PHILIPPINE ENGINEERING JOURNAL
PEJ 2017; Vol. 38, No. 1: 15-26

Development of Wind Vulnerability Curves of Low-Rise Wooden Frame Structures in the Greater Metro Manila Area, Philippines

Engr. Raniel M. Suiza
Institute of Civil Engineering
University of the Philippines - Diliman
Quezon City, Philippines

Abstract – *Wood frame structures comprise a substantial part of the building population in the Philippines and most of these serve as residential buildings. With the advent of risk management, researchers tend to study the susceptibility of various structures against different disasters. This study focuses on the determination of the susceptibility or the vulnerability of low-rise wood frame structures in the Greater Metro Manila Area to severe wind. The methodology includes developing a model database that identifies typical wood constructions in the area; which is followed by an interaction analysis to determine the wind pressures developed in the building envelope. Damage analysis then follows which leads to the derivation of wind fragility curves, curves that give the probability that the structures exceed a particular damage state. The last part of this study derives the vulnerability curve which expresses the ratio of the cost of repairing to the cost of replacing the structures. It was found out that for the same set of structures, the cost of repairing is half of that of replacing the structures at a wind speed of 177 kph.*

Keywords—wind vulnerability; low-rise wooden frame structures; typhoon Haiyan; computational fluid dynamics (CFD) analysis; vulnerability analysis

I. INTRODUCTION

1.1 Background of the Study

The Philippines, being surrounded by the Pacific Ocean, the South China Sea, and the West Philippine Sea, have been hit by at least 20 typhoons every year. These typhoons cause devastation in almost all the regions in the country not only in terms of casualties but also in terms of damages to properties. One notable event is the destruction caused by Typhoon Haiyan which destroyed most of the structures in the eastern Visayan region. The damages were said to be caused by severe wind with an estimated speed of 300 kph. Such extreme events pose a big threat to structures not only in rural areas, but within urban areas as well such as the Greater Metro Manila Area especially nowadays, where winds caused by typhoons are usually accompanied by winds caused by the Southwest Monsoon.

There is emerging need to determine the extent of damage on structures, such as the cost of repairing a building that is affected by wind hazards as compared to the cost of replacing the entire structure. This is usually expressed in terms of the wind vulnerability curve. This paper focuses on the derivation of the wind vulnerability curve for low-rise wooden frame structures.

1.2 Objective and Scope

This study aims to determine the following: first, a database of structural models for wooden frame buildings; second, the probability of exceeding a particular damage state of the population of buildings for a given wind speed; and third, the ratio of the repair cost to the replacement cost of such buildings for a given wind speed.

This research is limited to residential and commercial wooden frame structures with at most two storeys existing in the Greater Metro Manila Area. The structures are assumed to be isolated thus, shielding and other external factors such as debris are not included in the study.

1.3 Expected Output

The results of the study includes a collection of fragility curves and the vulnerability curves of wooden frame structures in the Greater Manila Area.

II. METHODOLOGY

Figure 1 shows the general procedure used in developing computational vulnerability curves considering severe wind hazard for buildings. The fragility curves for slight, moderate, extensive, and complete damage states are first derived for a population of structural models that incorporate different attributes which affect the behavior of the structure when subjected to wind loading.

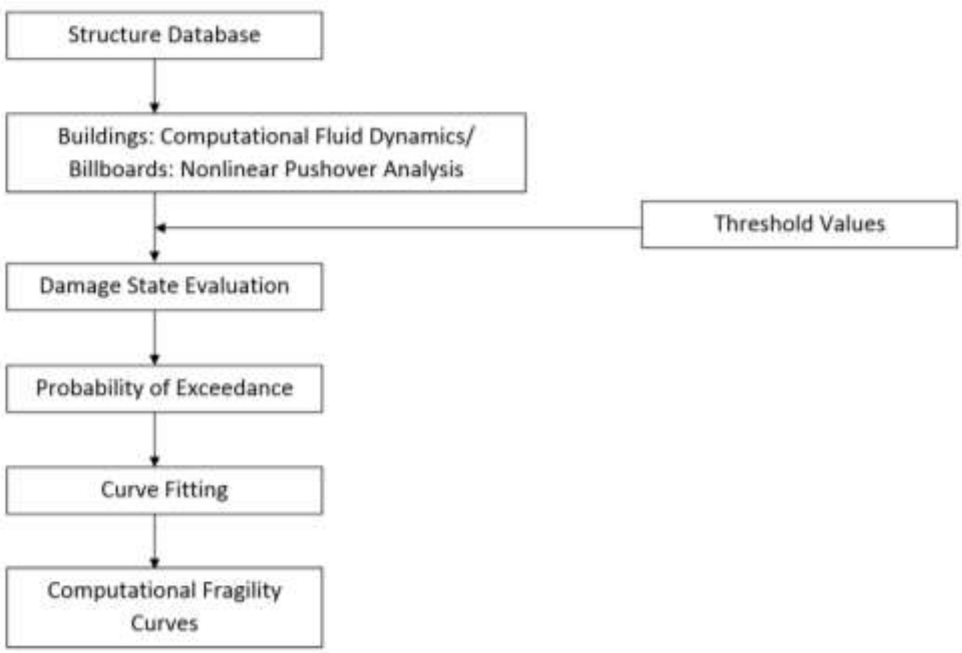

Figure 1. Methodological Framework [1]

2.1 Structure Modeling

During typhoons, it is frequently observed that the building envelope which includes the walls, doors, windows, and the roof are susceptible to damage by the resulting wind pressure and by wind-driven debris. It is then crucial to first identify building attributes which affect the magnitude and direction of wind pressure due to strong winds.

In order to quantify the vulnerability of a particular building type, a building model database that represents the population of the building type was formed. Each model was developed based on the possible combinations of different parameters that would affect the performance of the structure under wind loading. One assumption made was that the building frame will not be affected by severe wind loadings. However, negative pressures could be exerted on the cladding component leading to the pullout of the fasteners and the cladding or tearing failure of the cladding [1]. The following components were considered in the development of the building databases [2]:

- roof slope
- roof type
- roof connections
- building envelope materials
- plan dimensions
- window type

2.2 Interaction Analysis

Each structure from the building database was modeled using ANSYS, which is capable of performing computational fluid dynamics (CFD) analysis. Based on the building database, the geometry of each model was constructed. The orientation of the wind relative to the surfaces of the structure affects the pressures that may develop on the surfaces. Buildings in the database are symmetric, so only three wind directions were considered: 0°, 45°, 90° relative to the transverse axis of the building [2].

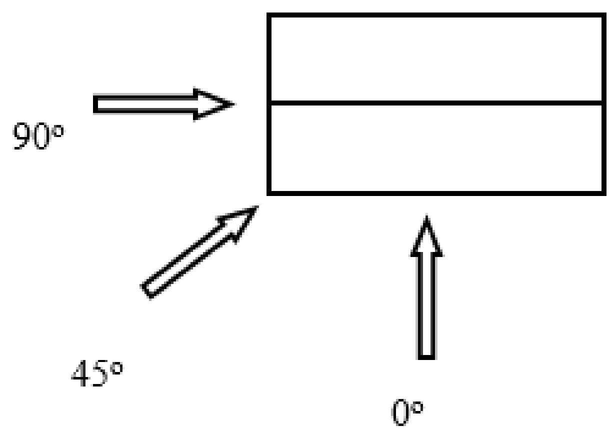

Figure 2. Applied Wind Directions

2.3 Damage Analysis

The capacity of each building envelope against strong winds depends on its material and connections. Roofs may be fastened using nails on wood or using screws on steel. Windows may be made of wood or glass, while walls may be made of wood, light-gage metal or masonry. One material may be stronger or weaker against strong winds compared to other materials. It is therefore critical to determine each threshold value of the different envelope and its materials. Threshold values of the building envelope are compared to the resulting wind pressure. Damage occurs when wind pressure exceeds the uplift threshold values. To assess the extent of damage to the building envelope, the pressure thresholds at which the cladding materials are detached from the structure had to be determined. The threshold values used in this study for roof nails and glass windows are 1,200 Pa [3] and 3,332 Pa [4], respectively.

Once the first solution for each wind speed and direction is carried out using CFD analysis, the distribution of pressures on the building envelope is inspected. Any region that exceeded the damage threshold for the applicable building envelope material is removed, implying that the particular region had been detached. The model is then remeshed with the region cut, and the analysis is carried out again to find out if more regions are damaged due to the change in the wind flow and pressure distribution. The removal of regions exceeding the threshold and recalculating the pressure distributions are carried out until no further region is damaged. If no further damage is observed for each wind speed and direction, the roof cover failure and window or door failure is observed and compared with the different damage states shown in Table 1. The damage state was adapted from the technical manual Hazards US: Multi-Hazard (HazUS-MH) of the US Federal Emergency Management Agency (FEMA) considering roof cover failure, window or door failure, and wall failure only. A similar procedure was done by Veron [1] in 2012 where only roof cover and window failures were considered which limited the study to the analysis of concrete structures. Since different types of structures were considered in this study, more components were added in the determination of the damage states.

Table 1. Damage States for Residential Construction Classes [5]

Damage State	Qualitative damage description	Roof Cover Failure	Window or Door Failure	Roof Structure Failure	Wall Structure Failure
0	No damage or very minor damage	≤2%	No	No	No
1	Minor damage	>2% and ≤15%	One window, door, or garage door failure	No	No
2	Moderate damage	>15% and ≤ 50%	> one and ≤ the larger of 20% and 3	No	No
3	Severe damage	> 50%	> the larger of 20% and 3 and ≤ 50%	No	No
4	Destruction	Typically >50%	>50%	Yes	No

The number of models that fall under a certain damage state was recorded for each wind speed. The damage state for each wind direction on each model was counted separately. From this, the damage probability matrix was assembled, which was necessary in order to develop the fragility and vulnerability curves. The frequency of occurrence of a damage state is equal to the number of times each damage state occurs for a particular wind speed. The percent probability of occurrence of a damage state is equal to the ratio of the number of occurrences of the damage state divided by the total number of cases analyzed.

These constitute the elements in the damage probability matrix. The probability of exceedance of a damage state was obtained by taking the cumulative probabilities of structures being in or exceeding a particular damage state. These served as the data points for fitting the fragility curve for each damage state.

2.4 Vulnerability Analysis

A standard lognormal cumulative distribution function was fitted to the data points from the matrix of probability of exceedance of a damage state. The fitted curves become fragility curves which will be used to develop the vulnerability curves. Figure 3 shows a typical set of fragility curves for a specific type of structure.

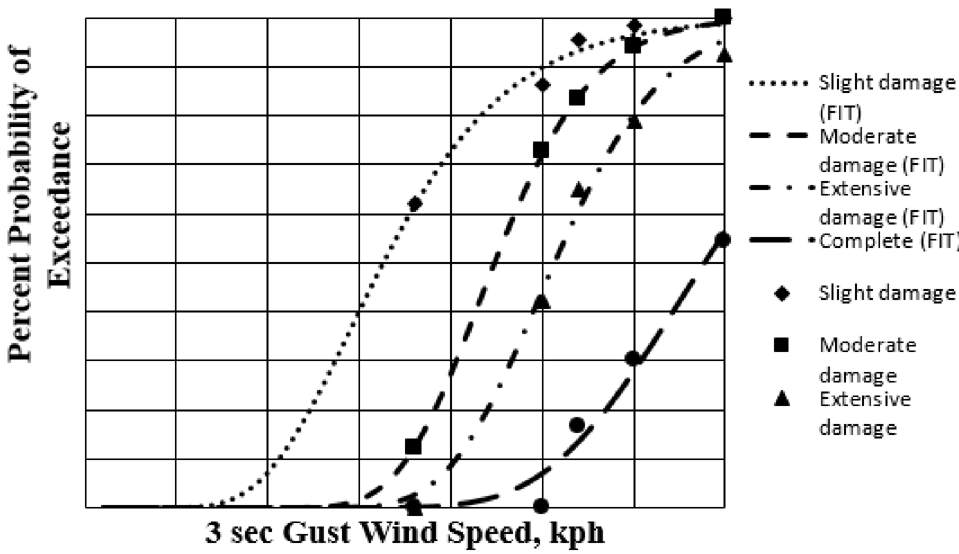

Figure 2. Sample Fragility Curve

For each building, the percentage of each component (roof, walls, and windows) with respect to the total cost of the structure was estimated. The percentage of cost for each component was then multiplied to the average of the range of damage for each damage state. This damage multiplier was multiplied to the probability of exceedance to come up with the damage for a certain damage state. For each wind speed, the damage index was computed by adding the damage for all damage states. The standard lognormal cumulative distribution function was then fitted to the damage indices to come up with the vulnerability curves a sample of which is shown in Figure 4.

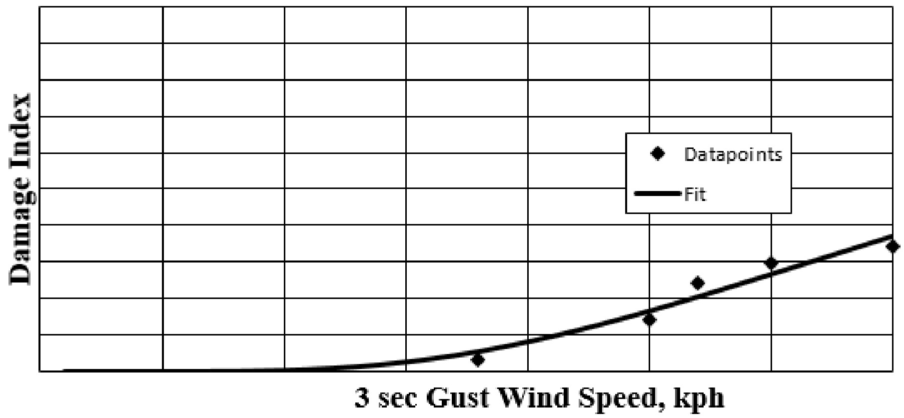

Figure 3. Sample Vulnerability Curve

III. RESULTS AND DISCUSSION

The structures considered in this study are those with wood frames (models labeled as *W1-L*). The height ranges from three to six meters and the floor area is limited to 47 sq. m. (500 sq. ft.) which is the maximum floor area for residential wooden structures based from the building categorization of HazUS-MH [5].

Figure 5. Light Wood Frame Residential Structure

3.1 Model Database

The building database was generated considering different wind-sensitive attributes. The floor areas considered were 15 m^2 (3m x 5m), 16 m^2 (4m x 4m) and 30 m^2 (5m x 6m). The roof of this type is either gable or hip. The material used for this is either galvanized iron or wood. Roof slopes considered were 18° (1:3), 26° (1:2) and 45° (1:1). Feasible combinations of these attributes were used resulting to the eight model configurations shown in Table 2 [2].

Table 2. Model Configurations

Model	Area (sq.m)	No. of Storeys	Roof		No. of Windows
			Type	Slope (°)	
W1L-1	15	1	Gable	45	5
W1L-2	30	1	Gable	26	8
W1L-3	15	1	Gable	18	5
W1L-4	15	2	Gable	26	12
W1L-5	30	2	Gable	18	17
W1L-6	30	1	Hip	26	8
W1L-7	16	1	Hip	45	5
W1L-8	16	2	Hip	18	11

Wind loads were applied at three directions: 0°, 45° and 90°. Wind speeds that were considered were 100, 150, 200, 250, 300, 350 kph. These resulted to 18 runs per model for the wooden frame structures.

3.2 Damage Matrices

The damage states of all the models were evaluated by comparing the pressure values on the components of each model for every wind speed to the damage thresholds and accounted the number of models exceeding the slight (S), moderate (M), extensive (E) and complete (C) damage states thus coming up with a damage probability matrix and a table for the probability of exceedance as shown in Tables 3 to 5.

Table 3. Sample Damage Matrix for 45° Wind Direction

Model	Damage	Wind Speed (kph)					
		100	150	200	250	300	350
W1L-1	Roof (%)	4.62%	40.13%	51.00%	51.00%	51.00%	51.00%
	Windows	-	-	4	4	4	4
	Walls	-	-	2 sides	2 sides	2 sides	2 sides
W1L-2	Roof (%)	-	32.82%	53.96%	55.00%	55.00%	55.00%
	Windows	-	2	2	3	3	3
	Walls	-	1 side	2 sides	2 sides	2 sides	2 sides
W1L-3	Roof (%)	-	-	38.71%	51.59%	51.59%	51.59%
	Windows	-	1	2	3	3	3
	Walls	-	1 side	2 sides	2 sides	2 sides	2 sides
W1L-4	Roof (%)	-	24.57%	51.38%	53.00%	53.00%	53.00%
	Windows	-	2	4	8	8	8
	Walls	-	1 side	2 sides	2 sides	2 sides	2 sides
W1L-5	Roof (%)	-	22.41%	58.74%	58.74%	58.74%	58.74%
	Windows	-	-	8	8	8	8
	Walls	-	-	2 sides	2 sides	2 sides	2 sides
W1L-6	Roof (%)	-	48.89%	71.45%	75.00%	75.00%	75.00%
	Windows	-	1	2	4	4	4
	Walls	-	1 side	1 side	2 sides	2 sides	2 sides
W1L-7	Roof (%)	-	35.00%	45.00%	55.00%	55.00%	55.00%
	Windows	-	-	2	4	4	4
	Walls	-	-	2 sides	2 sides	2 sides	2 sides
W1L-8	Roof (%)	-	14.58%	40.00%	45.00%	55.00%	55.00%
	Windows	-	-	6	8	8	8
	Walls	-	-	2 sides	2 sides	2 sides	2 sides

Table 4. Sample Damage State Identification for 45° Wind Direction

Model	Wind Speed (kph)					
	100	150	200	250	300	350
W1L-1	S	M	E	C	C	C
W1L-2	N	M	E	C	C	C
W1L-3	N	N	M	E	C	C
W1L-4	N	M	E	C	C	C
W1L-5	N	M	E	C	C	C
W1L-6	N	M	E	C	C	C
W1L-7	N	M	M	E	C	C
W1L-8	N	S	M	M	E	C

Table 5. Damage State Exceedance Probability

Wind Speed (kph)	Damage Probability Matrix				Probability of Exceedance			
	S	M	E	C	S	M	E	C
100	0.042	0.000	0.000	0.000	0.042	0.000	0.000	0.000
150	0.083	0.250	0.000	0.000	0.333	0.250	0.000	0.000
200	0.208	0.250	0.208	0.000	0.667	0.458	0.208	0.000
250	0.083	0.417	0.250	0.208	0.958	0.875	0.458	0.208
300	0.042	0.167	0.333	0.458	1.000	0.958	0.792	0.458
350	0.000	0.000	0.083	0.917	1.000	1.000	1.000	0.917

3.3 Wind Vulnerability Curve

The probabilities of exceedance were plotted against the wind speed and became the data points of the fragility curves. Lognormal cumulative distribution curves were then fitted into the provided data points. Table 6 summarizes the curve parameters of the fragility curves for each damage state.

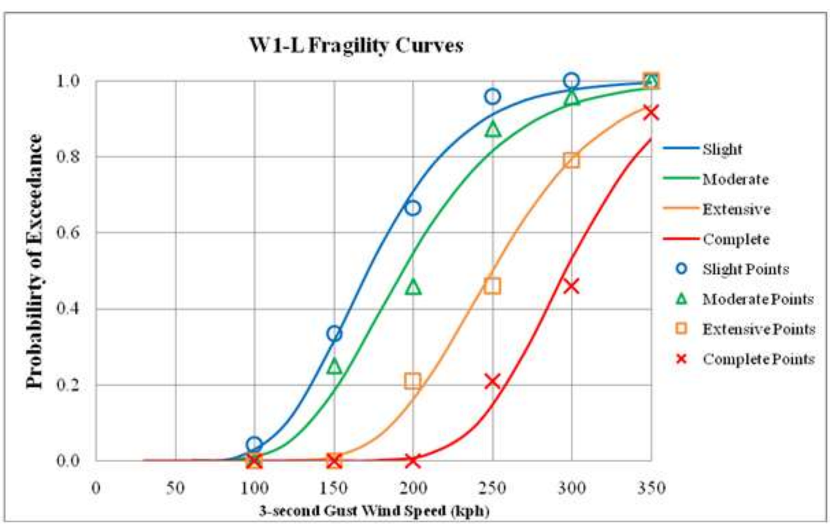

Figure 6. Wind Fragility Curves for Wood Frame Structures

Table 6. Wind Fragility Curve Parameters

Damage State	Median (kph)	Standard Deviation	Fit (R^2)
S	171.22	0.28	0.99
M	193.35	0.28	0.98
E	249.49	0.22	0.99
C	296.04	0.16	0.98

Table 7 summarizes the damage indices that were used in developing the vulnerability curve. It was assumed that the cost of the roof is 33% of the total cost of the structure and that the windows compose 5% of the same cost [2]. The damage state N stands for "no damage".

Table 7. Damage Indices

Damage State	Damage		
	Range		Index
N	0.000	0.007	0.003
S	0.007	0.055	0.031
M	0.055	0.185	0.120
E	0.185	0.380	0.283
C	0.380	1.000	1.000

Using these damage indices, it was observed that the resulting computational vulnerability curve was "too strong" relative to other building types in the higher wind speeds. A new form of the curve that is reflective of empirical data has to be generated which will come from the field. Table 8 contains the empirical data points that were used based from those obtained by PAGASA-DOST. The first data point was identified to be the take-off wind speed obtained which was obtained from the computational vulnerability curve. This agrees with the field data shown in the table. This wind speed was then used with the three other wind speeds shown, together with their respective field data, from which the "hybrid" curve was derived.

Table 8. Comparison of Field Data and Curve Values

Wind Speed	Probability of Exceedance		
	Field Data	Hybrid Curve	Computational Curve
150.0	0.000	0.035	0.003
205.2	1.000	0.952	0.084
237.6	1.000	0.999	0.236
320.4	0.950	1.000	0.735

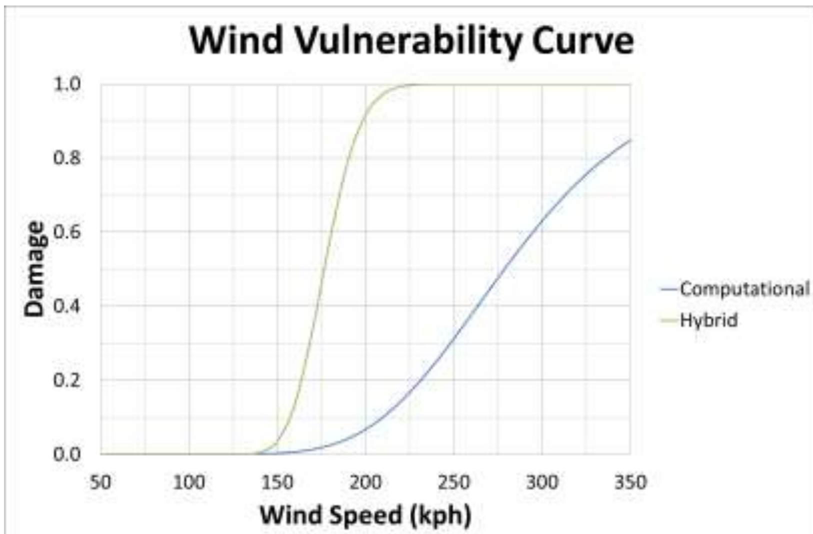

Figure 7. Wind Vulnerability Curve for Wood Frame Structures

This curve has a median value of around 177 kph and a standard deviation of 0.09. This basically means that the cost of repairing such structures in the Greater Metro Manila, that experience this amount of wind speed, is expected to be half of the cost of replacing them. Further, this implies that structures of such type shall be replaced once the wind speed experienced reaches 200 kph.

IV. CONCLUSIONS

In this study, the vulnerability of wood frame structures were determined in terms of two types of curves, the fragility and vulnerability curves. Fragility curves show the probability that a particular building population exceeds a certain damage state. It was found out that for wood frame structures, there is a 50% chance in exceeding the slight, moderate, extensive and complete damage states when the three-second gust wind speeds are equal to around 171 kph, 193 kph, 249 kph and 296 kph respectively. Vulnerability curves give the damage index, or the ratio of the cost of repair to the cost of replacement, of the structures. For wood frame structures, it was found out that the cost of repairing is half of that of replacing the structures at a wind speed of 177 kph.

V. REFERENCES

[1] M. C. Veron, "Development of computational fragility curves for residential buildings considering severe wind loadings," Undergraduate thesis, Inst. Civil Eng., Univ. Philippines Diliman, Manila, Philippines, 2012.

[2] University of the Philippines Diliman, "Wind vulnerability modeling," Proceedings, GMMA-RAP Technical Workshop, Manila, Philippines. 2012.

[3] K. H. Lee and D. V. Rosowsky, "Fragility assessment for roof sheathing failure in high wind regions," *Eng. Structures*, pp. 857-868, Mar. 2005.

[4] A. D. Cope, "Predicting the vulnerability of typical residential buildings to hurricane damage," Ph.D. dissertation, Dept. Civil and Coastal Eng., Univ. Florida, Florida, USA, 2004.

[5] Federal Emergency Management Agency, "HazUS-MH technical manual hurricane model," Department of Homeland Security and Federal Emergency Management Agency, Washington, D.C., USA, 2006.