ICONHIC 2016
1st International Conference on Natural Hazards & Infrastructure
28-30 June, 2016, Chania, Greece

Assessment of the Multi-Hazard Vulnerability of Priority Cultural Heritage Structures in the Philippines

D. D'Ayala[1] , C. Galasso, V. Putrino
University College London, UK

D, Fanciullacci, P. Barucco, V.Fanciullacci, C.Bronzino
ARS Progetti, S.P.A. Rome, Italy

E. Zerrudo, M. Manalo, C. Fradiquela, J.Regalado
CCCPET, St. Thomas University, Manila, Philippine

L. Garciano, A. Oreta, K. Yu
De La Salle University, Manila, Philippines

ABSTRACT

At the end of 2013 two consecutive 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 vulnerability assessment of heritage buildings, many of which were irretrievably lost in the disasters. The Philippines' Department of Tourism engaged ARS Progetti S.P.A., Rome, Italy, in collaboration with 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"*, supported by experts from University College London 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.
This paper presents the general methodology followed and the tailored procedures devised to assess seismic, typhoon and flood vulnerability of selected historic buildings. Data collection and analysis, from structural characterization to multi-risk evaluation, are illustrated through the presentation of a case study.

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), 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.

[1] Corresponding Author: Prof. Dina D'Ayala, *University College London, d.dayala@ucl.ac.uk*

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, and 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 starts with a brief overview of applicable methods for vulnerability assessment of historic buildings for individual hazards, followed by the hazard profile for the Philippines. Then, the detailed steps of the adopted methodologies are presented and their application shown for the compound of St. Nicola da Tolentino Church and Convent in Dimiao, on the island of Bohol.

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 straddles 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.

REVIEW OF AVAILABLE METHODS FOR MULTI-HAZARD VULNERABILITY ASSESSMENT

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 inferred 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. In this study only a value of peak ground acceleration (PGA) was provided to quantify the hazard at the site and hence the analysis is limited to the quantification of the structure collapse load factor. Further details are provided in the next section.

Wind vulnerability assessment
Pita et al. (2015) present a comprehensive review of methods to assess building vulnerability to extreme wind, in particular hurricanes. The review identified five main types of assessment: past-loss data, enhanced damage data, heuristic, physics, and simulation. The applicability of past-loss data-only vulnerability methods proved insufficient for the diversity of situations faced in actual wind risk assessment exercises. Therefore, modelers complemented this method with engineering and meteorology expert knowledge, yielding enhanced-data models. Expert opinion and subjective probabilities drive the heuristic models; these were short lived in the United States, but are still used when data are scarce. Component-based methods were developed as a more realistic alternative to enhanced-data models by assessing vulnerability within an engineering framework complemented with expert opinion. Simulation models enhanced the physical models with a probabilistic simulation of the wind-structure interaction and more realistic assessment of the hazard. In particular, the HAZUS-MH Hurricane Model (Vickery et al., 2006a,b) represents a well-established example of simulation-based model for wind vulnerability assessment. A modified approach of such method, location and typology specific, has been adopted in this study.

Flood vulnerability assessment
At present, there is a rather limited literature on flood risk assessment techniques suitable for the evaluation of damage and loss incurred to historic buildings located in flood-prone areas. Flood damage to buildings and contents are dependent on several variables in relation to the flood events.
Semi-empirical methods for flood damage assessment require parameters such as inundation level, flow velocity, flood duration and building characteristics (e.g., HAZUS-MH Flood). In empirical approaches, large dataset of buildings are required to account for different construction materials. Different building types are then allocated to different flood vulnerability classes with a predetermined range of probable scatter dependent on qualitative parameters. Owing to considerable uncertainty in predicting possible extent of damage, such tools are best suited for damage prediction of large building stocks in urban areas (Schwarz and Maiwald,

2008). For historic buildings, reference was made to PARNASSUS V1.0 proposed by Stephenson and D'Ayala (2014). This entails calculating a vulnerability index VI_F by scoring a specific set of vulnerability parameters relevant to historic buildings: age, listed status, use, footprint, number of storeys, materials and structure, condition, position of openings. The attributes of each indicator can be tailored for different geographic-cultural settings. They provide a qualitative estimate of the vulnerability of the building in presence of water, whether caused by flooding or by storm surge. A new improved version of this procedure has been applied to the Philippines' project and is presented in the next section.

METHODOLOGIES ADOPTED IN THE MULTI-HAZARD VULNERABILITY FRAMEWORK

Seismic vulnerability assessment

The FaMIVE approach (D'Ayala & Speranza 2003) has been developed in the last 15 years, starting from a procedure to identify possible and most probable collapse mechanisms for masonry façades with diverse level of lateral constraint, 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 construction details and fabric of load bearing masonry and floors/roof layout and structural elements. 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 shown in the companion FaMIVE Manual 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, (Figure1) 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).

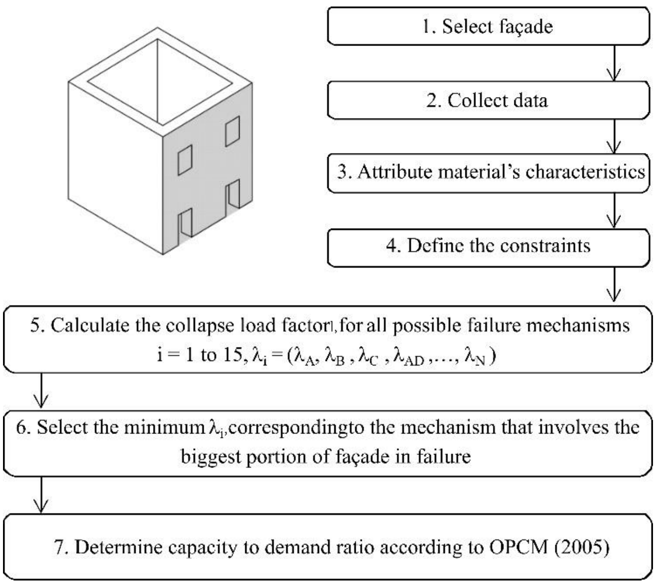


Figure 1. FaMIVE procedure outline

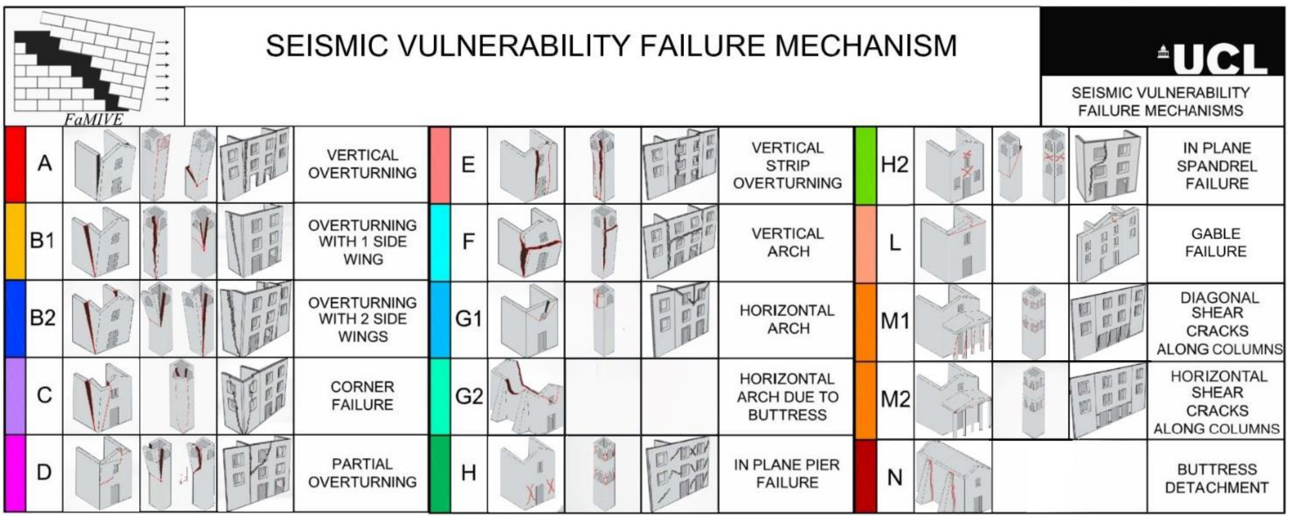


Figure 2. Suite of mechanisms analyzed by FaMIVE

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 push over analysis to determine the total capacity of the structure. According to this approach the safety for the ultimate limit state (SLU) 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.

Typhoon vulnerability assessment

Post-disaster surveys in the Philippines and around the world reveal that most economic losses in high wind-hazard areas can be related to breach of the building envelope. In particular, the breach of envelope includes roof panel uplift, roof-to-wall connection failure, roof system damage, and rupture of glass in windows and doors due to excessive pressure or missile impact. The severe rain accompanying high wind can cause severe water damage to the building contents after the envelope of the building is breached. Furthermore, the breach of the envelope can lead to significant increase of wind pressure on interior surfaces, leading to progressive failure of other portions of the building and even failure of the structural system as a whole in some instances. Specifically, many roofs in the Philippines, especially in low income areas and in informal settlements (including cultural heritage buildings), are built using wood frames and galvanized iron sheets. During strong typhoons these roofs are highly vulnerable to pullout and pullover failure modes: there is a need assess the vulnerability of roofs to extreme wind speeds especially non-engineered roof construction.

To this aim, the physical damage to a roof system subjected to winds is modeled here using an engineering-based load and resistance approach, where once the wind-induced loads acting on a building are computed, the physical damage model to the building is estimated in terms of roof failure. Given the quality of the available data, the uplift capacity of the roof is limited by the assembly's weakest link, i.e., a series system is considered. In particular, the considered limit states correspond to 1) pullout failure of the first fastener (screw or nail), and 2) pullover failure of the first panel. In fact, once failure of a single fastener occurs, the load is distributed to the surrounding fasteners causing failure to propagate thought the panel; similarly, there is a strong correlation between panel removal and subsequent damage to the building structure.

The assumptions in the analysis represent a mix of prescriptive and experience-based practice, consistently with state-of-the-art research in the field of wind vulnerability.

The proposed methodology covers the (typhoon) wind load determination, the surveying of various roofing systems for the case-study buildings, and the analysis of the vulnerability of those roofing systems through comparison between uplift resistances and wind loads, using a probabilistic approach and structural reliability concepts. In particular, uncertainties in structural component and system resistances (i.e., capacity) are modeled probabilistically while the gravity and wind load effects (i.e., demand) are considered deterministic and modeled according to the National Structural Code of the Philippines (NSCP, 2010). Plain Monte Carlo method is used for simulating random values of every variable (i.e., oven-dried specific gravity of wood, nail/screw diameters, nail/screw penetration, panel thickness, tensile strength of the panel) affecting the roof uplift resistance for both failure modes. The study made extensive use of surveying and experimental testing in the literature to obtaining the necessary data required for the analysis of roof properties. The conceptual frameworks of the vulnerability assessment used here is summarized in Fig.3. Details of the procedure are described in ARS Progetti et al., (2016) and Alvarez et al., (2013). Fragility functions, i.e., probability of pullout/pullover failure vs basic wind speed, are also developed for each building as a function of wind speed using the considered limit states and the methodology described above.

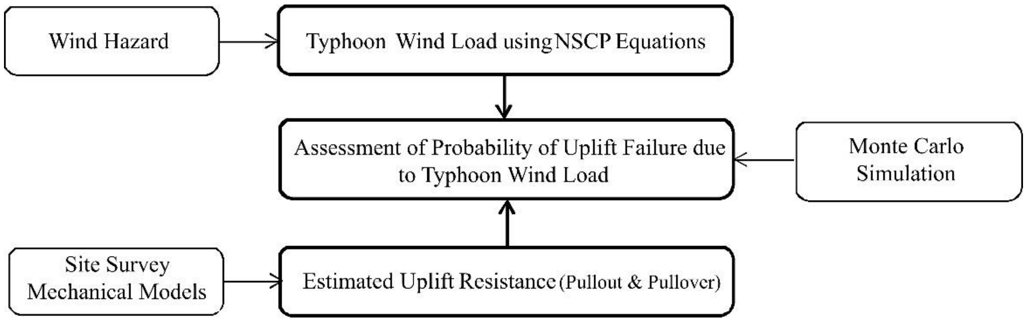


Figure 3. Conceptual framework for the wind vulnerability assessment (adapted from Alvarez et al., 2013)

Flood vulnerability assessment

To assess the flood vulnerability of the Philippines' Priority Heritage buildings the first step entails carrying out an assessment of eight quantifiable, yet qualitative vulnerability indicators as shown in Table 2. For each parameter a range of attributes varying between 3 and 5 was determined through logical derivation of the maximum possible number of responses and these were assigned a Vulnerability Rating (VR) on a scale from 10 to 100. The scale is divided into equal, un-weighted score ranges according to the number of attributes, lowest vulnerability being assigned the value 10, and highest 100 (Table 2). No attribute has been assigned the value 0, since it is considered that every historic building feature measured indicates some degree of vulnerability to the hazard, however in order that all of the descriptors contribute equally a lower boundary of 10 is applied to the rating scale for all descriptors except the land slope.

The level of protection of a building represents a formal acknowledgement of the historic value of the structure, and is designed to ensure that the heritage it encompasses is safeguarded. Buildings that are recognised as of World Heritage status and benefit from international protection framework are usually subjected to more strict conservation requirements in recognition of their higher heritage value. These buildings are usually also rarer and culturally more important, so flood damage to any of their parts (structural or non-structural) would results not just in physical loss but also in considerable loss of value. Other buildings might be protected at national or only local level in reason of their perceived heritage status. Their associated loss of value can be considered of a lower entity. Age and listed status combined therefore provide a measure of the value of the cultural asset. The typology is an indication of the use of the buildings and its value to the community. Hence the ranking of churches, convents, towers and private houses, reflects their value loss to the community. The materials and structural system relate to the susceptibility of the building fabric to be damaged by the flood, whilst the condition of the building is a measure of the resilience of the structure to the stresses placed upon it by this or other hazards. The footprint of the building and its number of storeys provide the metrics of the asset at risk. Finally an indicator for the local layout of the land around the building is also sought, so that this is a measure of how quickly water is likely to run off or stagnate after a flooding event.

The ranking of the attributes in each vulnerability indicator is guided by the following considerations:

- Older buildings, and those with higher listing classification present a more valuable asset and are therefore of higher vulnerability
- In the presence of superficial foundations a building with more storeys over the same footprint, will be more susceptible to the stress differentials generated by saturation and drying of the foundation soil during and after a flood.
- Lateral capacity of wall structure, combined with absorption capacity of building materials indicates solid stone masonry to be the least vulnerable, and timber-frame to be most.
- Buildings in overall poorer condition, with less evidence of repair and maintenance, will be more vulnerable to inundation, due to pre-existing defects in the structure and fabric.

This method can be compared to vulnerability indices frequently utilised in flood risk literature (e.g., Balica et al, 2009; 2012; Fedeski & Gwilliam, 2007; Schwarz & Maiwald, 2008). One key aim of this methodology is to provide a simple and hence widely applicable means of holistically assessing the vulnerability of a heritage building, so that it can be considered appropriately when comparing the flood risk to other risks, locally and across the region or geographical area of interest. Therefore the approach has been to combine the responses for each parameter to give a single measure of vulnerability, by defining a Vulnerability Index (*VI*).

Table 2. Vulnerability Indicators (adapted from Stephenson & D'Ayala (2014)

Parameter	Attribute	VR	Parameter	Attribute	VR
Protection	International	100	*Condition*	Poor	100
	National	55		Mediocre	70
	Local	10		Good	40
Age	17th century	100	*# of Storeys*	4	100
	18th century	77.5		3	70
	Early 19th century	55		2	40
	Late 19th century	32.5		1	10
	20th century	10	*Construction*	All timber	100
Typology	Church	100		Masonry and timber	70
	Convent	70		Multi leaf Masonry with poor core	40
	Tower (other minor building)	40		Multi leaf Masonry with solid core	10
	Private houses	10	*Foot Print [m2]*	3000<FP<6000	100
Land Slope	Concave	100		1000<FP<3000	70
	Flat	65		500<FP<1000	40
	Convex	30		FP<500	10

This is the value obtained from summating each attribute value (VR_j) for the parameters contributing to vulnerability to give a total ranging between 100 and 800, as shown in Equation 3

$$100 \leq \left(VI_F = \sum_j VR_j \right) \leq 800 \qquad (3)$$

The vulnerability index VI_F can then be normalised to base 100, and 4 intervals can be identified within the range of normalised values to provide a vulnerability classification in 4 corresponding classes according to 25% percentiles, as shown in Table 3. Further to the qualitative analysis a quantitative method can also be used, by comparing the minimum height of breachable defence, i.e. typically the door threshold level above ground datum, with the expected flood depth above ground datum. For the Priority Heritage buildings of the Philippines it was often noted that the internal floor datum was lower than the external ground level, so this has been used as local reference datum to determine the maximum height of water in the building, corresponding to the hazard level computed by NOHA (A.M.F. Lagmay, 2014). Both riverine floods and storm surge have been considered, depending on the exposure of the specific site.

Table 3. Correlation between probability of failure and classes of vulnerability for flood

Statistical grouping	Vulnerability classification
0 – 25%	Low
25 – 50 %	Medium – Low Medium
50 – 70 %	Medium High
75 – 100 %	High

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, 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.

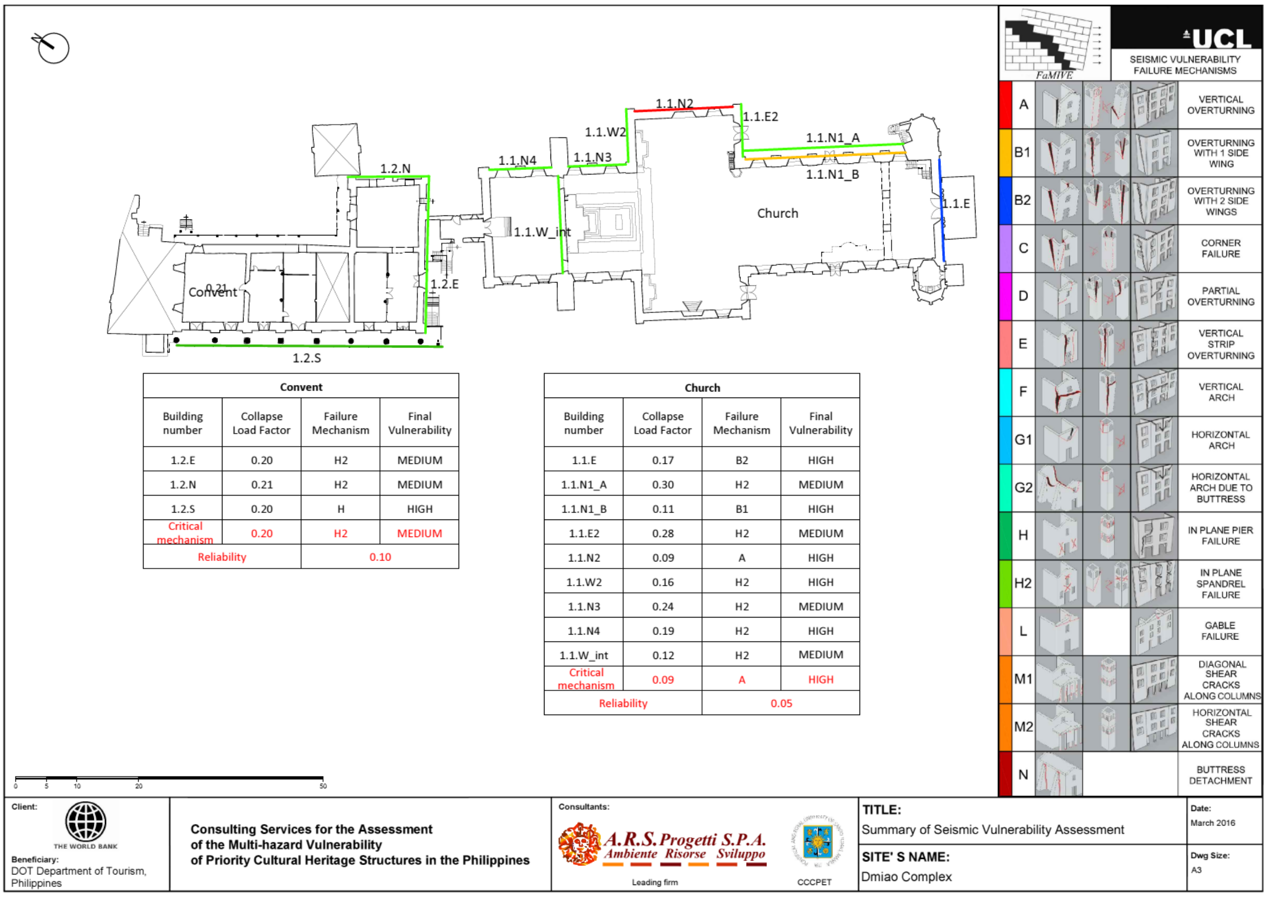
Hazard intensities at the site
According to the procedure explained in the section 6.3 of "Multi-hazard risk assessment manual of the Philippines' built environment" (ARS Progetti et al., 2016), the following reference values for the intensity of earthquake, typhoon and storm surge have been considered:

- For earthquake the intensity measure of reference is PGA, taken as 0.3g for 475 year return period.
- For typhoon a basic wind speed of 200 kph, corresponding to a 3s gust speed at an elevation of 10m on open terrain for a return period of 50 years, according to the NSCP (2010).
- Storm surge water level: according to the NOAH (A.M.F. Lagmay, 2014) hazards maps, for the most hazardous Storm Surge Advisory Level, SSA 4, the heritage site would be inundated to a depth greater than 1.5 m, classified as high hazard.

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

Results for single hazard vulnerability

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.



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 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.

Typhoon Vulnerability Assessment

The assessment is based on the interpretation of the data collected on site, as well as technical drawings, where available, and engineering judgment. The reliability of the data collected on site is considered low. Fasteners and panels at the roof corners are investigated as they are subjected to the highest wind uplift forces: the local pressure coefficients are the highest of any point on the roof surfaces. The plain Monte Carlo method is used for simulating 1,000 random values of the considered random variable; for each variable affecting the roof uplift capacity, a normal probability distribution model is used. As an example, the generated 1,000 random samples of the roof uplift resistances (pullout and pullover) per purlin are shown in the form of corresponding histograms for Dimiao Church in Figure 7a,b. The uplift load per purlin assuming a basic wind speed of 200kph, i.e., the design wind speed stipulated in the NSCP, is shown in the same figure (vertical red dashed line). By ‘counting’ the number of simulated resistance values less than the uplift load per purlin (i.e., the simulated values falling to the left side of the vertical red dashed line) and diving it by the total number of simulation (1,000), the probability of pullout failure of fasteners (screw/nail) for the specific example is 5% while the probability of pullover failure of panel is 1%. Fragility functions for both buildings are shown in Figure 7c (for pullout failure mode) and Figure 7d (for pullover failure mode).

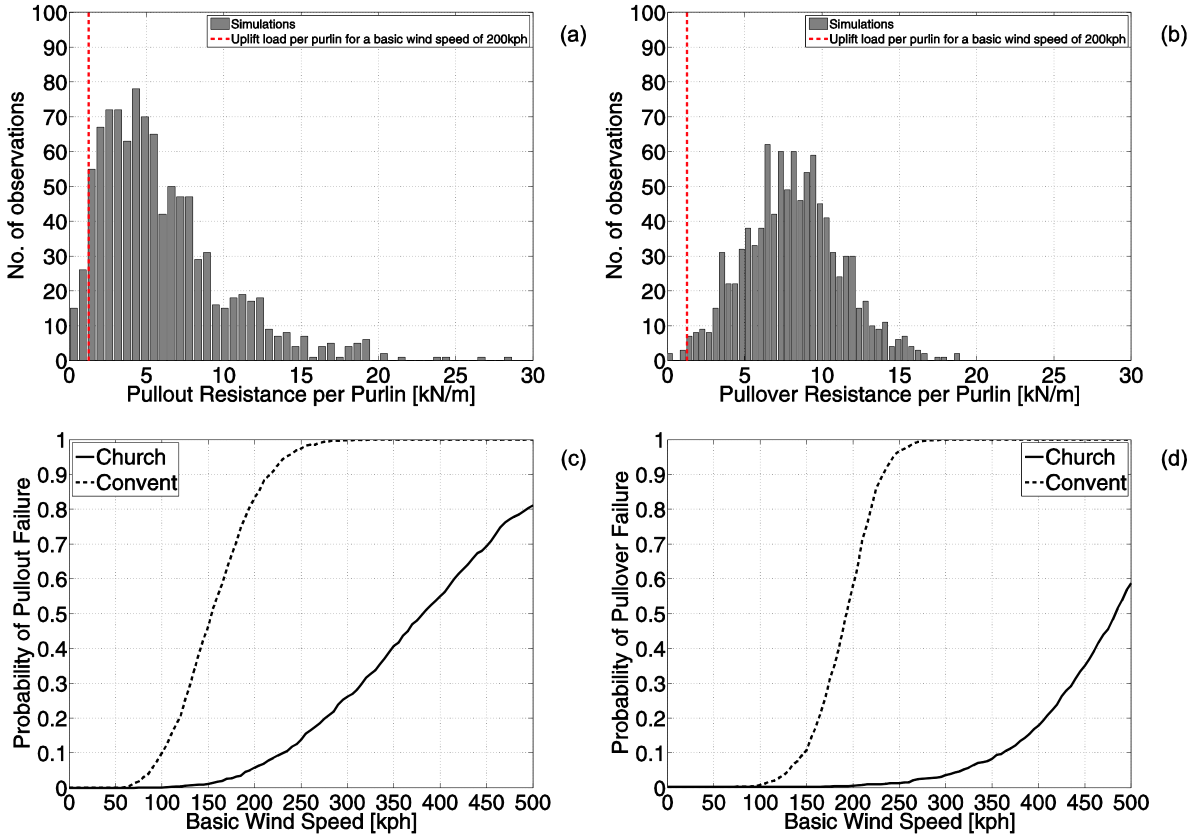


Figure 7. Summary of Wind Vulnerability Results – Dimiao Complex

It is worth noting that the results of the analysis are based on conservative assumptions and strongly depend on the poor quantity and quality of the available data. An improved data collection is highly recommended before recommending/considering any mitigation strategy for wind risk reduction. Also, recent studies suggest lower design wind speed for the considered location, thus the actual risk values are expected to be lower than the considered one. An improved wind hazard assessment for the consideration location is highly desirable. For a more detailed explanation of the results and their interpretation refer to Chapter 5 of the "Multi-hazard risk assessment manual of the Philippines' built environment" (ARS Progetti et al., 2016).

Flood Vulnerability Assessment

For Dimiao Compound the scoring of the parameters introduced above are presented in Table 4 and Table 5:

Table 4. Vulnerability Rating

Age	Protection	Typology	Construction	Condition	Storeys	Footprint	Land Layout
19 E	NAT	CH	H1	M	2	1762	CC
19 E	NAT	CO	H1	M	2	719	CC

Table 5. Vulnerability Scores

Age	Protection	Typology	Construction	Condition	Storeys	Footprint	Land Layout	Total Vulnerability
55	55	100	10	70	40	70	100	500
55	55	70	10	70	40	50	100	450

The resulting Vulnerability Index for the two buildings in the Dimiao Compound is shown in Table 6 together with the estimate of the hazard and the risk assessment.

Table 6. Risk Assessment

Building ID	Vulnerability Index	Vulnerability Class	Hazard	Water differential	Inundation Risk	Damage Loss
St. Nicholas de Tolentino Parish-Dimiao Church	6.3	Moderate - High	HIGH	2.5	HIGH	HIGH
St. Nicholas de Tolentino Parish-Dimiao Convent	5.6	Moderate - High	HIGH	2.4	HIGH	HIGH

CONCLUSIONS

This study presents a comprehensive methodology to assess the impact of earthquake, windstorms and floods on priority heritage buildings in the Philippines. Although the proposed method endeavors to assess the vulnerability of buildings subjected to multiple sources of hazard by means of state-of-the-art approaches, the intrinsic nature of each of the three procedures is such that they are not yet completely homogenized. Multiple and diverse issues remain to be addressed, such as a more detailed study of the construction techniques, the need to collect more detailed data to fulfil some of the modelling requirements, the development of a full analytical approach for the flood hazard. 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 modest quality of the information relating to the hazard. Nonetheless present development in the Philippines, such as the Department of Science and Technology's Project NOAH will provide much greater potential in the near future. An important benefit of the procedure developed is its applicability to different heritage building typologies, namely, churches, towers, houses and convents. This notwithstanding, improvements are still needed to produce a more integrated data collection protocol, which can address directly the vulnerability to all three hazards. The application to the case studies, of which Dimiao is just an example, has brought to light the well-known difficulty of collecting some of the essential data required to accurately conduct the vulnerability assessment in buildings of high historic value, where opening-up is not allowed or not possible, given the resources available. Indeed in a level 2 vulnerability assessment, such as the one proposed here, semi-destructive or destructive investigations, albeit very contained, are usually not at all considered. This is sometime remedied by referring to existing databases of building structural typologies to reduce uncertainties, however 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 such a database. Hence, this study represents a first and pioneering approach to assess the risk posed by independent hazards 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 for prioritization and allocation of resources for repair, strengthening and mitigation.

REFERENCES

A.M.F. Lagmay, Project NOAH Storm Surge Team. (2014). Devastating Storm Surges of Typhoon Yolanda. *DOST-Project NOAH Open-File Reports*, Vol. 3 (2014), pp. 82-95. ISSN 2362 7409.

A.M.F. Lagmay. (2012). Disseminating near real-time hazards information and flood maps in the Philippines through Web-GIS. *DOST-Project NOAH Open-File Reports*, Vol. 1 (2013), pp. 28-36. ISSN 2362 7409.

Alvarez, I. P. R., Colobong, J. A. M., Decal, C. Q., Tan, A. B. S. (2013). Pull-Out and Pull-Over Failure Probability of Residential House Roofs due To Extreme Wind Speeds: a Case Study in Malate, Metro Manila. BSc Dissertation. Gokongwei College of Engineering of De La Salle University – Manila, Philippines.

ARS Progetti, CCCPET, UCL EPICentre, UDLS, Multi-hazard assessment manual of Philippines' built heritage, Report for the Department of Tourism, Philippines 2016

ASCE. (2014). "Seismic evaluation and retrofit of existing buildings." ASCE 41-13, Reston, VA

Association of Structural Engineers of the Philippines, Inc. National Structural Code of the Philippines (NSCP) Volume 1. 6th Edition. ASEP Inc., Quezon City. 2010.

Balica SF, Douben N, Wright NG. 2009. Flood vulnerability indices at varying spatial scales. Water Science and Technology: 2571-2580.

Balica SF. 2012. Applying the flood vulnerability index as a knowledge base for flood risk assessment, Delft University.

CEN (2005) Eurocode 8: Design of Structures for Earthquake Resistance. Part 3: General Rules, Seismic Actions and Rules for Buildings, prEN 1998-1. CEN: Brussels, Belgium.

D. D'Ayala and E. Speranza (2003) Definition of collapse mechanisms and seismic vulnerability of historic masonry buildings, Earthquake Spectra, vol. 19, no. 3:479–509.

D'Ayala D. (2013) Assessing the seismic vulnerability of masonry buildings. Handbook of seismic risk analysis and management of civil infrastructure systems. Woodhead publishing, Oxford, pp 334–365

D'Ayala D., Putrino V. FaMIVE MANUAL, © 2016 Annex to Multi-hazard assessment manual of Philippines' built heritage, 2016.

D'Ayala D. (2005), "Force and Displacement Based Vulnerability Assessment for Traditional Buildings"; Bulletin of Earthquake Engineering, Vol.3, Springer, pp. 235-265

Direttiva del Presidente del Consiglio dei Ministri del 12/10/2007, pubblicata in G.U. n. 24 del 29 gennaio 2008, per la valutazione e la riduzione del rischio sismico del patrimonio culturale con riferimento alle norme tecniche per le costruzioni (in Italian)

Fedeski, M., Gwilliam, J., 2007. Urban sustainability in the presence of flood and geological hazards: The development of a GIS-based vulnerability and risk assessment methodology. Landscape and Urban Planning, Vol. 83, No. 1, pp. 50-61

Garciano, L. E., Alvarez, P., Colobong, J., Decal, C., and Tan, A.: Mapping the Vulnerability of Low-Cost House Roofs in Malate, Metro Manila due to Extreme Wind Speeds, 13th East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-13), Hokkaido, Japan, September 11 - 13, 2013.

Nadal, N., Zapata, R., Pagán, I., López, R and Agudelo, J., (2010) Building Damage due to Riverine and Coastal Floods. Journal of Water Resources, Planning and Management 136(3), pp. 327-336.

NSCP (2010) National Structural Code of the Philippines. Volume I: buildings, towers and other vertical structures, 6th Edition, 2010, First Printing.

OPCM (2003) OPCM 3274—Primi elementi in materia di criteri generali per la classificazione sismica del territorio nazionale e di normative tecniche per le costruzioni in zona sismica, 20/03/2003 (in Italian)

OPCM (2005) OPCM 3431—Ulteriori modifiche ed integrazioni all OPCM 3274/03, 09/05/2005 (in Italian)

Pita, G., Pinelli, J., Gurley, K., and Mitrani-Reiser, J. (2014). "State of the Art of Hurricane Vulnerability Estimation Methods: A Review." Nat. Hazards Rev., 10.1061/(ASCE)NH.1527-6996.0000153, 04014022.

Schwarz, J., Maiwald, H., (2008) Damage and loss prediction model based on the vulnerability of building type. 4th International Symposium on Flood Defence: Managing Flood Risk, Reliability and Vulnerability, Toronto, Ontario: Canada.

Stephenson, V., & D'Ayala, D. F. (2014). A new approach to flood loss estimation and vulnerability assessment for historic buildings in England,. Nat. Hazards Earth Syst. Sci., 14 (5), 1035-1048. doi:10.5194/nhess-14-1035-2014

Trota, J. Regalado. Simbahan: Church Art in Colonial Philippines, 1565-1898. (1991).Makati: Ayala Foundation.

Vickery, P. J., Lin, J. X., Skerlj, P. F., Twisdale, L. A., and Huang, K. 2003. "HAZUS-MH hurricane model methodology. I: Hurricane hazard, terrain and wind load modeling." Nat. Hazards Rev., 7(2):82–93.

Vickery, P. J., Skerlj, P. F., Lin, J. X., Twisdale, L. A., Young, M. A., and Lavelle, F. M. 2006. "HAZUS-MH hurricane preview model methodology. II: Damage and loss estimation." Nat. Hazards Rev., 7(2): 94–103.