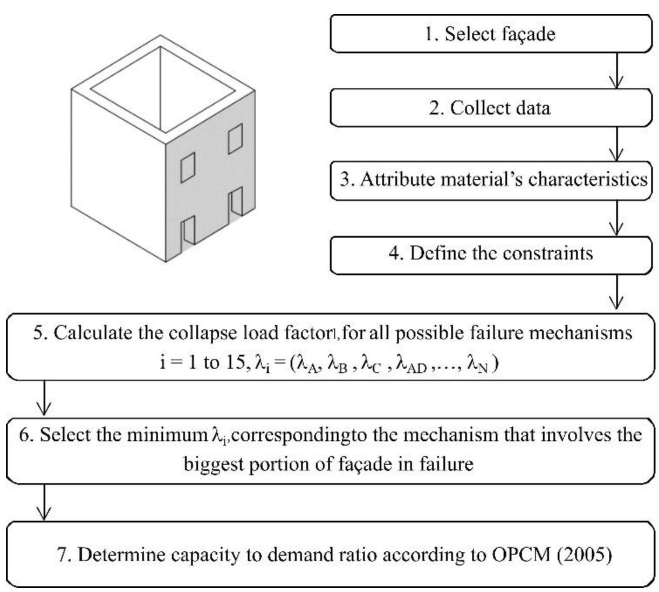


Figure 1. FaMIVE procedure outline

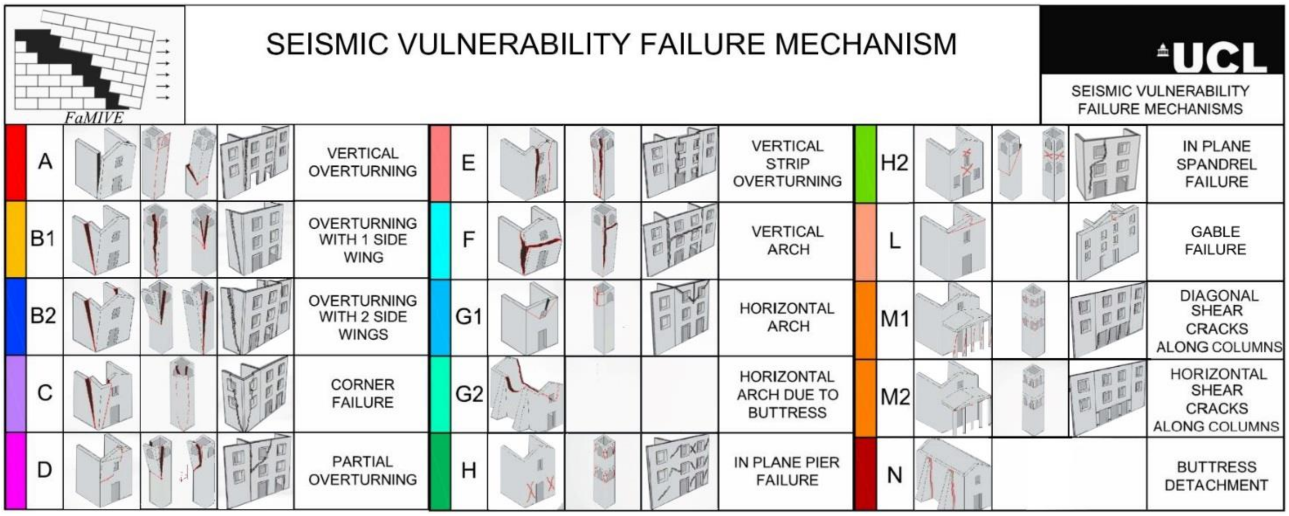


Figure 2. Suite of mechanisms analyzed by FaMIVE

A slightly modified approach is proposed in this application, which takes advantage of the computations made with FaMIVE and does not require to perform a full non linear push over analysis to determine the total capacity of the structure. According to this approach the safety for the ultimate limit state can be computed using Equation 1:

$$\gamma = \frac{a_0^*}{\frac{a_g S}{q}\left(1 + 1.5\frac{Z}{H}\right)} \tag{1}$$

where γ is the safety factor, a_0^* is the computed total lateral capacity of the building, as shown in Equation 2:

$$a_0^* = \frac{\lambda_{\min}\alpha_{\max} + \lambda_{\max}\alpha_{\min}}{\alpha_{\max}\alpha_{\min}} \tag{2}$$

where $\lambda_{\min}$ is the minimum collapse load factor associated to the building, calculated by FaMIVE, $\lambda_{\max}$ is the maximum collapse load factor associated to the building, and α is the proportion of total mass participating to each mechanism, as more extensively explained in the next section; a_g is the demand peak ground acceleration; S is the spectral amplification factor, which can reach a maximum of 2.5 or can be chosen according to the national guidelines for elastic demand spectra, depending on soil conditions; Z is the height from the building foundation to the center of gravity of the weight forces, whose masses generate horizontal forces on the elements which are mobilized in the mechanism; H is the total height of the building from the foundation; q is the structural behaviour factor, with $q = 2.0\ \alpha_u/\alpha_1$ for regular buildings, $q = 1.5\ \alpha_u/\alpha_1$ for irregular buildings, where α_1 is the horizontal seismic force multiplier for which, while all other design forces remain constant, the first masonry wall reaches its strength capacity (in shear or flexure), i.e. is the minimum collapse load factor computed with the FaMIVE approach, among all the walls analysed for a given building; αu is 90% of the horizontal seismic force multiplier for which, while all design forces remain constant, the building reaches its maximum strength capacity, i.e. is $0.9a_0$* with a_0* equal to the sum of the minimum and the maximum lateral capacity of all the wall analysed for that particular building. This approach allows taking into account the post elastic behaviour of the structure even though the ductility might not be known, as in the case of the priority heritage buildings, as exhaustive tests on the materials were not carried out.

D'Ayala (2005) [12] proposes a version of FaMIVE that uses the mechanism's characteristics to derive an equivalent non-linear single degree of freedom capacity curve to be compared to a spectrum demand curve, and eventually define performance points as illustrated in Figure 4.12. The post-elastic displacement is quantified in terms of simple stability considerations and bilinear pushover curves are obtained. Considering that performance assessment in terms of expected displacement better represents the post-elastic behaviour of the building, the approach has been implemented by defining limit displacement condition and compares these values to the displacement demands obtained through inelastic displacement spectra. To carry this out at the level of the building, the capacity curves obtained for each elevation are assembled together to determine the 3D behaviour of the structure as shown in the next section.

CASE STUDY: SAN NICHOLAS THE TOLENTINO COMPLEX, DIMIAO, BOHOL

The Dimiao Complex is made of two major buildings, church and convent, and two minor ones, sacristy and kitchen. The present Church was built between 1797 and 1815, during the three terms of the parish priest Fray Enrique Garcia de Santo Tomas de Villanueva. All the interior furnishing (retablos, pulpit, pipe organ) dates back to the 19th century; the belfries of the church have seven bells, the oldest being cast in 1841. The construction of the present Convent dates back to the years 1840s-1860s. The present rectory itself was completed under the supervision of Fray Manuel Carasusan de San Pascual, parish priest from 1842 to 1855 and from 1860 to 1864. Although much of it has been turned into a school, much of the old wood and building materials is still extant; the brick stove in the kitchen is one of the surviving examples of its kind. (Trota, 1991). The church, shown in Figure 4 has a simple Latin cross plan with a single nave and sacristy attached at the back of the presbytery. A narthex is not present, instead the façade is flanked by two octagonal bell towers and holds a wooden choir loft internally supported by an arched structure spanning the whole width of the church with two intermediate pillars. In alignment with the wall separating the main church body from the sacristy externally there is a large buttress on each side. No other buttresses are present on the long longitudinal walls, only some pilasters. The main façade and the two facades of the transepts have imposing gables. All the other walls show sign of timber ties anchored to the masonry through pegs. However these ties must have been cut at some point in the past. The church also has a lightweight vaulted false ceiling, hiding the roof truss system. This is composed of two orders of rafter, differently inclined, and connected by a single collar tie, made of Molave wood. The current roof cover is made of light thin weight metal sheets.

The Convent, shown in Figure 5, is a two storeys building characterized by an L-shaped plan. The ground floor is made of solid rubble stone and a colonnade portico, while the second floor is built of a system of large timber poles, connected by beams and infilled by panels made of timber posts and cane lath. The roofing system of the Convent is similar to the one of the Church.

Hazard intensities at the site

According to the procedure explained in the section 6.3 of "Multi-hazard risk assessment manual of the Philippines' built heritage assets" (ARS Progetti et al., 2016), for earthquake the intensity measure of reference is PGA, taken as 0.44g for 475 year return period, as per indication for zone 4 and soil type D of the Philippines earthquake code.

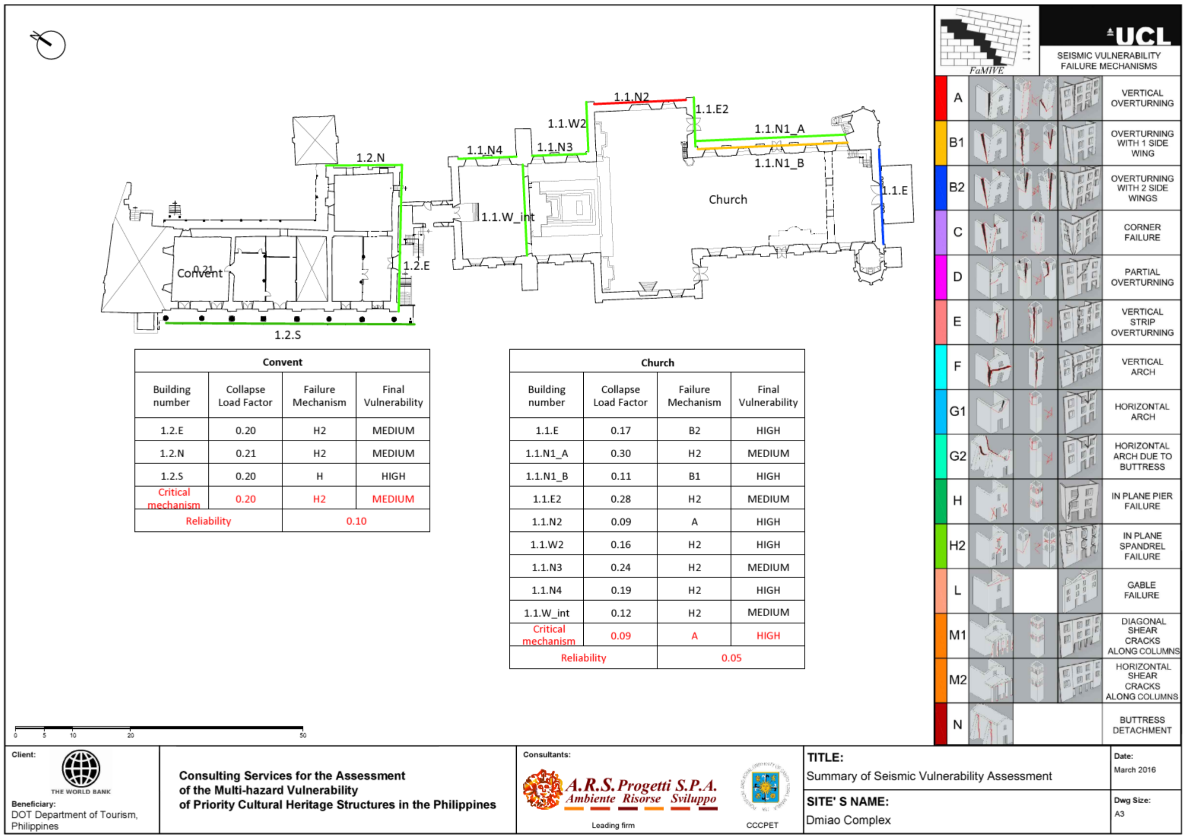
Figure 4-5. Main Façade of San Nicholas de Tolentino Church and Convent

SEISMIC VULNERABILITY ASSESSMENT

According to the methodology explained in the section above, the data of eight facades of the Church and three facades of the Convent have been collected and processed within the FaMIVE procedure.

Figure 6 summarizes the vulnerability of each analyzed façade. Values of collapse load factor, failure mechanism and final vulnerability are computed for each façade and a final critical mechanism is identified for the overall building. For the main façade and the nave lateral wall different conditions are considered, by taking or not into account the alcoves as openings. The most realistic case is the one with one full opening at ground floor and three at the second level yielding a mechanism B2 and collapse load factor λ= 0.17g. For the nave lateral wall, as already mentioned, there is evidence of past insertion of ties. In the current state the mechanism is B1 with λ =0.11g, while in reinstating the ties the mechanism obtained would be H2 with λ = 0.30, hence a substantial increase in resilience. The most critical value of λ is 0.09 g, corresponding to high vulnerability, for the north side façade of the transept associated to mechanism A. The façade is characterized by the presence of a gable, whose weakening action is worsened by the absence of lateral connections. Although the building has not experienced any partial collapse, there are clear vertical cracks that show the detachment of the transept facades from the side walls. The convent walls have a much more homogenous response, in agreement with the greater homogeneity of geometry and structure of the walls. The collapse mechanism is consistently H or H2 and the collapse load factor range between 0.2 and 0.22g.

From the above description it is evident that given the large size of the church, the different architectural portion of the church, main nave, transepts, ambulatory and sacristy, have relatively independent seismic response. This is confirmed by both the different crack patterns observed and the collapse mechanism obtained with FaMIVE. Following this observation, the main façade and side walls can be treated as a macroelement, similarly the transept façades with their return walls and finally the back façade of the church and the ambulatory. This approach assumes that the gables façades will have substantially an out of plane behavior, while the side walls will exert mainly an in-plane response which will help restraining the façades overturning. The compounded capacity curves obtained with these assumptions for each portion of the church are shown in Figure 7. It is evident the weaker capacity of the transept area with respect to the main façade and ambulatory portions of the church.



Convent			
Building number	Collapse Load Factor	Failure Mechanism	Final Vulnerability
1.2.E	0.20	H2	MEDIUM
1.2.N	0.21	H2	MEDIUM
1.2.S	0.20	H	HIGH
Critical mechanism	0.20	H2	MEDIUM
Reliability		0.10	

Church			
Building number	Collapse Load Factor	Failure Mechanism	Final Vulnerability
1.1.E	0.17	B2	HIGH
1.1.N1_A	0.30	H2	MEDIUM
1.1.N1_B	0.11	B1	HIGH
1.1.E2	0.28	H2	MEDIUM
1.1.N2	0.09	A	HIGH
1.1.W2	0.16	H2	HIGH
1.1.N3	0.24	H2	MEDIUM
1.1.N4	0.19	H2	HIGH
1.1.W_int	0.12	H2	MEDIUM
Critical mechanism	0.09	A	HIGH
Reliability		0.05	

Figure 6. Summary of Seismic Vulnerability Assessment – Dimiao Complex

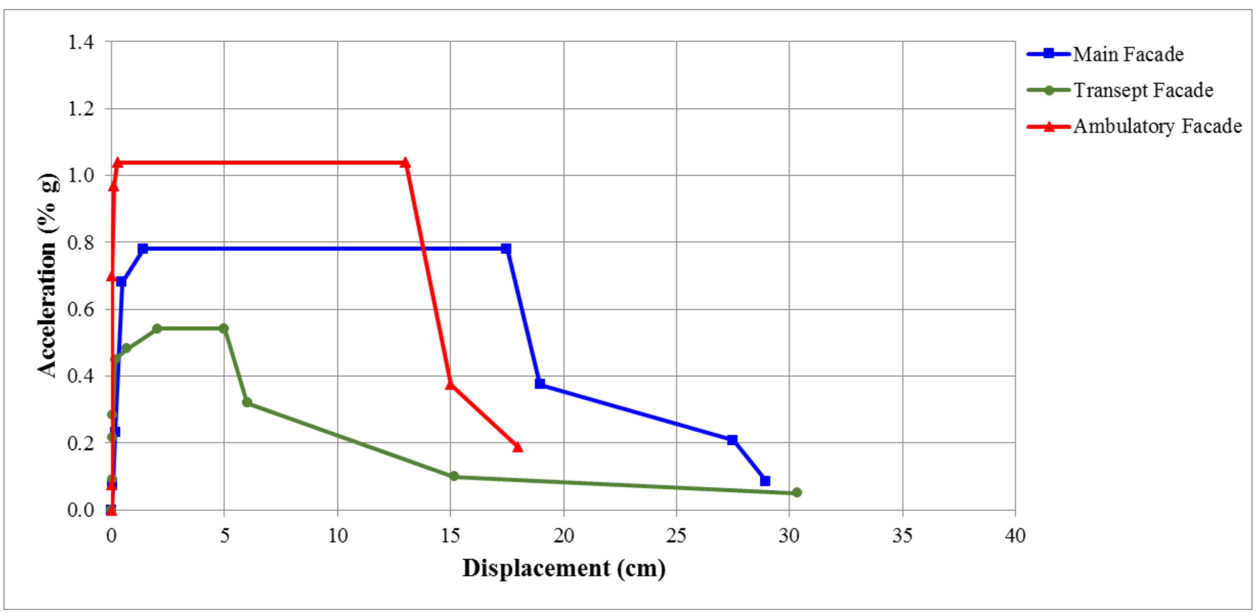


Figure 7. Macroelement capacity curves – Dimiao Complex

The three capacity curves shown in Figure 7 provide a clear picture of the global capacity of the Dimiao church. The threshold points representing the various damage limit states of each of the curves can be used to derive median and standard deviation and determine fragility functions representative of the probability of the building to be in different states of damage. In order to derive the performance points we use the N2 approach (Fajfar 1999) with the equal displacement condition, to determine the intersection between the capacity curve and the spectral demand at the site. Figure 8 shows the results an example for the main nave area.

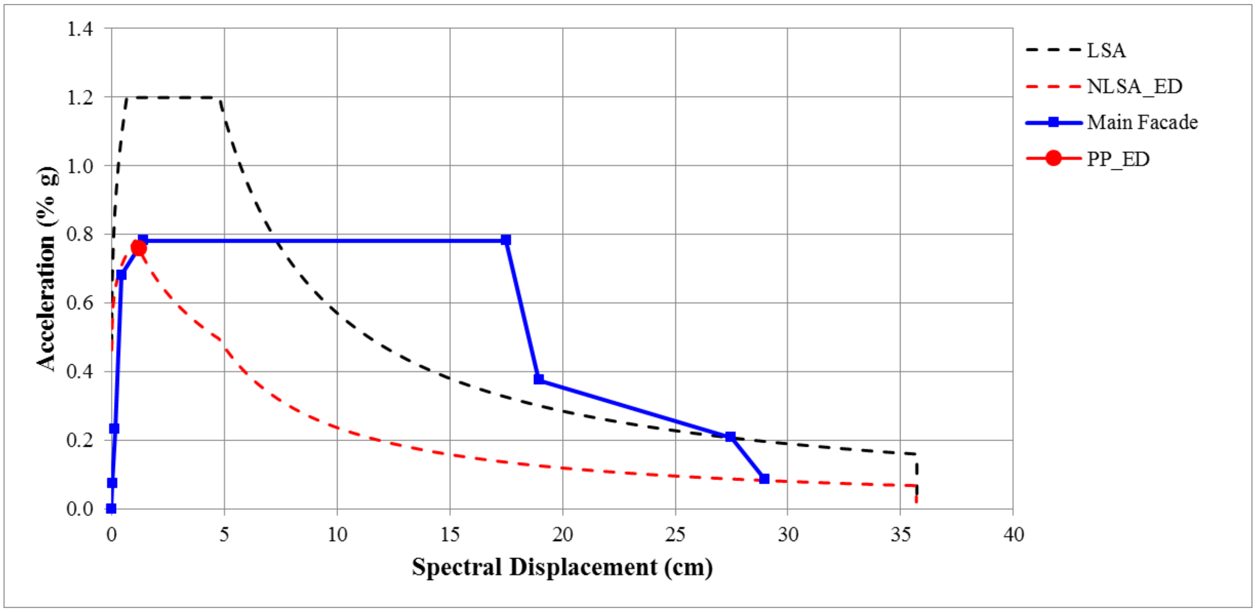


Figure 8. Performance point obtained for the macroelement representing the main main nave of Dimiao church, using Philippines Earthquake Code design spectrum

Finally probability of each of the 3 macroelements to be in a given damage states can be visualised by making use of the performance point and the fragility functions expressed in terms of displacement. These are shown in Figure 9.

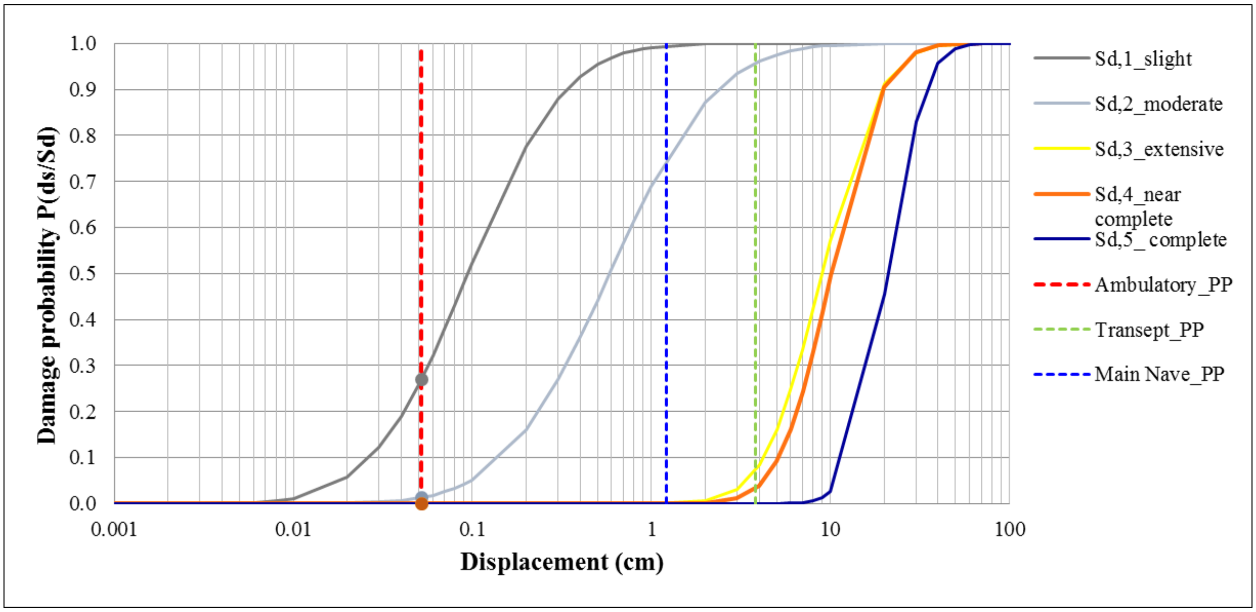


Figure 9. Fragility function and performance points for the macroelemnts of Dimiao Church

CONCLUSIONS

The paper presents a comprehensive methodology to assess the seismic impact of earthquake on priority heritage buildings in the Philippines as part of a larger framework for multi-risk assessment. The methodology is adaptable to different levels of refinement of the data available relating to construction techniques and material characteristics. The reliability framework set in place allows to measure the level of uncertainty associated with the quality of input data. A risk assessment procedure is always only as good as the worst of its components and, while some of the aspects of the vulnerability have been developed thoroughly, limitations are inherent due to the current availability of the information relating to the hazard. An important benefit of the procedure developed is its applicability to different heritage building typologies, namely, churches, towers, houses and convents. The application to the case studies, of which Dimiao is just an example, shows that it is possible to conduct an engineering grounded Performance based assessment to accurately determine the seismic vulnerability of important heritage assets of large scale where different part of the buildings can exhibit independent seismic response. Moreover, in the case of the Philippines heritage, the current effort can be considered as one of the first studies of this type and indeed the documentation of the construction fabric and techniques collected here will form the first seed of an integrated database, which can be used to assess these heritage assets under a variety of hazards. Hence, this study represents a first and pioneering approach to determine the seismic risk posed to a large number of valuable historic assets distributed over a vast territorial scale. Its applicability has been demonstrated through the evaluation of more than 50 different buildings to produce a support tool for the prioritization and allocation of resources for repair, strengthening and mitigation.

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The main author Prof. Dina D'Ayala has 25 years' experience of working in the field of seismic assessment and retrofit of heritage building worldwide, having consulted for main Cultural Heritage departments in countries such as India, Nepal, the Middle East and Italy. The long list of authors reflects the partnership and the collegial and interdisciplinary approach sought and brought to bear in the present project.