NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING
2019 Pacific Conference on Earthquake Engineering
TURNING HAZARD AWARENESS INTO RISK MITIGATION
4 – 6 April | SkyCity, Auckland | New Zealand

Development of seismic vulnerability curves of key building types in the Philippines

E.A.J. Tingatinga, B.M. Pacheco, J.Y. Hernandez Jr., M.C. Pascua, L.R.E. Tan, R.M. Suiza, W.L. Mata, R.E.U. Longalong, U.P. Ignacio Jr., & F.J. Germar

Institute of Civil Engineering, University of the Philippines Diliman, Quezon City, Philippines.

ABSTRACT

In this paper, vulnerability curves of key building types in the Philippines are developed and presented. Vulnerability curves, expressed as damage ratio versus Modified Mercalli Intensity (MMI) scale, for each building type are derived using computational, empirical, and/or heuristic methods. In the computational method, nonlinear static pushover of each building model was carried out and the capacity spectrum method was used to compute the fragility curves and then the vulnerability curves are derived from assumed damage ratios. Empirical vulnerability curves are derived using available data on damage to buildings compiled from field surveys and reports after past earthquakes. Heuristic vulnerability curves are derived by processing opinion of structural engineers in the Philippines on the possible damage to buildings when subjected to different earthquake intensities. For most building types made from reinforced concrete and steel, computational curves are recommended while for building types made of wood, masonry, and/or light materials, empirical or heuristic curves are recommended. The set of vulnerability curves proposed represents a coherent set of damage functions across structural types, construction material, number of floors, and age of construction.

1 INTRODUCTION

The Philippines, because of its geographic location, is very prone to earthquakes and to reduce and manage risk of future earthquakes, vulnerability functions or curves associated with the existing buildings are needed. Vulnerability curves depend on a number of parameters such as geometry, structural type, number of stories, construction material, quality of construction, etc. Since there are as many types and configurations as there

Paper 86

are number of actual buildings, comprehensive risk assessment can only be performed by grouping buildings into standard types to reduce the number of calculations in estimating losses.

Recent developments on building classification for earthquake loss estimation in the Philippines were initiated by the Philippine Institute of Volcanology and Seismology (PHIVOLCS) to enhance the capability of their software called Rapid Earthquake Damage Assessment System or REDAS (Pacheco et.al. 2011). In order to produce seismic hazard maps and loss estimate maps after a potentially damaging earthquake, REDAS needs vulnerability curves of buildings in the study area. The building stock must therefore be created using different methods and then grouped using an adopted building classification system.

The vulnerability curves of key building types may be derived using four approaches: computational, empirical, heuristic, and hybrid approach. Computational approach utilizes simulations of the response of a population of buildings subjected to demand earthquakes. The empirical approach relies on available post-earthquake data and the heuristic approach relies on experts' opinion on the structural response. Any combination of the aforementioned approaches is referred to as hybrid (Pacheco et.al. 2011).

In this paper, vulnerability curves, assumed to be lognormal cumulative distribution functions of damage ratio versus the Modified Mercalli Intensity (MMI) scale, will be developed using the computational, empirical, and heuristic approaches. A seismic vulnerability curve is a standard lognormal cumulative probability distribution function (Giovinazzi et.al. 2002, Saidi et.al., 2009, Pacheco et.al., 2012) of the form

$$DR[MMI] = \Phi\left[\frac{1}{\beta} ln\left(\frac{MMI}{\mu}\right)\right] \tag{1}$$

where $DR[MMI]$ is the damage ratio (or the cost of repairs of the damage to the replacement cost of the building) of a building for the given MMI; Φ is the standard lognormal cumulative distribution function; β is the standard deviation of the natural logarithm of MMI which will be referred in this text as uncertainty or simply beta; μ as the median value of MMI. The controlling parameters, namely the median μ and the uncertainty β, of the vulnerability curves for the key building types identified will be estimated. A typical vulnerability curve is shown in Figure 1.

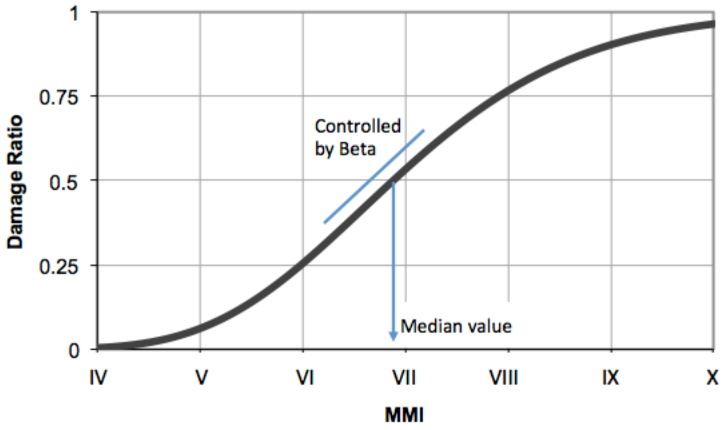
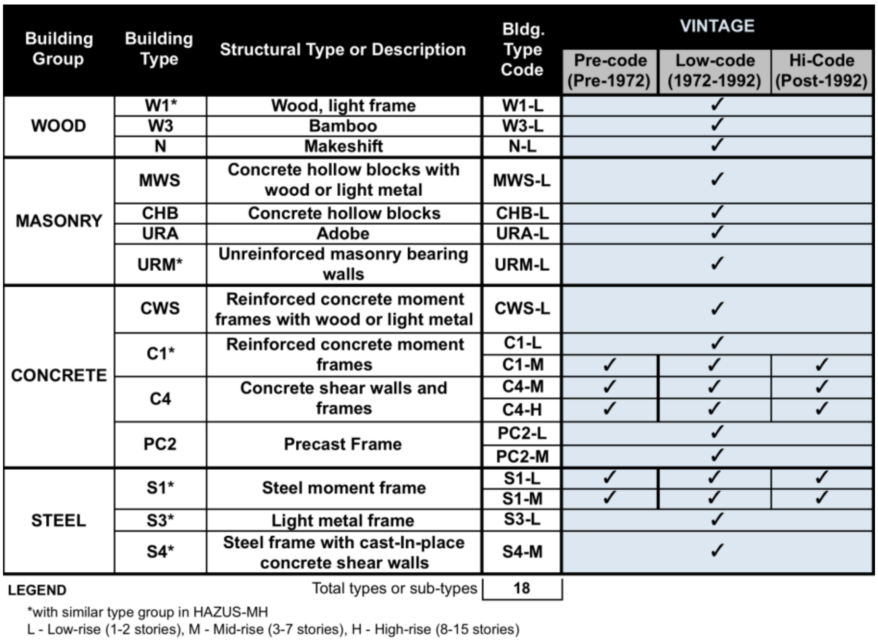


Figure 1: Typical seismic vulnerability curve developed in this study

2 BUILDING TYPOLOGY

The National Building Code of the Philippines (NBCP 1977) classifies buildings according to types of construction and material and by use of occupancy, but neither classification distinguishes structural systems that are important in the assessment of seismic risk (Dickson et.al 2012). Because of this, the University of the Philippines Diliman through the Institute of Civil Engineering (UPD-ICE), in partnership with the Association of Structural Engineers of the Philippines and the Philippine Institute of Civil Engineers, proposed a building classification (shown in Table 1) similar to HAZUS-MH (FEMA 2003). As shown, buildings are categorized according to construction material, number of stories, the lateral-force-resisting system, and vintage based on the year of publication of the different editions of the National Structural Code of the Philippines (NSCP).

Table 1: Proposed building classification.



Building Group	Building Type	Structural Type or Description	Bldg. Type Code	VINTAGE		
				Pre-code (Pre-1972)	Low-code (1972-1992)	Hi-Code (Post-1992)
WOOD	W1*	Wood, light frame	W1-L	✓		
	W3	Bamboo	W3-L	✓		
	N	Makeshift	N-L	✓		
MASONRY	MWS	Concrete hollow blocks with wood or light metal	MWS-L	✓		
	CHB	Concrete hollow blocks	CHB-L	✓		
	URA	Adobe	URA-L	✓		
	URM*	Unreinforced masonry bearing walls	URM-L	✓		
CONCRETE	CWS	Reinforced concrete moment frames with wood or light metal	CWS-L	✓		
	C1*	Reinforced concrete moment frames	C1-L	✓		
			C1-M	✓	✓	✓
	C4	Concrete shear walls and frames	C4-M	✓	✓	✓
			C4-H	✓	✓	✓
	PC2	Precast Frame	PC2-L	✓		
			PC2-M	✓		
STEEL	S1*	Steel moment frame	S1-L	✓	✓	✓
			S1-M	✓	✓	✓
	S3*	Light metal frame	S3-L	✓		
	S4*	Steel frame with cast-In-place concrete shear walls	S4-M	✓		
		Total types or sub-types	18			

LEGEND

*with similar type group in HAZUS-MH

L - Low-rise (1-2 stories), M - Mid-rise (3-7 stories), H - High-rise (8-15 stories)

3 METHODOLOGY

In this study, the method used to develop the vulnerability curves depend on the building type and the availability of data needed in its development. For engineered building types that may be easily modeled, e.g., concrete and steel building types, computational method will be used but for non-engineered building types or types difficult to model analytically, empirical or heuristic approaches are generally recommended.

3.1 Computational method

Computational approach employs nonlinear static pushover analysis and the capacity spectrum method (ATC-40 2009) to obtain statistical data of seismic vulnerability of a specific building type. For each type, a building database is assumed wherein the details, configurations, and location of each building are based from an existing building inventory for a region of interest.

Each building models are evaluated against several earthquake intensities, represented by the factored design response spectra. The performance of each building model for a given level of earthquake is evaluated using the intersection point of the superimposed capacity and demand curves – this is known as the performance point. The performance point is used to categorize the damage state of the particular building model by comparing it against the threshold values that are defined for each damage state. From the damage state evaluation of various building models, the statistics on the percentage of the building models exceeding a particular damage state can be obtained for a given earthquake intensity. Separate sets of data points are generated for each damage states where lognormal cumulative distribution curves are fitted resulting to the seismic fragility curves (in PGA). The following Gutenberg and Richter (1942) relationship is used to convert fragility curves in PGA to MMI

$$log(PGA[gals]) = \frac{MMI}{3} - 0.5 \qquad (2)$$

The vulnerability curves are then developed from these fragility curves by assigning damage indices defined by HAZUS-MH. The detailed procedure can be found in related papers by the authors (Pacheco, et. Al. 2013, Suiza et.al. 2013) but is also presented in Figure 2.

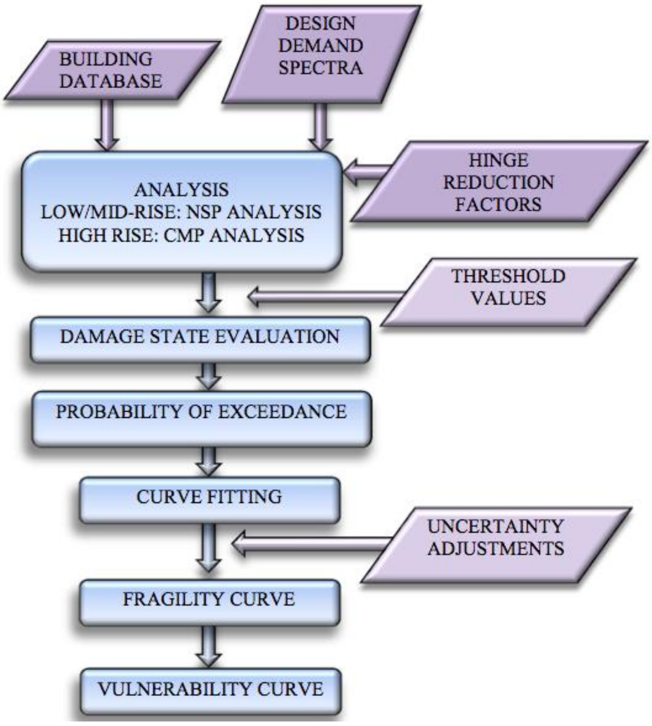


Figure 2: Simplified flowchart used in deriving computational vulnearbility curves

3.2 Empirical method

Empirical approach makes use of data of historical earthquake events and the observed or reported post-earthquake damage to buildings. The method used in this study may be outlined as follows:

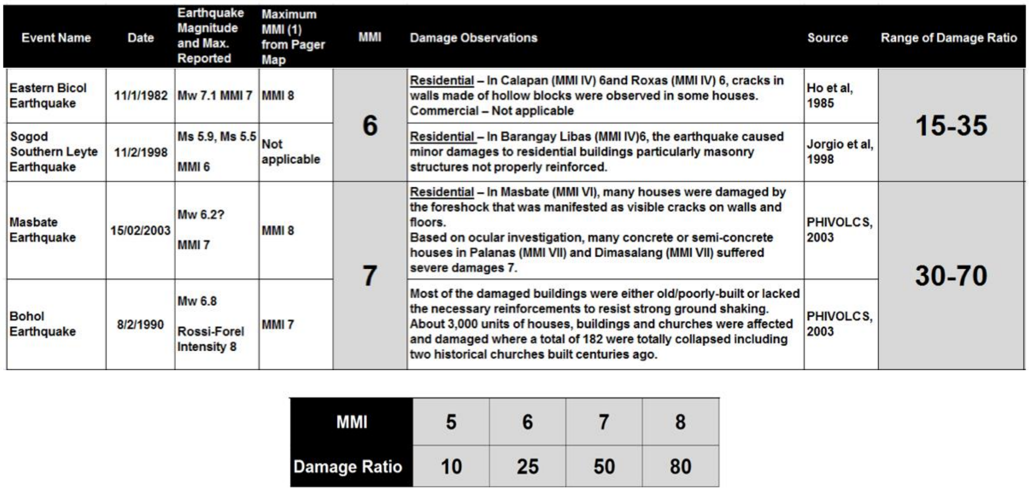
i. Collection of building damage observations due to recent/historical earthquakes from published papers, field reports, etc. The data used in this study was obtained from field reports collected and jointly reviewed by PHIVOLCS and Geoscience Australia (PHIVOLCS and GA, 2012).
ii. Classification of building types. Building will be classified using key phrases that describe the structural material or structural system, e.g., “residential house” or “masonry” for CHB and MWS; “church”, “stone”, “adobe” for URA or URM; and “wood”, “nipa roof”, and “light material” for wood-framed (e.g., W1-L) buildings.
iii. Assignment of damage ratio for each recorded earthquake intensity. For a particular building type, data from different earthquakes regardless of location will be used to assign damage ratios corresponding to the same earthquake intensity. Assumption will be made on the similarity in construction materials and practices and that the damage are only due to ground shaking.
iv. Estimation of parameters μ and β of the vulnerability curve that best fits the data points.

Figure 3 shows the assigned MMI and damage ratios (shown in gray columns) to a sample data set for CHB building type.

3.3 Heuristic Method

Heuristic approach is conducted through collection of experts’ opinion on the extent of damage of different building types under different ground motion intensities. The experts, who are guided by experience and expertise, approximate the damage ratios for the different MMIs. Figure 4 shows a sample of the table to be filled-out by the experts.

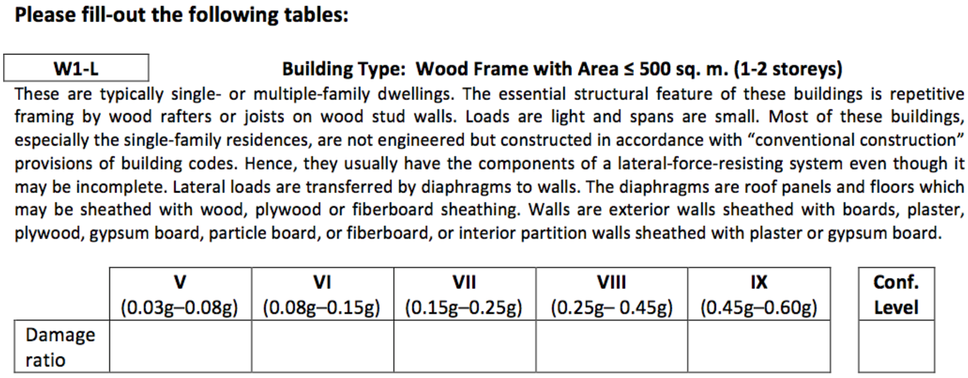
For a given building type, the vulnerability curve is developed by first computing the weighted mean of responses for damage ratio at the given ground motion intensities. The two parameters defining the lognormal vulnerability curve, μ and β in Eq. (1), are then determined using curve fitting methods.



Event Name	Date	Earthquake Magnitude and Max. Reported	Maximum MMI (1) from Pager Map	MMI	Damage Observations	Source	Range of Damage Ratio
Eastern Bicol Earthquake	11/1/1982	Mw 7.1 MMI 7	MMI 8	6	Residential – In Calapan (MMI IV) 6and Roxas (MMI IV) 6, cracks in walls made of hollow blocks were observed in some houses. Commercial – Not applicable	Ho et al, 1985	15-35
Sogod Southern Leyte Earthquake	11/2/1998	Ms 5.9, Ms 5.5 MMI 6	Not applicable		Residential – In Barangay Libas (MMI IV)6, the earthquake caused minor damages to residential buildings particularly masonry structures not properly reinforced.	Jorgio et al, 1998	
Masbate Earthquake	15/02/2003	Mw 6.2? MMI 7	MMI 8	7	Residential – In Masbate (MMI VI), many houses were damaged by the foreshock that was manifested as visible cracks on walls and floors. Based on ocular investigation, many concrete or semi-concrete houses in Palanas (MMI VII) and Dimasalang (MMI VII) suffered severe damages 7.	PHIVOLCS, 2003	30-70
Bohol Earthquake	8/2/1990	Mw 6.8 Rossi-Forel Intensity 8	MMI 7		Most of the damaged buildings were either old/poorly-built or lacked the necessary reinforcements to resist strong ground shaking. About 3,000 units of houses, buildings and churches were affected and damaged where a total of 182 were totally collapsed including two historical churches built centuries ago.	PHIVOLCS, 2003	

MMI	5	6	7	8
Damage Ratio	10	25	50	80

Figure 3: Empirical data used to derive vulnerabiilty curves for CHB building type.



Please fill-out the following tables:

W1-L **Building Type: Wood Frame with Area ≤ 500 sq. m. (1-2 storeys)**

These are typically single- or multiple-family dwellings. The essential structural feature of these buildings is repetitive framing by wood rafters or joists on wood stud walls. Loads are light and spans are small. Most of these buildings, especially the single-family residences, are not engineered but constructed in accordance with "conventional construction" provisions of building codes. Hence, they usually have the components of a lateral-force-resisting system even though it may be incomplete. Lateral loads are transferred by diaphragms to walls. The diaphragms are roof panels and floors which may be sheathed with wood, plywood or fiberboard sheathing. Walls are exterior walls sheathed with boards, plaster, plywood, gypsum board, particle board, or fiberboard, or interior partition walls sheathed with plaster or gypsum board.

	V (0.03g–0.08g)	VI (0.08g–0.15g)	VII (0.15g–0.25g)	VIII (0.25g– 0.45g)	IX (0.45g–0.60g)	Conf. Level
Damage ratio						

Figure 4: Survey questionnaire used to develop the heuristic vulnerability curve for W1-L type.

4 RESULTS AND DISCUSSIONS

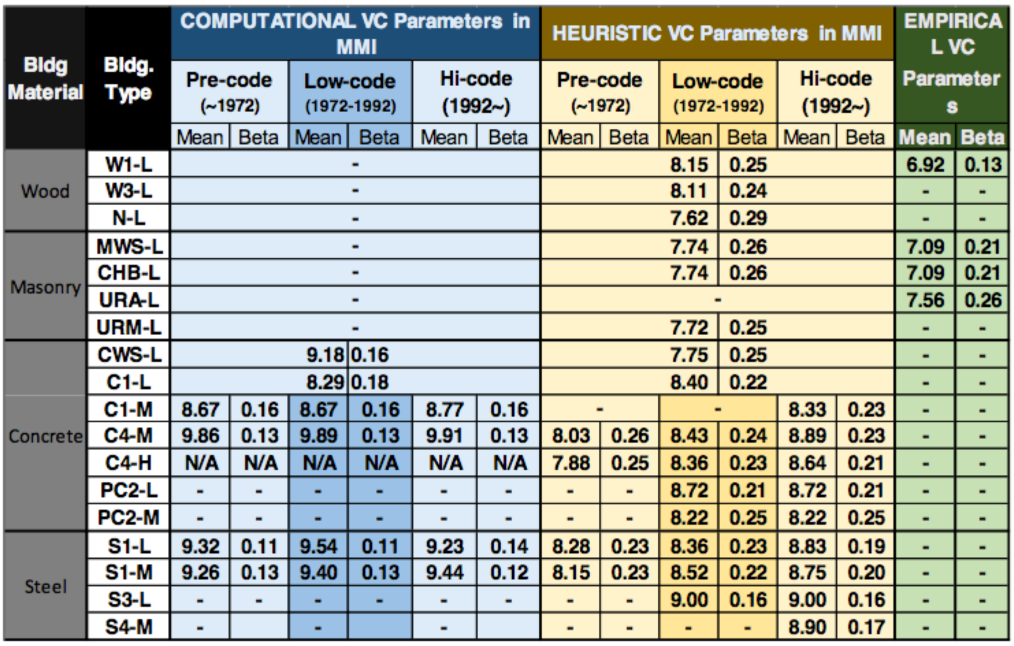
4.1 Vulnerabiity Curves

The computational vulnerability curves of engineered types, namely CWS-L, C1-L, C1-M, C4-M, C4-H, S1-L, and S1-M, were derived and the lognormal parameters of the curves are tabulated in Table 2. These curves were derived from fragility curve parameters (in PGA) incorporating aleatory and epistemic uncertainties. It was noted that the final uncertainty parameters have a wide variation when compared to HAZUS which reported their fragility curves' standard deviations across building types using only one value (equivalent to 0.64) in PGA.

The empirical vulnerability curves of W1-L, CHB-L and URA-L building types were developed using the empirical method and the data from PHIVOLCS. The vulnerability curves of for wood, concrete, and steel building types as well as URM type were not developed because there are no significant data needed in the development. The lognormal parameters of the W1-L, CHB-L, and URA-L types are listed in Table 2.

The heuristic vulnerability curves of the most building types were derived from a survey of thirty-eight specialists and the corresponding lognormal parameters are shown in Table 4. Results show that the heuristic vulnerability curves of low- and mid-rise buildings are similar for both concrete and steel types. Moreover, seismic vulnerability of buildings, according to specialists, is dictated by the material used in construction rather than the number of floors of a building (Tingatinga, et.al. 2013).

Table 2: Lognormal parameters of seismic vulnerability curves derived using computational, heuristic and empirical method.



Bldg Material	Bldg. Type	COMPUTATIONAL VC Parameters in MMI						HEURISTIC VC Parameters in MMI						EMPIRICAL VC Parameters	
		Pre-code (~1972)		Low-code (1972-1992)		Hi-code (1992~)		Pre-code (~1972)		Low-code (1972-1992)		Hi-code (1992~)			
		Mean	Beta	Mean	Beta	Mean	Beta	Mean	Beta	Mean	Beta	Mean	Beta	Mean	Beta
Wood	W1-L	-								8.15	0.25			6.92	0.13
	W3-L	-								8.11	0.24			-	-
	N-L	-								7.62	0.29			-	-
Masonry	MWS-L	-								7.74	0.26			7.09	0.21
	CHB-L	-								7.74	0.26			7.09	0.21
	URA-L	-						-						7.56	0.26
	URM-L	-								7.72	0.25			-	-
Concrete	CWS-L			9.18	0.16					7.75	0.25			-	-
	C1-L			8.29	0.18					8.40	0.22			-	-
	C1-M	8.67	0.16	8.67	0.16	8.77	0.16	-		-		8.33	0.23	-	-
	C4-M	9.86	0.13	9.89	0.13	9.91	0.13	8.03	0.26	8.43	0.24	8.89	0.23	-	-
	C4-H	N/A	N/A	N/A	N/A	N/A	N/A	7.88	0.25	8.36	0.23	8.64	0.21	-	-
	PC2-L	-	-	-	-	-	-	-	-	8.72	0.21	8.72	0.21	-	-
	PC2-M	-	-	-	-	-	-	-	-	8.22	0.25	8.22	0.25	-	-
Steel	S1-L	9.32	0.11	9.54	0.11	9.23	0.14	8.28	0.23	8.36	0.23	8.83	0.19	-	-
	S1-M	9.26	0.13	9.40	0.13	9.44	0.12	8.15	0.23	8.52	0.22	8.75	0.20	-	-
	S3-L	-	-	-	-	-	-	-	-	9.00	0.16	9.00	0.16	-	-
	S4-M	-		-		-		-	-	-	-	8.90	0.17	-	-

4.2 Recommended curves

4.2.1 Wood building types

The empirical vulnerability curve of W1-L was developed but not recommended because very few available data was used and the result is very different from the resulting heuristic curves of W1-L and W3-L – the former imply that wood-framed buildings are significantly more vulnerable to earthquakes than bamboo (houses). Therefore, the heuristic vulnerability curve for W1-L is recommended. The heuristic vulnerability curves for W3-L and N-L are also recommended.

4.2.2 Masonry building types

The heuristic and empirical methods were used to derive the vulnerability curves of most masonry building types. The empirical method utilizing significant amount of damage survey data of building damage to earthquake is usually regarded as the more reliable method since it reflects actual condition of buildings during earthquakes. Therefore, empirical vulnerability curves of MWS-L, CHB-L, URA-L will be recommended. For URM-L, the heuristic vulnerability curve will be used.

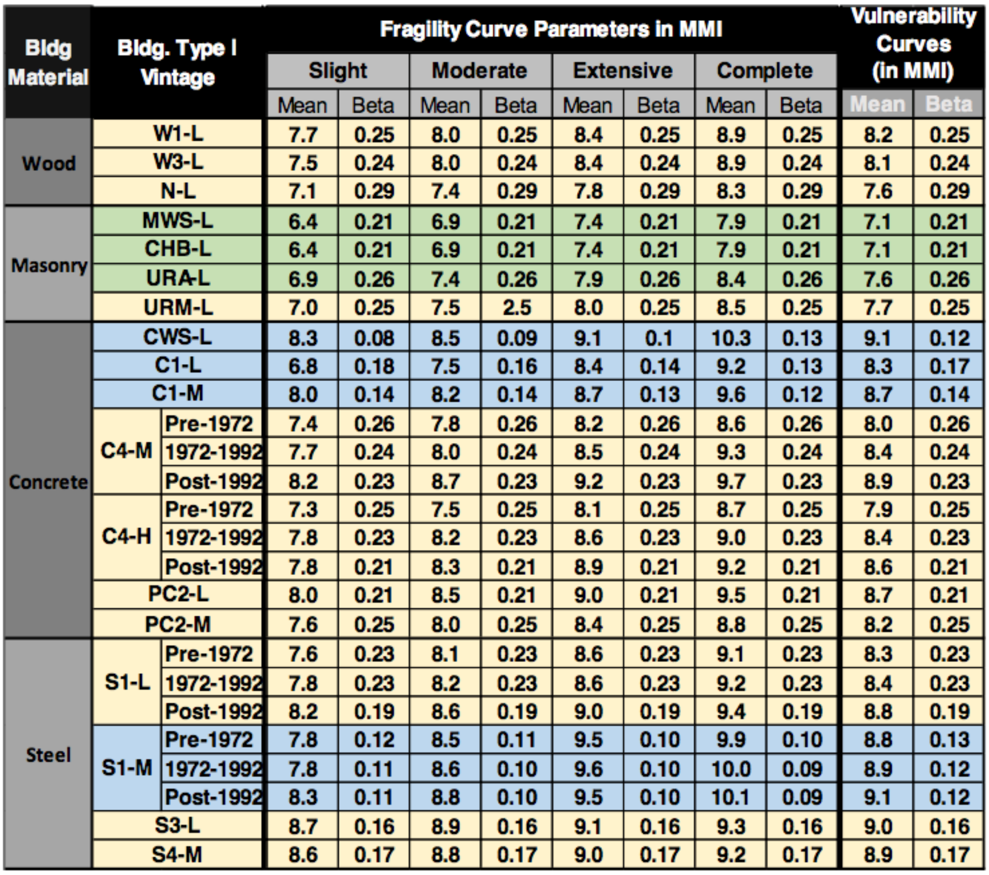
4.2.3 Concrete building types

The computational vulnerability curve of C1-L is recommended. Although, corresponding heuristic vulnerability curve is very similar, there is high confidence on the computational curve because of the significant variations (total of 62) of building models used in the computation. The computational vulnerability curve of CWS-L is also recommended since CWS-L is expected to be more resilient (due to lighter materials used in the second floor) to earthquakes when compared with C1-L. The heuristic curve implies a building as vulnerable as CHB-L or URM-L and even to a makeshift structure. For C1-M, the (low-code) computational vulnerability curve is also recommended. Although, computations resulted to very similar parameters, the low-code lognormal parameters will be used and recommended. The corresponding heuristic vulnerability curve implies that C1-M buildings are as vulnerable as C1-L buildings, a trend that is not expected since medium-rise buildings, i.e., 3-7 stories, require stricter design requirements. For C4-M and C4-H, the heuristic vulnerability curves are recommended. The lognormal parameters of C4-M across different vintages are more consistent and are more reasonable when compared with C1-M, a building type with the same height. For PC2-L and PC2-M, the heuristic curves are recommended.

4.2.4 Steel building types

The computational vulnerability curves for S1-L suggest trends that are not expected of the three vintages of this building type. Therefore, the heuristic vulnerability curves of S1-L are recommended. For S1-M, the computational vulnerability curves are recommended instead of the heuristic curve because it is consistent across vintages and with the result of S1-L. For S3-L and S4-M, heuristic curves were developed and recommended.

Table 3: Fragility and vulnerability curves of key building types in the Philippines.



Bldg Material	Bldg. Type / Vintage		Fragility Curve Parameters in MMI								Vulnerability Curves (in MMI)	
			Slight		Moderate		Extensive		Complete			
			Mean	Beta	Mean	Beta	Mean	Beta	Mean	Beta	Mean	Beta
Wood	W1-L		7.7	0.25	8.0	0.25	8.4	0.25	8.9	0.25	8.2	0.25
	W3-L		7.5	0.24	8.0	0.24	8.4	0.24	8.9	0.24	8.1	0.24
	N-L		7.1	0.29	7.4	0.29	7.8	0.29	8.3	0.29	7.6	0.29
Masonry	MWS-L		6.4	0.21	6.9	0.21	7.4	0.21	7.9	0.21	7.1	0.21
	CHB-L		6.4	0.21	6.9	0.21	7.4	0.21	7.9	0.21	7.1	0.21
	URA-L		6.9	0.26	7.4	0.26	7.9	0.26	8.4	0.26	7.6	0.26
	URM-L		7.0	0.25	7.5	2.5	8.0	0.25	8.5	0.25	7.7	0.25
Concrete	CWS-L		8.3	0.08	8.5	0.09	9.1	0.1	10.3	0.13	9.1	0.12
	C1-L		6.8	0.18	7.5	0.16	8.4	0.14	9.2	0.13	8.3	0.17
	C1-M		8.0	0.14	8.2	0.14	8.7	0.13	9.6	0.12	8.7	0.14
	C4-M	Pre-1972	7.4	0.26	7.8	0.26	8.2	0.26	8.6	0.26	8.0	0.26
		1972-1992	7.7	0.24	8.0	0.24	8.5	0.24	9.3	0.24	8.4	0.24
		Post-1992	8.2	0.23	8.7	0.23	9.2	0.23	9.7	0.23	8.9	0.23
	C4-H	Pre-1972	7.3	0.25	7.5	0.25	8.1	0.25	8.7	0.25	7.9	0.25
		1972-1992	7.8	0.23	8.2	0.23	8.6	0.23	9.0	0.23	8.4	0.23
		Post-1992	7.8	0.21	8.3	0.21	8.9	0.21	9.2	0.21	8.6	0.21
	PC2-L		8.0	0.21	8.5	0.21	9.0	0.21	9.5	0.21	8.7	0.21
	PC2-M		7.6	0.25	8.0	0.25	8.4	0.25	8.8	0.25	8.2	0.25
Steel	S1-L	Pre-1972	7.6	0.23	8.1	0.23	8.6	0.23	9.1	0.23	8.3	0.23
		1972-1992	7.8	0.23	8.2	0.23	8.6	0.23	9.2	0.23	8.4	0.23
		Post-1992	8.2	0.19	8.6	0.19	9.0	0.19	9.4	0.19	8.8	0.19
	S1-M	Pre-1972	7.8	0.12	8.5	0.11	9.5	0.10	9.9	0.10	8.8	0.13
		1972-1992	7.8	0.11	8.6	0.10	9.6	0.10	10.0	0.09	8.9	0.12
		Post-1992	8.3	0.11	8.8	0.10	9.5	0.10	10.1	0.09	9.1	0.12
	S3-L		8.7	0.16	8.9	0.16	9.1	0.16	9.3	0.16	9.0	0.16
	S4-M		8.6	0.17	8.8	0.17	9.0	0.17	9.2	0.17	8.9	0.17

5 CONCLUDING REMARKS

This paper presented vulnerability curves of key building types in the Philippines using three different methods: computational, empirical, heuristic. A building classification system was also proposed.

The computational vulnerability curves were derived using nonlinear static pushover analysis and the capacity spectrum for concrete and steel building types. The method allowed distinction between different levels of damage on buildings thus allowing also the development of fragility curves. The empirical and heuristic approaches, proposed in this study, develop the vulnerability curves of the key building types from the available damage reports and survey of specialists, respectively.

The set of vulnerability curves proposed and listed in Table 3 represents a coherent set of damage functions across structural types, construction material, number of floors, and age of construction. The corresponding lognormal parameters of the fragility curves were also computed and reported. These curves are the first generation of building vulnerability functions developed for the Philippines by the Filipino engineers. We recognize that these functions require an iterative approach so that the functions derived using any of the three methods are similar or cross-validate one another. The computational method may be improved by better analytical modeling and results that are validated with experiments. The empirical vulnerability curves should be updated when additional data or a better set of damage report (e.g., report that does not focus on severely damaged structures and has better description of the overall building exposure) becomes available. The heuristic vulnerability curves, as well as the method, will continue to evolve as the knowledge of the behaviour of Philippine buildings in response to ground shaking is better understood.

6 REFERENCES

NBCP. 1972. *National Building Code of the Philippines*, Presidential Decree 1096, Republic of the Philippines, 1977.

FEMA. 2003. *Multi-Hazard Loss Estimation Methodology Earthquake Model*. Washington, D.C.: Department of Homeland Security and Federal Emergency Management Agency.

Dickson, E., Baker, J., Hoornweg, D. & Tiwari, A. 2012. *Urban Risk Assessments: Understanding Disaster and Climate Risk in Cities*, The World Bank, Washington D.C.

Applied Technology Council. 1996. *ATC-40 Seismic Evaluation and Retrofit of Concrete Buildings*, California: Seismic Safety Commission.

Saedi, A., Deck, O. & Verdel, T. 2009. Development of building vulnerability functions in subsidence regions from empirical methods, *Engineering Structures*, Vol 31 2275-2286.

Pacheco, B.M., Hernandez Jr., H., Ignacio Jr., U., Tingatinga, E.A.J., Tan, L.R., Pascua, M.C., Suiza, R.M., Longalong, R.E., Mata, W. & Zarco, M.H. 2011. Development of earthquake vulnerability curves for key building types in Iloilo City, *Proc. PICE National Conference, Cagayan De Oro, Nov. 2011*.

PHIVOLCS & Geoscience Australia. 2012. *Review of Historical Philippines Earthquake Events and Building Consequences*, November 2012.

Suiza, R.M., Pacheco, B.M., Tingatinga, E.A.J., Hernandez, J., Ulpiano, I., Germar, F., Pascua, M.C., Tan, L.R., Longalong, R.E., Mata, M. & Zarco, M.A. 2013. Development of Fragility Curves of Mid-rise Reinforced Concrete Moment Resisting Frame Structures in the Greater Metro Manila Area, Philippines, *Proc, 10th International Conference on Urban Earthquake Engineering, 1-2 March 2013. Tokyo, Japan*.

Tingatinga, E.A.J., Pacheco, B., Hernandez, J., Ignacio, U., Germar, F., Longalong, R.E., Mata, W., Pascua, M.C., Suiza, R. & Tan, L.R. 2013. Development of Heuristic Seismic Vulnerability Curves of Key Building Types in the Philippines, *Proc. 10th International Conference on Urban Earthquake Engineering, 1-2 March 2013. Tokyo, Japan*.

Acknowledgment. The authors would like to acknowledge the support from the Australian Agency for International Development (AusAID) through the Greater Metro Manila Area – Risk Analysis Project between the Philippine Institute of Volcanology and Seismology (PHIVOLCS-DOST), the Philippine Atmospheric Geophysical and Astronomical Services Administration (PAGASA-DOST), Geoscience Australia (GA).