13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP13
Seoul, South Korea, May 26-30, 2019

Probabilistic Quantification of Hurricane Resilience of Communities through a Distributed Simulation Platform

Ahmed U. Abdelhady
Graduate Student, Dept. of Civil Engineering, Univ. of Michigan, Ann Arbor, USA

Seymour M.J. Spence
Assistant Professor, Dept. of Civil Engineering, Univ. of Michigan, Ann Arbor, USA

Jason McCormick
Associate Professor, Dept. of Civil Engineering, Univ. of Michigan, Ann Arbor, USA

ABSTRACT: Resilience is an essential requirement in mitigating the effects of natural hazards such as hurricanes. This paper presents a framework to probabilistically quantify the damage of residential communities subject to hurricane hazards which is an essential step in quantifying community resilience. An engineering-based vulnerability model is developed for typical residential buildings. In particular, damage due to the two mechanisms of net pressure and wind-borne debris impact on the envelope components is considered. By integrating full hurricane wind field models into the framework, damage can be estimated for any given hurricane category and storm track. A distributed simulation platform, using Lightweight Communications and Marshalling (LCM) libraries, is proposed for modeling the debris-induced interdependencies between the damages sustained by the buildings defining the community.

1. INTRODUCTION

Risks and consequences of natural hazards have been increasing over time with hurricanes one of the costliest natural hazards, particularly in the United States (sigma, 2017). Mitigation of the risks of natural hazards can be achieved through the concept of community resilience which is an essential requirement for the nation's security and welfare. The National Academy of Science defined community resilience as, "*the ability to prepare and plan for, absorb, recover from, and more successfully adapt to actual or potential adverse events*" (NAS, 2012). It is clear from this definition that the first step to quantify community resilience, is to calculate the direct damage and losses to the community after the hurricane event.

This paper presents a framework to probabilistically quantify physical damage to the built environment of residential communities subject to hurricane hazards. In particular, damage to the envelope of residential buildings is quantified using an engineering-based vulnerability model that considers damage due to two mechanisms: (1) excessive direct wind pressure; and (2) impact of wind-borne debris. Damage calculation is achieved via a time-stepping approach which integrates a parametric hurricane wind field model. The damage state of each component is updated at every time step of the simulated hurricane passage.

The damage caused by the two mechanisms outlined above is interdependent and may lead to a progressive damage mechanism as dicussed in (Lin et al., 2010) due to significant variation in the internal pressure. It is proposed here to model these Interdependencies through a distributed simulation platform. The basic idea is to decompose the vulnerability model into four separate analysis model denominated respectively: (1) hurricane simulator; (2) pressure simulator; (3) debris simulator; and (4) damage simulator. Each simulator interacts with the simulation environment by publishing its output and subscribing to input from other simulators. The proposed distributed simulation platform is based on Lightweight Communications and Marshalling (LCM) libraries. The proposed platform is modifiable and extensible therefore enabling each model of the framework to be updated/improved with minimal effect on the other simulators of the framework.

A case study consisting in a typical Florida residential community is presented. Probabilistic damage estimations are evaluated through setting the proposed framework within a Monte Carlo simulation strategy. This framework provides a tool that enables the estimation of probabilistic community resilience indexes for use by decision-makers in defining effective mitigation plans and post-disaster recovery strategies.

2. FRAMEWORK OVERVIEW AND SIMULATION STRATEGY

The framework consists of three main phases: simulation input, vulnerability model, and simulation output, as show in Figure 1. All inputs required to define the community under consideration and the hurricane event are defined in the simulation input phase which are listed as following:

1. The community layout: each building's location and orientation.
2. The structural characteristics of each building: the probabilistic and/or deterministic resistances to direct wind pressure and impact resistance of vulnerable components.
3. Hurricane attributes that are required to define the considered hurricane event, e.g. storm track, storm size and category.

The vulnerability model uses data provided by the simulation input phase to quantify the damage caused by the specified hurricane event to the community under consideration. It consists of four simulators: (1) hurricane simulator; (2) pressure simulator; (3) debris simulator; and (4) damage simulator. For each time step, the hurricane simulator generates a wind speed and direction at the centroid of each building. The pressure simulator uses the wind speed and direction to calculate dynamic wind pressure for each component of the building. The damage simulator compares the dynamic wind pressure against the component's resistance to determine if the component is damaged or not. In case of damage occurrence, i.e. breach of the building's envelope, internal pressurization (calculated by the pressure simulator) is induced which may cause more damage to the building's components. The Pressure simulator and the damage simulator continue to iterate until balance occurs between damage and internal pressure.

Once balance occurs between the pressure simulator and the damage simulator, damaged components that are considered as potential sources of wind-borne debris (e.g. roof sheathing, roof cover, etc.) are traced by the debris simulator using a three-dimensional debris trajectory model. If any of the flying debris hit a vulnerable component (e.g. a glass window, a glass door, etc.), the damage simulator compares the impact kinetic energy with the vulnerable component's impact resistance to determine if more damage occurs. In case of any new damage, variation of internal pressure may lead to more damage and the release of more wind-borne debris. Iterations between the three simulators (hurricane, damage and debris) continues until balance occurs between damage and internal pressure.

The above outlined algorithm is repeated at every time step of the simulated hurricane passage through the community. After the last time step, final damage states for each component of each building are passed to the simulation output phase for post-processing. By embedding the above the framework into a Monte Carlo simulation strategy, probabilistic estimations of the damage metrics can be obtained for a given hurricane track and intensity while considering uncertainties in gust wind speeds, capacities of the components, and debris trajectories.

As discussed above, the framework is defined by multiple simulators, as shown in Figure 1, that are interdependent. To account for this, a distributed computing platform, based on Lightweight Communications and Marshalling (LCM) libraries is proposed herein. Within this setting, each simulator is treated as a black box that subscribes to input data from other simulators and publishes output data to be used by any subscribing simulator. Advantages of this platform are extensibility (i.e. any future simulators can be added easily with minor effects on the other simulators) and modifiability (i.e. future improvements in any given simulator should be easily incorporated into the platform without adversely affecting the other simulators).

3. ENGINEERING BASED VULNERABILITY MODEL

The first step to quantify resilience of a given community is to accurately estimate the amount of damage and losses that occurs after the hurricane event. For this purpose, quantification of damage caused by both excessive direct wind pressure, and wind-borne debris impact is considered in the proposed framework. The following sub-sections provide more details on the four simulators (hurricane, pressure, debris and damage) that form the vulnerability model of Figure 1.

3.1. Hurricane simulator

The main function of the hurricane simulator is to calculate wind speeds and directions at each time step of the simulation at the centroid of each building of the community. The hurricane wind field can be divided into two components: the environmental scale component, and the storm scale component (Jakobsen and Madsen, 2004). The length scale of the environmental scale processes is ~ 500 km. If the length scale of the community under consideration is significantly smaller than the environmental scale, then the environmental scale component can be considered constant and equal to the hurricane translational velocity. In this case the vector summation of the environmental and storm scales can be written as:

$$\vec{U} = \vec{U}_{tr} + \vec{U}_S \tag{1}$$

where $\vec{U}$ is the hurricane wind velocity, $\vec{U}_{tr}$ is the translational velocity of the hurricane eye, and $\vec{U}_S$ is the storm scale velocity.

By ignoring the non-linear interaction between the environmental scale and storm scale processes, the storm scale component can be obtained using a stationary hurricane model, for example the model outlined in (Shapiro, 1983). Following this approach, the momentum equations are solved for a slab boundary layer of constant depth under an imposed symmetric pressure distribution. In cylindrical coordinates (radial, r, centered at the hurricane's eye and azimuthal, λ, measured counterclockwise from the East) the radial and tangential momentum can be written as:

$$U_r \frac{\partial U_r}{\partial r} - \frac{U_t^2}{r} - fU_t + \frac{U_t}{r}\frac{\partial U_r}{\partial \lambda} + \frac{\partial \phi}{\partial r} - K\left(\nabla^2 U_r - \frac{U_r}{r^2} - \frac{2}{r^2}\frac{\partial U_t}{\partial \lambda}\right) + F(U_{tr}, U_r) = 0 \tag{2}$$

$$U_r \left(\frac{\partial U_t}{\partial r} + \frac{U_t}{r}\right) + fU_r + \frac{U_t}{r}\frac{\partial U_t}{\partial \lambda} - K\left(\nabla^2 U_t - \frac{U_t}{r^2} + \frac{2}{r^2}\frac{\partial U_r}{\partial \lambda}\right) + F(U_{tr}, U_t) = 0 \tag{3}$$

where U_r and U_t are the radial and tangential components, respectively, of the storm scale velocity ($\vec{U}_S$), f is the Coriolis parameter, ϕ is the pressure distribution within the storm, K is the constant coefficient of eddy diffusion, and F is the frictional drag force.

Jakobsen and Madsen (2004) proposed procures for solving Eq. (2) and (3) and provided parametric models for the radial and tangential components of the storm scale velocity. The parametric models are used in the framework outlined in this paper to calculate $\vec{U}_S$. From the solution of Eqs. (2) and (3), the mean hourly hurricane wind speed can be estimated (Vickery and Twisdale, 1995). After converting the wind speed to the mean 3-second gust wind speed, spatial variation of the later can be considered by sampling from a Type I (Gumbel) distribution using a coefficient of variation of 0.1 (Grayson et al., 2013). The sampled wind speed can then be used by any subscribing simulator and will be referred to as $\vec{u}$ in the following sections.

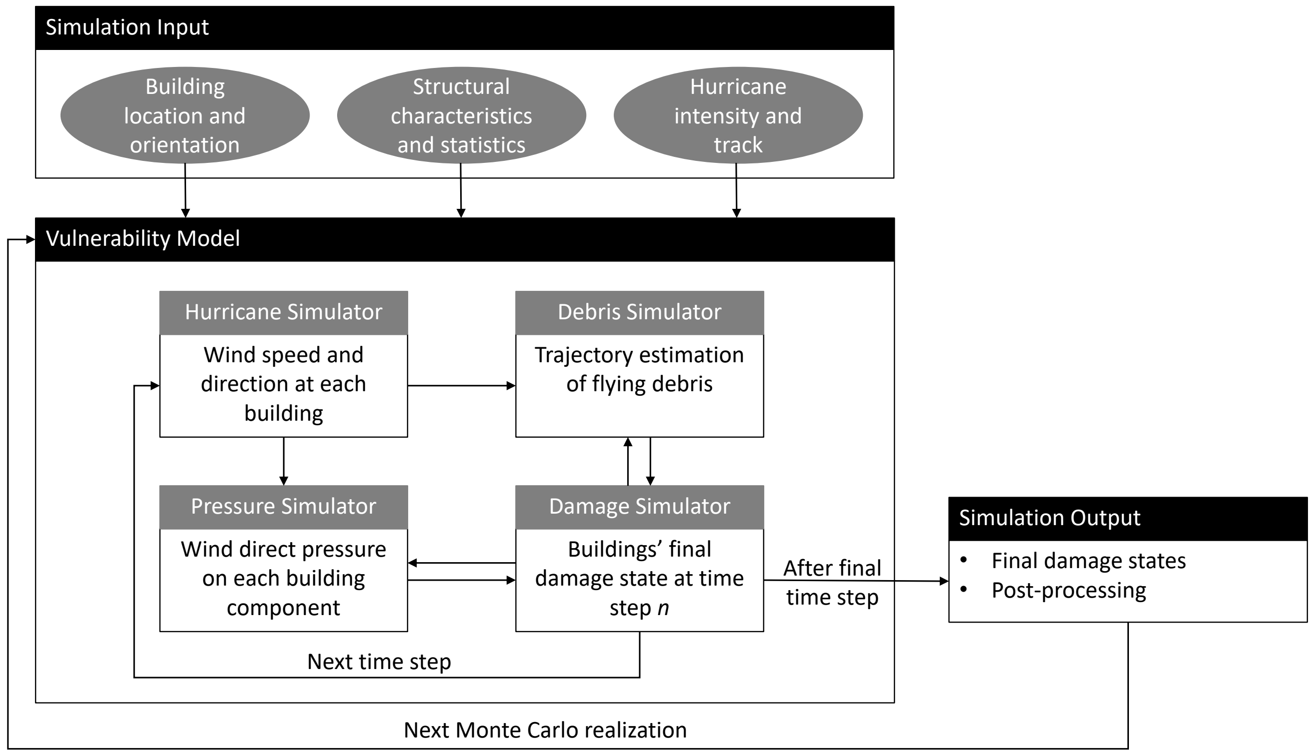

Figure 1: Flowchart of the proposed framework.

3.2. *Pressure simulator*

In this simulator, the direct wind pressure is calculated for each component of the building as a function of wind speed and direction. As a hurricane passes through a community, the wind speeds and directions change continuously. This implies that the maximum wind speed is not necessarily coming from the critical direction which renders the use of code-specified wind pressures inadequate. Indded, code-specified wind pressure represent the envelope of maximum pressures over the building's envelope due to all directions. For this reason, the component and cladding wind pressure provided in ASCE/SEI 7-16 (2017) is modified according to the Florida Public Hurricane Loss Projection Model (FPHLPM) (Gurley et al., 2005) in order to model the directional wind pressure that a residential building will experience during a hurricane event as follows:

$$q_h(t) = 0.521|\vec{u}(t)|^2;\ |\vec{u}(t)| \text{ in m/s} \quad (4)$$

$$P(t) = 0.8 \cdot q_h(t)\left[GC_p(t) - GC_{pi}(t)\right] \ (\text{N/m}^2) \quad (5)$$

where $q_h(t)$ (in N/m^2) is the velocity pressure evaluated at mean roof height $h < 4.5$ m, the coefficient of 0.8 is to exclude the factor of safety inherent in the code equation, $GC_p(t)$ and $GC_{pi}(t)$ are the external and internal pressure coefficients with built-in gust factor.

The calculation of $GC_p(t)$ is key for calculating wind pressure as a function of wind direction. $GC_p(t)$ is estimated for the eight nominal directions shown in Figure 2. Values for $GC_p(t)$ are estimated based on information provided in the FPHLPM, available wind tunnel data, ASCE/SEI 7-16 (2017), and engineering judgment. Linear interpolation is carried out for other directions.

The internal pressure coefficient $GC_{pi}(t)$ for an undamaged building is taken as ± 0.18, as suggested in (ASCE/SEI 7-16, 2017). In case of any breach to the building envelope (damage occurrence), internal pressure is updated depending on the level of damage. A simple, but intuitive, approach is to calculate the internal pressure by taking the weighted average of the external pressure on the damaged components.

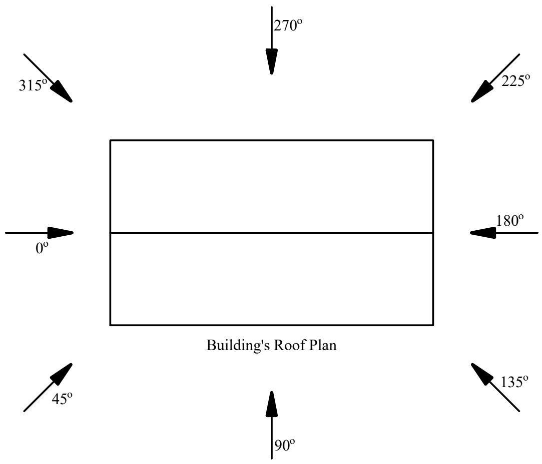

Figure 2: The eight nominal wind directions.

3.3. Debris simulator

Wind-borne debris is one of the major causes of damage to buildings subject to hurricanes. The debris simulator traces the trajectory of relased portions of damaged components until landing. The approach is based on the three-dimensional 6-degree-of-freedom debris trajectory model presented in (Richards et al., 2008) and extended by Grayson et al. (2012) to consider uncertainties in the debris flight path.

Grayson et al. (2012) proposed that uncertainties in the debris flight can be modeled by considering the angle of attack and the angle of tilt of the flying debris object as normal random variables. Validation of this methodology was carried out by showing the agreement of the resulting pattern of debris landing locations generated by the model and the pattern of landing locations obtained from wind tunnel tests (Visscher and Kopp, 2007; Kordi et al., 2010).

Debris sources considered in this work are roof coverings, roof sheathing, and gable-end sheathing. All considered debris sources are geometrically classified as plate-type. Aerodynamic force coefficients and moment coefficients for plate-type debris are obtained from Richards (2010). The final outputs of the debris simulator are the debris landing locations and the kinetic energy at landing.

3.4. Damage simulator

The damage simulator determines if any component is damaged as a result of the following two mechanisms: excessive direct wind pressure and/or debris impact. For the first mechanism, damage is determined by comparing the calculated dynamic wind pressure ($P(t)$) with the component's pressure capacity (C_P). For the second mechanism, damage is determined by comparing debris kinetic energy at impact ($KE(t)$) with the component's impact capacity (C_I). With respect to the second mechanism, components that are considered venerable are glass windows, doors, and garage doors. Debris landing locations are used to determine whether the debris object will hit a vulnerable component or not. The above outlined conditions can be modeled through the following limit state function D:

$$D(t) = \begin{cases} 0 & P(t) < C_P \text{ and } KE(t) < C_I \\ 1 & P(t) \geqslant C_P \text{ or } KE(t) \geqslant C_I \end{cases} \tag{6}$$

where 1 indicates damage occurrence and 0 indicates no damage.

4. APPLICATION

To demonstrate the capabilities of the proposed distributed computing platform, the virtual community shown in Figure 3 was subjected to a category 3 hurricane. In particular, the community consists of 21 archetype buildings of the form shown in Figure 4. Table 1 lists the probabilistic properties of the venerable components with uncertain capacities of the archetype buildings. The resistance to debris impact of the vulnerable components (glass windows, doors and garage doors), in terms of kinetic energy, is taken as a deterministic value equal to 68 Nm. Figure 5 shows the storm track location with respect to the community.

Wind speed and direction for each time step are generated by the hurricane simulator, as shown in Figure 6. As mentioned earlier, the sampled 3-sec gust wind speed is used as input to the pressure and debris simulator. The 1-min open-water wind speed is used to determine the hurricane category.

Figure 7 shows the evolution of the probability of damage for each component of the buildings composing the community. The results were generated

Building component	Mean resistance	COV	Distribution
Glass window	3.33 kPa	0.20	Normal
Door	2.39 kPa	0.20	Normal
Garage door	0.957 kPa	0.20	Normal
Wall sheathing	2.61 kPa	0.11	Lognormal
Roof sheathing	2.61 kPa	0.11	Lognormal
Roof cover	3.35 kPa	0.40	Normal

Table 1: Resistance to pressure of the venerable building components (Vickery et al., 2006; Gurley et al., 2005).

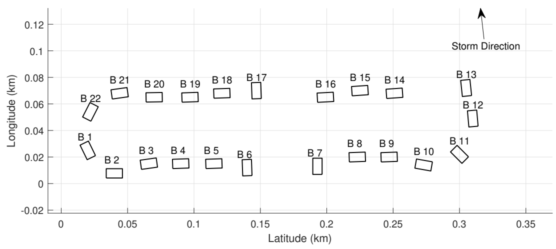

Figure 3: Layout of the virtual community.

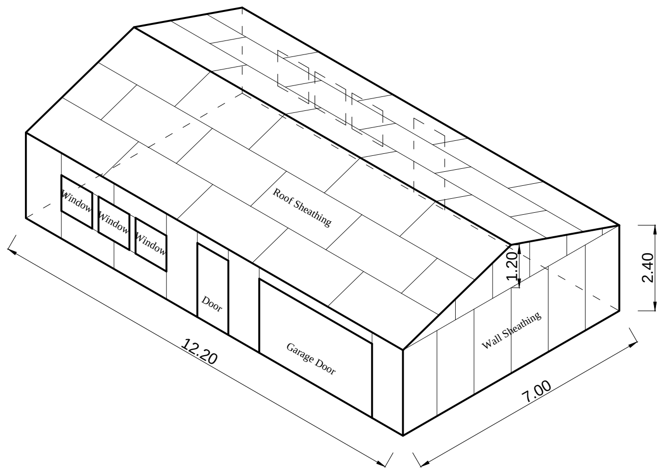

Figure 4: Archetype residential building of the virtual community (Yau, 2011).

through Monte Carlo simulation using 1000 samples. Although all buildings are at a similar distance from the storm track (i.e. similar values of r), the probability of damage can be seen to vary over the community. In particular, the probability of damage to windows, doors and garage doors (i.e. debris vulnerable components) varies from one building to another due to damage caused by wind-borne debris which depends on the location of the building with respect to the others.

A detailed quantification of the damage to each vulnerble component of each building is considered key for estimating community resilience. In particular, the four properties of resilience: (1) robustness; (2) rapidity; (3) resourcefulness; and (4) redundancy are directly related to the amount of damage occuring directly after the hazard (Bruneau et al., 2003). In this respect, the detailed quantification of damage obtained from the proposed framework will be used as input to future resiliency simulators.

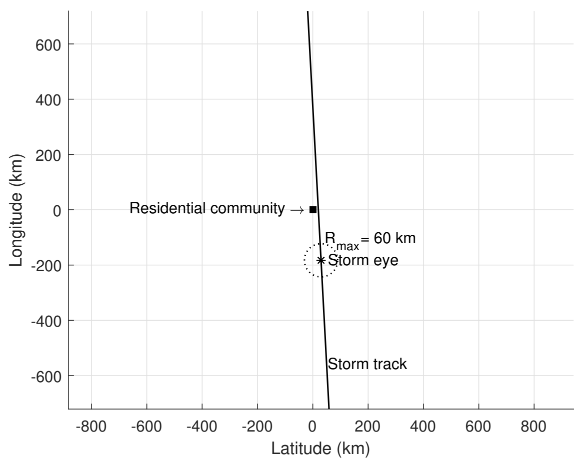

Figure 5: Hurricane storm track.

5. CONCLUSIONS

In light of the importance of developing frameworks that are capable of quantifying community

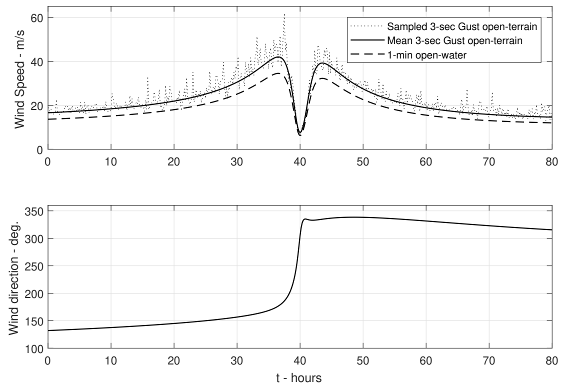

Figure 6: Wind speed and direction time history at the center of the community.

resilience to mitigate the risks and consequences of hurricanes, this paper presented an engineering-based vulnerability model that is capable of quantifying the damage and losses to residential communities subject to hurricanes. The vulnerability model was integrated with a parametric hurricane wind field model that was capable of generating wind speeds and directions at each building for a given storm track and hurricane category. Using a time stepping approach, wind speeds and directions were used as the basis for damage calculation due to two mechanisms: excessive direct wind pressure, and wind-borne debris impact. These two damage mechanisms are interdependent and their interpendency can lead to a progressive damage due to internal pressurization. The idea of distributed computing was presented as an attractive approach to model these interdependencies through decomposing the vulnerability model into four simulators, namely the hurricane, pressure, debris and damage simulator. Lightweight Communications and Marshalling (LCM) libraries were used as the basis on which the proposed distributed computing platform operated. It is believed that such platforms are essential for quantifying community resilience when high-fidelity models are used to model the response of each element (e.g. buildings) of the community.

Outputs from the presented framework can be used directly by functionality restoration models to quantify community resilience metrics. This will lead to a probabilistic measure of various community resilience indexes to be utilized by decision makers, government officials, developers, and designers to define possible mitigation plans and post-disaster recovery strategies.

6. ACKNOWLEDGMENTS

This work was supported by the National Science Foundation (NSF) through grants ACI-1638186 and CMMI-1562388. Any opinions, findings, conclusions, and recommendations expressed in this work are those of the authors and do not necessarily reflect the views of the sponsors.

7. REFERENCES

(2012). *Disaster Resilience: A National Imperative*. The National Academies Press, Washington, DC, <https://www.nap.edu/catalog/13457/disaster-resilience-a-national-imperative>.

ASCE/SEI 7-16 (2017). *Minimum design loads and associated criteria for buildings and other structures*. American Society of Civil Engineers, Reston, VA.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., A.Wallace, W., and vonWinterfeldti, D. (2003). "A framework to quantitatively assess and enhance the seismic resilience of communities." *Earthquake Spectra*, 19(4), 733–752.

Grayson, J. M., Pang, W., and Schiff, S. (2012). "Three-dimensional probabilistic wind-borne debris trajectory model for building envelope impact risk assessment." *Journal of Wind Engineering and Industrial Aerodynamics*, 102, 22–35.

Grayson, J. M., Pang, W., and Schiff, S. (2013). "Building envelope failure assessment framework for residential communities subjected to hurricanes." *Engineering Structures*, 51, 245–258.

Gurley, K., Pinelli, J.-P., Subramanian, C., Cope, A., Zhang, L., Murphree, J., Artiles, A., Misra, P., Gulati, S., and Simiu, E. (2005). *Florida public hurricane loss projection model, engineering team final report*. International Hurricane Research Center Florida International University, Miami, FL.

Jakobsen, F. and Madsen, H. (2004). "Coparison and further development of parametric tropical cyclone models for storm surge modelling." *Journal of Wind Engineering and Industrial Aerodynamics*, 92, 375–391.

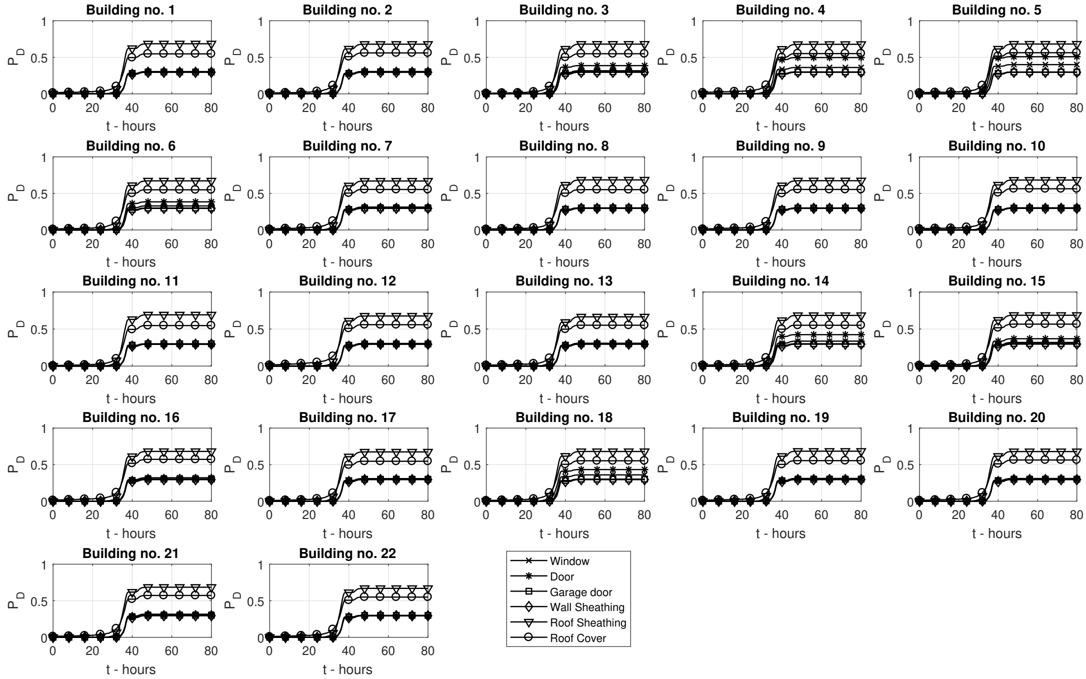

Figure 7: Time evolution of the probability of damage (P_D) for each vulnerable component of each building of the community.

Kordi, B., Traczuk, G., and Kopp, G. A. (2010). "Effects of wind direction on the flight trajectories of roof sheathing under high winds." *Wind and Structures*, 13, 145–167.

Lin, N., Vanmarcke, E., and Yau, S.-C. (2010). "Wind-borne debris risk analysis - part ii. application to structural vulnerability modeling." *Wind and Structures*, 13, 207–220.

Richards, P. J. (2010). "Steady aerodynamics of rod and plate type debris." *Proc. of 17th Australian Fluid Mechanics Conference*.

Richards, P. J., Williams, N., Laing, B., McCarty, M., and Pond, M. (2008). "Numerical calculation of the three-dimensional motion of wind-borne debris." *Journal of Wind Engineering and Industrial Aerodynamics*, 96, 2188–2202.

Shapiro, L. J. (1983). "The asymmetric boundary layer flow under a translating hurricane." *Journal of the Atmospheric Sciences*, 40, 1984–1998.

sigma (2017). *Natural catastrophes and man-made disasters in 2016: A year of widespread damages*. sigma 2/2017, Swiss Re., London.

Vickery, P. J., Skerlj, P. F., Lin, J., Jr., L. A. T., Young, M. A., and Lavelle, F. M. (2006). "Hazus-mh hurricane model methodology. ii: Damage and loss estimation." *Natural Hazards Review*, 7(2), 94–103.

Vickery, P. J. and Twisdale, L. A. (1995). "Wind-field and filling models for hurricane wind speed predicitons." *Journal of Structural Engineering*, 121, 1700–1709.

Visscher, B. T. and Kopp, G. A. (2007). "Trajectories of roof sheathing panels under high winds." *Journal of Wind Engineering and Industrial Aerodynamics*, 95, 697–713.

Yau, S. C. (2011). "Wind hazard risk assessment and management for structures." Ph.D. thesis, Princeton University, NJ, USA.