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Windborne debris risk analysis - Part II. Application to structural vulnerability modeling

Ning Lin*, Erik Vanmarcke and Siu-Chung Yau

Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey, USA

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Abstract. The 'chain reaction' effect of the interaction between wind pressure and windborne debris is likely to be a major cause of damage to residential buildings during severe wind events. The current paper (Part II) concerns the quantification of such pressure-debris interaction in an advanced vulnerability model that integrates the debris risk model developed in Part I and a component-based wind-pressure damage model. This vulnerability model may be applied to predict the cumulative wind damage during the passage of particular hurricanes, to estimate annual hurricane losses, or to conduct system reliability analysis for residential developments, with the effect of windborne debris fully considered.

Keywords: windborne debris; risk; vulnerability; hurricane.

1. Introduction

Windstorms, and hurricanes in particular, often cause significant damage and losses in the United States and many other places around the world. Windborne debris is a major cause of wind-induced damage to residential structures, due to its direct impact on building envelopes and, perhaps more significantly, its interaction with wind pressure. Windborne debris, often generated from building materials damaged by wind pressure, can penetrate building envelopes and induce internal pressurization, which increases pressure damage, generating more debris and related damage, causing a 'chain' of failures. Quantification of this pressure-debris interaction is an important aspect of structural vulnerability modeling and wind damage risk analysis.

The current paper (Part II) describes the application of the debris risk model developed in the Part I companion paper (Lin and Vanmarcke 2010) to structural vulnerability assessment for hurricane (or other windstorm) damage risk analysis. We explicitly model, for the first time, the interaction between pressure damage and debris damage as well as the temporal evolution of this interaction over the period of storm passage. The (one-way) effect of debris damage on pressure damage has been considered, to some extent, in other vulnerability models, namely in the FEMA HAZUS-MH model (Vickery, *et al.* 2006) and the Florida Public Hurricane Loss Projection (FPHLP) model (Gurley, *et al.* 2005). Herein, we account for the pressure-debris interaction by integrating the debris risk model and a component-based pressure damage model, resulting in a next-generation

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* Corresponding Author, E-mail: nlin@princeton.edu

vulnerability model.

This integrated vulnerability model can be used to predict progressive wind-induced damage during the passage of a particular hurricane or to estimate annual hurricane losses for clustered housing environments, such as residential developments. In addition to quantifying the performance of individual buildings, this vulnerability model also considers the interaction, owing to debris effects, between neighboring buildings, thus more closely representing their damage and failure consequences in real hurricane events. The model can also be used in system reliability analysis to identify weak links, such as buildings likely to cause significant debris-related contributions to total damage, in residential developments.

The vulnerability model is described in detail in the following sections. The use of the model and the interpretation of analysis results are discussed by means of simple numerical examples. A more comprehensive example of site- and storm- specific analysis is also provided, namely an assessment of wind damage risk to a residential neighborhood in Sarasota County, Florida, during the passage of Hurricane Charley (2004).

2. Integrated vulnerability model

An integrated vulnerability model is developed in this section, seeking to fully couple the debris risk model developed in Part I to a component-based pressure damage model. The latter estimates wind-pressure damage to structural components and predicts the mean numbers of generated debris objects from buildings (needed to estimate the debris damage risk), under specified wind conditions. Based on the predicted debris risk, the pressure damage model then adjusts internal pressures, recalculates pressure damage, and evaluates the mean numbers of newly generated debris objects, and so on. The debris risk model, the pressure damage model, and the integrated vulnerability model are described in this section.

2.1. Debris risk analysis methodology

In Part I, the Lin and Vanmarcke (2008) debris risk model is extended to describe the debris damage risk to vulnerable components on a building envelope. This extension enables the coupling of the debris risk model and a component-based pressure damage model, in which the debris damage risk on each window or glass door may need to be quantified.

To estimate the debris damage risk to a window (or a door; designated w) of a (target) building (j; having area A_j), the extended debris risk model makes use of four probabilistic quantities. They are, for each type (s) of debris generated from each (source) building (i) in the area, the mean number of debris objects generated ($\lambda_{s,i}$), the probability of debris hitting the target building ($A_j\mu_{s,i}(j)$; in the approximate form), the probability of debris impacting the window given it hits the target building ($p_{s,i}(j_w|j)$), and the probability of the debris horizontal momentum (Z) exceeding the window resistance (ζ_{j_w}) when the debris object impacts the window ($\Phi_{s,i}(Z>\zeta_{j_w}|j_w)$). Under a specific wind condition (i.e., wind speed and direction), the probability of debris damage to the window is described by Eq.(13) of Part I as

$$P_D(j_w) = 1 - e^{-\alpha(j_w)}, \tag{1}$$

where

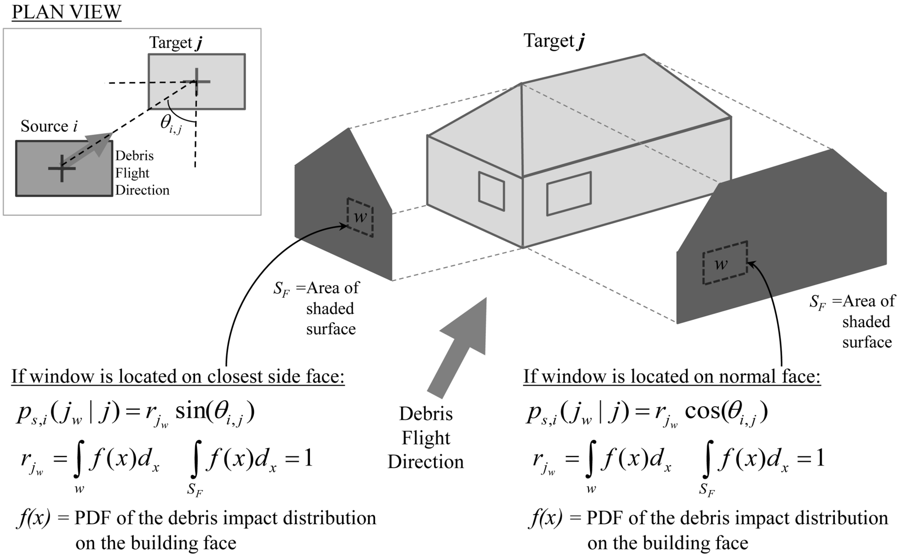
$$\alpha(j_w) = \sum_{s=1}^{S}\sum_{i=1}^{I}\lambda_{s,i}A_j\mu_{s,i}(j)p_{s,i}(j_w|j)\Phi_{s,i}(Z>\zeta_{j_w}|j_w)\,. \tag{2}$$

Stochastic models are developed in Section 3 of Part I to estimate the two probabilistic debris trajectory parameters. The spatial distribution of debris landing positions, $\mu_{s,i}$, is modeled with a two-dimensional Gaussian distribution. The exceedance probability of debris horizontal impact momentum, $\Phi_{s,i}(Z>\zeta_{j_w}|j_w)$, is obtained by modeling the debris non-dimensional horizontal speed with a Beta distribution. Model statistics are estimated based on wind-tunnel experimental data from Lin, *et al*. (2006 and 2007) and post-damage survey data from Twisdale, *et al*. (1996).

The method used to estimate the probability of a debris object impacting a vulnerable component of a house, given that the debris object hits the house, $p_{s,i}(j_w|j)$, is schematically depicted in Fig. 1. If the line connecting the center point of a debris source house, i, to that of a impact target house, j, is oriented $\theta_{i,j}$ ($0 \le \theta_{i,j} \le 90$) degrees from the normal direction of a face (defined as the normal face) of house j, we assume that the probabilities of a debris item hitting the various building faces are, respectively, $\cos(\theta_{i,j})$ for the normal face, $\sin(\theta_{i,j})$ for the perpendicular side face closest to the source house (defined as the close side face), and 0 for the other two faces. We denote by r_{j_w} the probability of debris impacting a window (or a glass door; w) on a building face, given that the debris object hits the building face (including the wall and the roof part above it). This probability is obtained from the spatial probability distribution of debris impact on the building face, integrated over the window area. Then

$$p_{s,i}(j_w|j) = r_{j_w}\cos(\theta_{i,j}) \tag{3}$$

if the window is located on the normal face;



If window is located on closest side face:

$$p_{s,i}(j_w\,|\,j) = r_{j_w}\sin(\theta_{i,j})$$

$$r_{j_w} = \int_w f(x)d_x \qquad \int_{S_F} f(x)d_x = 1$$

f(x) = PDF of the debris impact distribution on the building face

If window is located on normal face:

$$p_{s,i}(j_w\,|\,j) = r_{j_w}\cos(\theta_{i,j})$$

$$r_{j_w} = \int_w f(x)d_x \qquad \int_{S_F} f(x)d_x = 1$$

f(x) = PDF of the debris impact distribution on the building face

Fig. 1 Estimation of the conditional probabilities of debris impacting specific vulnerable components of a house

$$p_{s,i}(j_w|j) = r_{j_w} \sin(\theta_{i,j}) \tag{4}$$

if the window is located on the close side face; and

$$p_{s,i}(j_w|j) = 0 \tag{5}$$

if the window is located on one of the other two faces.

We may assume that the debris impact on a building face is uniformly distributed, so that r_{j_w} equals the ratio of the area of the window to the area of the building face on which the window is located. This assumption of the spatial uniformity of debris impacts is based on the numerical tests by Twisdale, *et al.* (1996), who produced a large number of plots of impact positions on walls and found that the impacts of roof-originating debris is approximately uniformly distributed. Without other supporting data, this assumption is used in the examples in this paper; however, it is not necessary in the modeling framework. For example, if future observations show that windows close to building corners are actually more severely damaged by debris impacts than windows in the middle of building walls, the impact distribution may be assigned higher likelihood values towards corners and lower ones in the middle of walls.

The other parameter in the model, $\lambda_{s,i}$, the mean of the number of type s debris generated from house i, may be estimated from a component-based pressure damage model. Such a pressure damage model can predict the extent of damage to structural components, under specific wind conditions. The number of damaged roof components (the generated debris objects) can thus be estimated. This parameter, as further discussed in the following sections, links the debris- and pressure-damage models in the vulnerability assessment methodology.

2.2. Component-based pressure damage model

The component-based pressure damage model in the current methodology is developed based on the engineering component of the Florida Public Hurricane Loss Projection (FPHLP) model (Gurley, *et al.* 2005). Computer models are built for one-story residential structures with various dimensions, representing concrete gable roof structures, concrete hip roof structures, wood frame gable roof structures, and wood frame hip roof structures (see Fig. 2 for an example). Specifications of the resistance of, and the wind force coefficient on, each building component follow the FPHLP model. The impact resistance of typical glass windows is assumed to be 0.025 kg m s^{-1} (as in the FPHLP model). (This impact resistance capacity is much lower than the typical debris impact momentum, so, if there is no window protection, $\Phi(Z > \zeta_{j_*}|j_*) \approx 1$ in almost all cases.)

By comparing component resistance and force under specified wind conditions, the pressure damage model predicts wind-pressure damage to roof covers, roof sheathing panels, roof-to-wall connections, walls, and openings (including windows, doors, and garage doors). The levels of damage to these building components are correlated in most cases. Especially when opening damage occurs due to pressure or debris damage, the internal pressure is changed (increased when windward openings are damaged and decreased when other openings are damaged), affecting the damage conditions of almost all components. The methodology to estimate the internal pressure is also adopted from the FPHLP model. When opening damage occurs, the internal pressure is adjusted to a weighted-average external pressure acting on the areas of the broken components (see

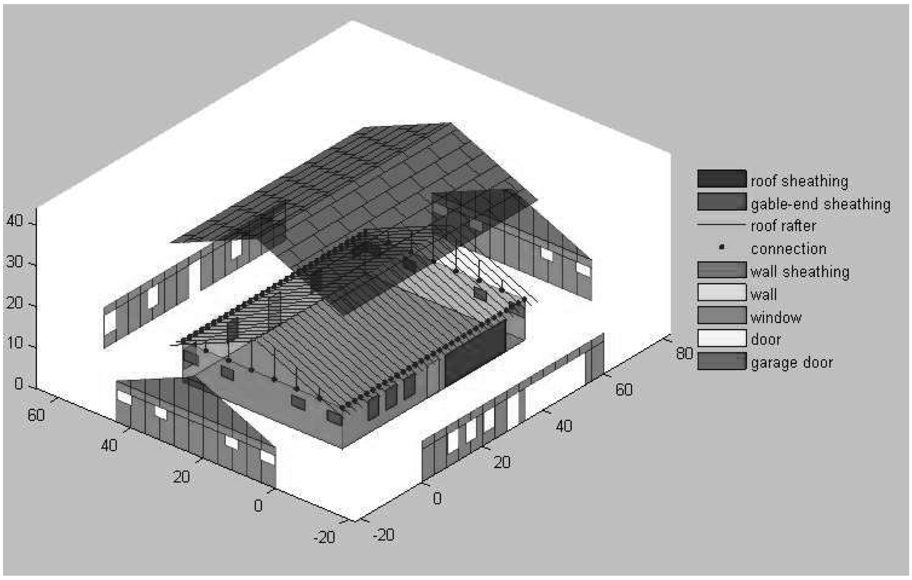


Fig. 2 Computer model representing a one-story concrete gable roof structure

Gurley, *et al.* 2005).

After initial internal-pressure adjustment, further pressure damage to openings may again change the internal pressure. An iterative algorithm is built into the pressure damage model, seeking to obtain the equilibrium between the internal pressure and damage condition, under given wind and debris-damage conditions; the damage conditions are checked for every internal pressure change. It should be noted that although debris damage may initialize the loop of pressure change and pressure damage, the effect of debris damage cannot be repeated and thus should not be involved in this loop. The interaction between pressure and debris damage is modeled at a higher level in the vulnerability analysis framework (see below).

2.3. Integration of debris and pressure damage models

The developed debris and pressure damage models are integrated into an advanced structural vulnerability model. A flowchart of this model is shown in Fig. 3. The vulnerability assessment starts with data collection. A study area containing a residential development is defined, by specifying the location and orientation of each residence. Statistics on relevant house characteristics, such as geometrical features, structural components, and component resistances, as well as the types and characteristics of potential debris sources on the house roof, may be obtained from information about the local building stock, as in many cases building-specific data is not available. The wind-field characteristics in the study area are represented by time series of wind speed and direction during a storm's passage. All of the data are input into a Monte Carlo simulation engine.

At the beginning of each simulation run, the values of all pertinent parameters are randomly assigned to each house, according to the input statistics. The analysis in each run steps through the entire wind time history. At each step, the component-based pressure damage model is applied to estimate wind pressure damage to the structural components of each house in the area. The model-

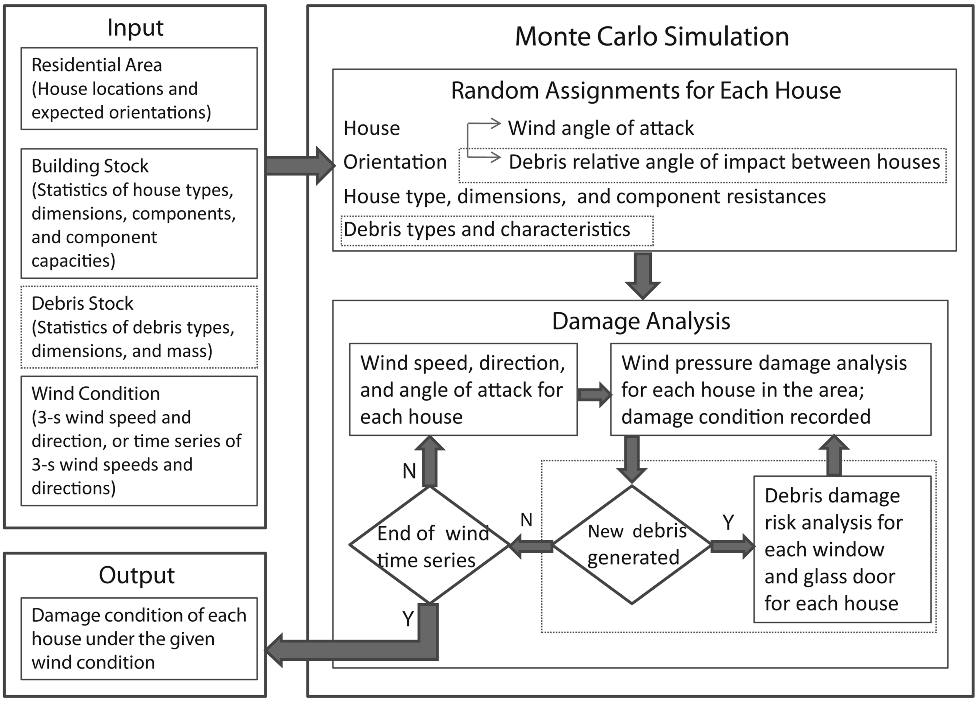


Fig. 3 Flowchart of the integrated vulnerability model for residential developments. (Dash line boxes highlight the components related to debris risk analysis; the functions of these components may be turned off if the debris effect is ignored or if the openings are fully protected from debris damage)

estimated number of items of roof material is assumed to be equal to the mean number of debris objects generated, the parameter λ in the debris risk model. The value of $\lambda_{s,i}$ for each type of debris generated from each house is sent to the debris risk model, which estimates the probability of debris damage to each window and glass door (Eq. (1); other probabilistic quantities are estimated within the debris model, using the methods outlined in Section 2.1 above and Section 3 in Part I). Based on the debris damage probabilities, the pressure damage model determines whether or not windows are damaged (by comparing the damage probabilities with random numbers uniformly distributed in [0, 1]), updates internal pressure, and recalculates the damage to structural components. The estimates of the numbers of new items of debris ($\lambda_{s,i}$) are again sent to the debris risk model to evaluate their damage potential, starting a loop of pressure-debris damage interaction, until no more debris is generated from any house. The damage condition and the internal pressure condition are then recorded and carried to the next analysis step until the end of the wind time history. Based on a large number of Monte Carlo simulation runs, the time history of the mean and variance of damage condition is obtained for each house in the study area, and further statistical analyses may then be carried out.

3. Numerical examples and discussion

We can apply the integrated vulnerability model to predict progressive wind damage to residential

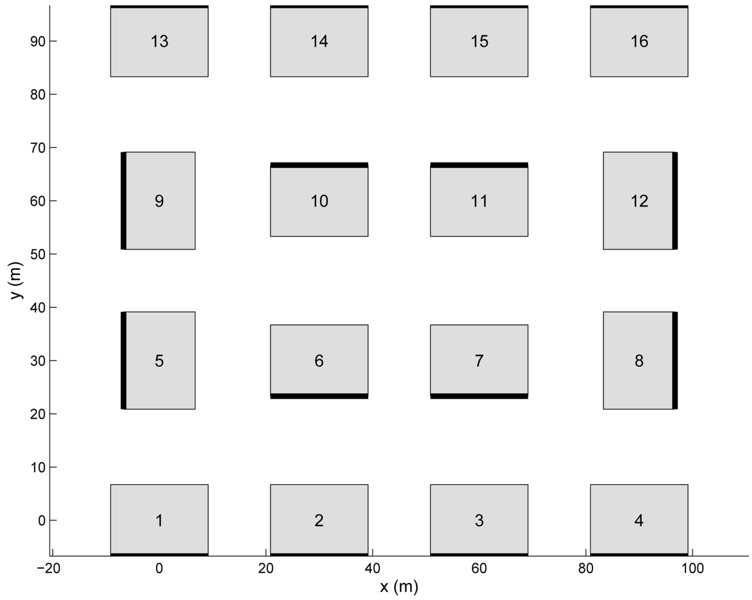


Fig. 4 Plan view of a hypothetical residential development. (The center distance between adjacent houses is 30 m; the thick line on a side of the house represents the front face of the house)

developments during the passage of particular hurricanes. The model can also be used to estimate the damage condition of residential developments under a given wind speed and direction (e.g., the maximum wind velocity during a storm's passage); or analyses may be carried out for a range of wind speeds and directions. Annual damage may then be obtained by combining the annual frequencies of these wind conditions with the wind damage predictions (see, e.g., Pinelli, *et al.* 2004; Li and Ellingwood 2005). As a simple hypothetical example, consider a residential development of 16 identical concrete block gable roof structures, as shown in Fig. 4. We consider roof cover, roof sheathing, and gable-end sheathing as debris sources, and windows and glass doors as debris-impact vulnerable components. Vulnerability assessment for this cluster of houses is described in this section, first for specified wind velocities and then for a wind-velocity time history during a storm's passage.

3.1. Instantaneous wind damage estimation

Vulnerability analysis of the 16-house cluster is conducted for a wind speed of 65 m/s, and a sampling of results is presented in Table 1. First, suppose the wind direction is at a 45-degree angle (from northeast); note that House 16 is less threatened by debris impact, while House 10 and House 11, which have the same house characteristics and orientation as House 16, suffer more debris impact. As might be expected, House 10 and House 11 sustain more damage, especially to their windows and doors, due to direct debris impact damage as well as the induced internal pressurization. The damage to other structural components on suction zones, such as garage doors, roof sheathings, and roof covers, is also increased due to the internal pressurization induced by debris damage. For given structural type and dimensions, house orientation, and wind conditions, the uncertainty in the damage estimation stems mainly from the uncertainty of component resistances (represented in the

Table 1 Estimated wind damage conditions of the hypothetical residential development in Fig. 4, under a wind speed of 65 m/s and various wind directions

Mean Damage (in %) (Std of Damage (in %))		Cover	Sheathing	Connection	Window	Door	Garage Door	Wall
65 m/s wind at 45 deg	House 10	26.87 (24.94)	13.88 (29.09)	14.85 (28.06)	44.00 (19.92)	82.00 (27.08)	53.00 (50.16)	5.25 (14.78)
	House 11	25.66 (22.64)	12.11 (26.38)	17.91 (28.55)	35.20 (21.67)	66.00 (34.73)	60.00 (49.24)	6.75 (17.36)
	House 16	23.61 (20.02)	9.95 (23.25)	14.58 (26.40)	13.60 (29.13)	18.50 (36.00)	39.00 (49.02)	6.00 (18.84)
65 m/s wind at eight main directions	House 10	35.76 (31.39)	24.76 (36.53)	29.33 (36.39)	53.18 (26.32)	68.50 (34.77)	53.75 (49.89)	11.09 (23.79)
	House 11	35.91 (32.12)	25.52 (37.17)	30.36 (37.12)	53.63 (24.48)	70.38 (34.26)	55.88 (49.68)	10.56 (22.36)
	House 16	36.50 (33.06)	25.98 (38.32)	29.47 (37.31)	35.06 (33.61)	40.31 (43.44)	49.63 (50.03)	10.56 (21.83)
	All 16 Houses	37.06 (32.95)	26.58 (38.23)	30.77 (37.70)	45.59 (33.34)	50.60 (42.54)	54.18 (49.83)	11.74 (23.42)

input by probability distributions). (Uncertainties owing to modeling assumptions and approximations are not considered here.)

If the wind direction is uncertain, and only the wind speed is given, the wind damage condition may be estimated as a weighted average of the damage conditions under different wind directions. For instance, assuming the wind direction is uniform, the damage due to each of the eight main directions (increasing from 0 to 360 for every 45 degrees) is given equal weight. The analysis results in Table 1 show that the estimates of damage to House 10, House 11, and House 16 are all greatly increased if the wind direction is assumed to be uniform over the eight directions, compared to the case when the wind direction is fixed at a 45-degree angle. This is mainly because these three houses tend to be more vulnerable to debris damage when the wind comes from directions other than 45 degrees (and especially when it comes from the southwest).

The overall damage condition of a residential development may be estimated by averaging the damage conditions of individual houses in the area. However, if the average damage condition of the area is used as representative of the damage condition of a particular house in the area, the uncertainty in the damage estimation for the particular house is of course increased due to the uncertainty in its orientation and location, which may greatly affect its debris damage risk. (Note that for this example the average damage condition for all of the 16 houses is not very different from the damage condition of individual houses, when the wind direction is assumed to be uniform over all directions (Table 1), due to the highly symmetrical layout of houses in this hypothetical development.)

3.2. Cumulative wind damage analysis

We estimate the damage condition to the hypothetical residential development in Fig. 4, under an observed hurricane wind time history, namely, in this example, the 1-minute wind (speed and direction) time history measured by the Florida Coastal Monitoring Program (FCMP; Masters 2004) during the passage of Hurricane Isabel (2003). (The observed 1-minute wind speeds are multiplied by a factor of 1.35 to approximate the 3-second gust wind speeds.) One method of introducing the wind time history into the vulnerability analysis consists of using the maximum wind speed (and corresponding direction) during each time interval of the wind time history. Fig. 5 shows the predicted (average) progressive damage condition of the hypothetical residential development, for every 15 minutes, over the entire Isabel wind time history. Larger values of the estimated mean damage to windows and doors than those to other structural components indicate the significant effect of debris damage, even under this low-end Category 2 hurricane wind condition.

The first method, applying the maximum wind velocity in each time interval to the vulnerability analysis, requires a relatively long computing time, because many wind-speed and -direction data points are used in the analysis (when the time history is long). Indeed, the duration effect on the damage condition is mainly due to the variation of the wind direction. (Note that fatigue is not considered in current damage analysis.) An alternative, computationally more efficient method is to select the maximum wind speed (and corresponding direction) in each wind direction segment of the wind time history. Fig. 6 shows the estimated progressive damage condition of the hypothetical residential development for every 15 degrees of direction change, over the entire Isabel wind time history. The cumulative damage conditions estimated based on the two methods are compared in Table 2. Most results are very close, while the second method is much more efficient, as only a relatively small number of wind-velocity data points are selected for the analysis (16 compared to 118 in the first method, for this time history).

In addition, Table 2 compares the damage condition estimated by the time series analysis and by maximum-wind-speed damage analysis. The latter estimates the damage condition under the maximum wind speed (and corresponding direction) of the entire wind time history. The results from the maximum wind damage analysis are expected to be lower than those from the time series analysis, since during a storm's passage winds approach structures from different directions, causing

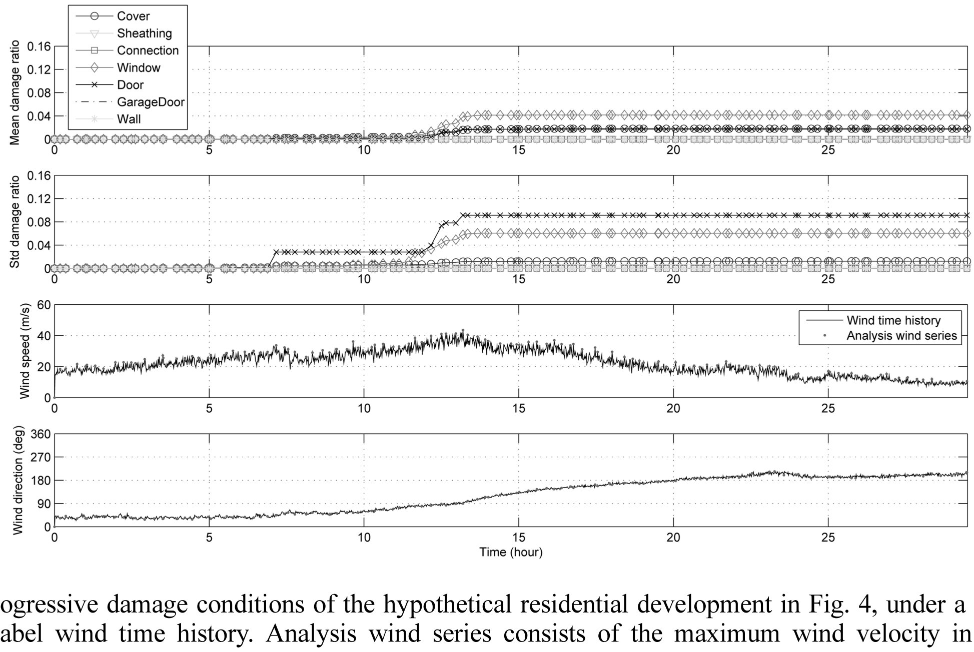


Fig. 5 Progressive damage conditions of the hypothetical residential development in Fig. 4, under a Hurricane Isabel wind time history. Analysis wind series consists of the maximum wind velocity in each 15-minute time interval of the measured wind time history

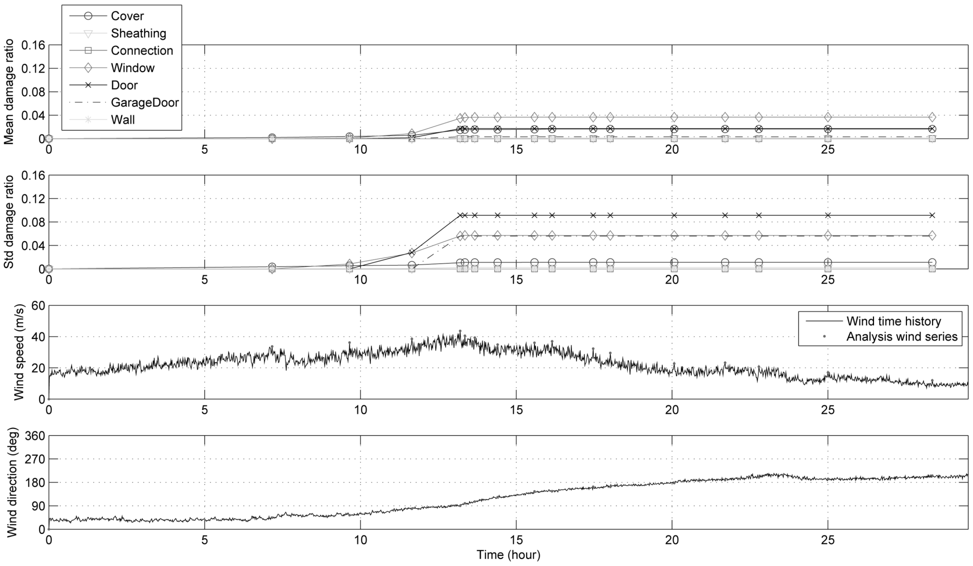


Fig. 6 Same as in Fig. 5, but analysis wind series consists of the maximum wind velocity in each 15-degree direction segment of the measured wind time history

Table 2 Comparison of the estimated wind damage conditions of the hypothetical residential development in Fig. 4, under a Hurricane Isabel wind time history, by time series and maximum wind analyses, respectively. (Series 1 represents the time series analysis method 1, which uses the maximum wind velocity of each 15-minute time interval of the wind time history; Series 2 represents the time series analysis method 2, which uses the maximum wind velocity of each 15-degree direction segment)

Mean Damage (in %) (Std of Damage (in %))		Cover	Sheathing	Connection	Window	Door	Garage Door	Wall
Cumulative wind damage (Isabel wind history)	Series 1	1.71 (1.22)	0.086 (0.23)	0.00 (0.00)	4.15 (6.03)	1.72 (9.12)	0.00 (0.00)	0.00 (0.00)
	Series 2	1.64 (1.12)	0.088 (0.23)	0.00 (0.00)	3.67 (5.70)	1.72 (9.12)	0.31 (5.59)	0.00 (0.00)
Maximum wind damage (43 m/s at 90 deg)		1.32 (1.12)	0.099 (0.30)	0.00 (0.00)	3.77 (5.34)	1.41 (8.28)	0.00 (0.00)	0.00 (0.00)

damage to accumulate. However, maximum wind damage analysis may overestimate debris damage, if it assumes that all debris items are generated at the time of occurrence of the maximum wind speed and fly far, while in reality much of the debris generated may hit the ground under lower-wind-speed conditions. Also, if the maximum wind damage analysis estimates the average damage condition at the maximum wind speed over all directions, it may overestimate the damage, if the building is less vulnerable in the actual direction of the maximum wind than in other directions.

Whether the time series analysis or instantaneous wind damage analysis should be used depends in part on the application. The time series analysis has the great advantage of predicting cumulative damage during the passage of particular hurricanes, as it models the consequences of structural damage in real storms. The instantaneous wind damage analysis may be used in annual wind damage and loss estimation, as it can be easily combined with information about the wind climate (e.g., the probability distributions of wind conditions). The coupled vulnerability model, which fully considers windborne debris effects, is flexible enough to be used in either of these applications to estimate the wind damage risk for a particular house or for an entire residential development.

4. Site-specific analysis: Case study

We now demonstrate the use of this structural vulnerability estimation methodology through an example of site- and storm-specific analysis. The selected study site is a residential development of 358 one-story (site-built) houses in Sarasota County, Florida (Fig. 7). The locations of the residential houses are known, while the structural characteristics of each house are unknown and estimated based on information about local building stock. The structural type, dimensions, and populations (Table 3) are determined from the building stock of the central region of Florida, according to the FPHLP report (Gurley, *et al.* 2005). We model the orientation of each house in terms of a Gaussian random variable with as its mean the direction perpendicular to the main street of the house and as its standard deviation 15 degrees. The characteristic data on various types of shingles, tiles, and

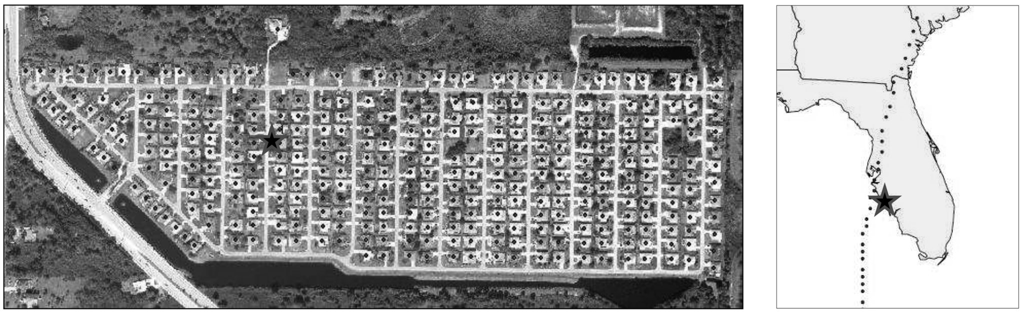


Fig. 7 Study area of a residential development of 358 houses in Sarasota County, Florida (left; the dots represent the centers of the houses) and simulated storm track of Hurricane Charley of 2004 (right). The star (in both panels) represents the recording location of the wind time history during the passage of the simulated storm

Table 3 Structural type models of one-story residential houses for the central region of Florida, according to the building stock in the FPHLP report (Gurley, *et al.* 2005)

Structural type	Plan (ft × ft)	Wall height (ft)	Roof slope	Overhang (#)	Window (#)	Door (#)	Garage door (#)	Population
Conrete block gable roof	60 × 44	10	$\frac{5}{12}$	2	7 medium 8 small	1 glass 1 wood	1	51%
Conrete block hip roof	60 × 44	10	$\frac{5}{12}$	2	7 medium 8 small	1 glass 1 wood	1	27%
Wood frame gable roof	60 × 38	10	$\frac{5}{12}$	2	7 medium 8 small	1 glass 1 wood	1	15%
Wood frame hip roof	60 × 38	10	$\frac{5}{12}$	2	7 medium 8 small	1 glass 1 wood	1	7%

sheathings are collected from local construction material manufacturers. The types of cover and sheathing debris are randomly assigned to each house. Also, as in the previous hypothetical analysis example, we consider roof cover, roof sheathing, and gable-end sheathing as debris sources, and windows and glass doors as debris-impact vulnerable components. In the site-specific analysis, uncertainties in the damage estimation for each house are mainly due to the uncertainties of the structural characteristics, debris features, and house orientations.

In this example, we estimate the wind damage to the study area from Hurricane Charley (2004), which passed to the left of the study area. Hurricane Charley is numerically simulated using the Weather Research and Forecasting (WRF) model (Skamarock, *et al*. 2005). A simulated wind-velocity time history (recorded for every 15 minutes) at a location within the study region is obtained (see Fig. 7). The estimated time history of the damage condition in this development, under the simulated wind time history, is shown in Fig. 8. As a comparison, Fig. 9 shows the estimated time history of the damage condition when debris effects are ignored. It is obvious that the mean as well as the variation of the damage to almost all structural components are greatly increased when debris effects are considered, especially for windows and doors. The predicted cumulative damage conditions are also compared in Table 4, together with the results from the maximum wind damage analysis. The maximum wind analysis underestimates the damage condition in this case. Moreover, without considering debris impact effects, no damage is estimated for almost all of the structural components, except for roof covers and sheathings, by either the time series analysis or the maximum wind analysis. This does not agree with the observations that many areas experienced moderate to severe damage during the passage of Hurricane Charley. Again, the most accurate method to predict the wind damage to residential developments during storm passage is a dynamic vulnerability assessment methodology which fully considers the interaction between pressure damage and debris damage over the duration of strong winds.

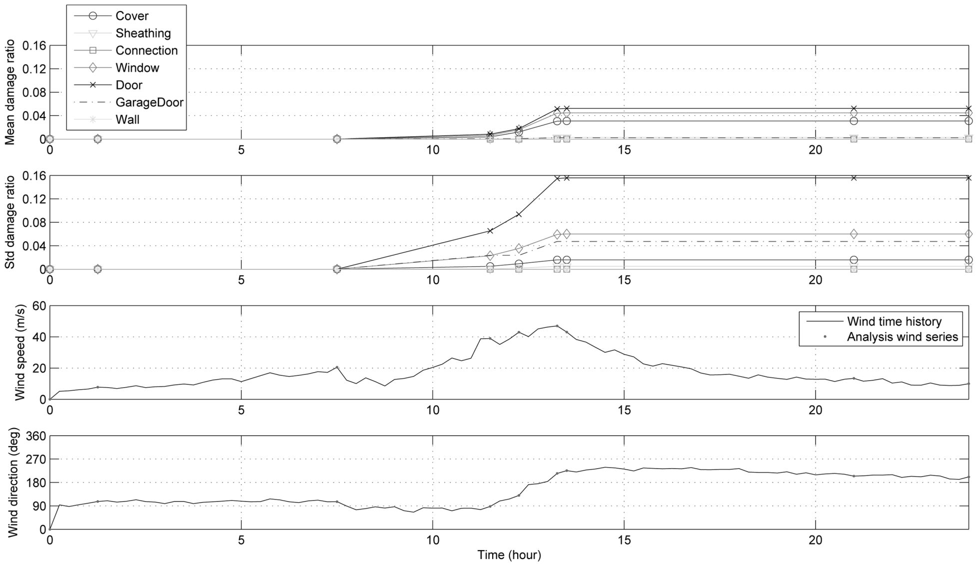


Fig. 8 Progressive damage conditions of the study area in Sarasota County, Florida (Fig. 7), during the passage of Hurricane Charley. Analysis wind series consists of the maximum wind velocity in each 15-degree direction segment of the simulated wind time history

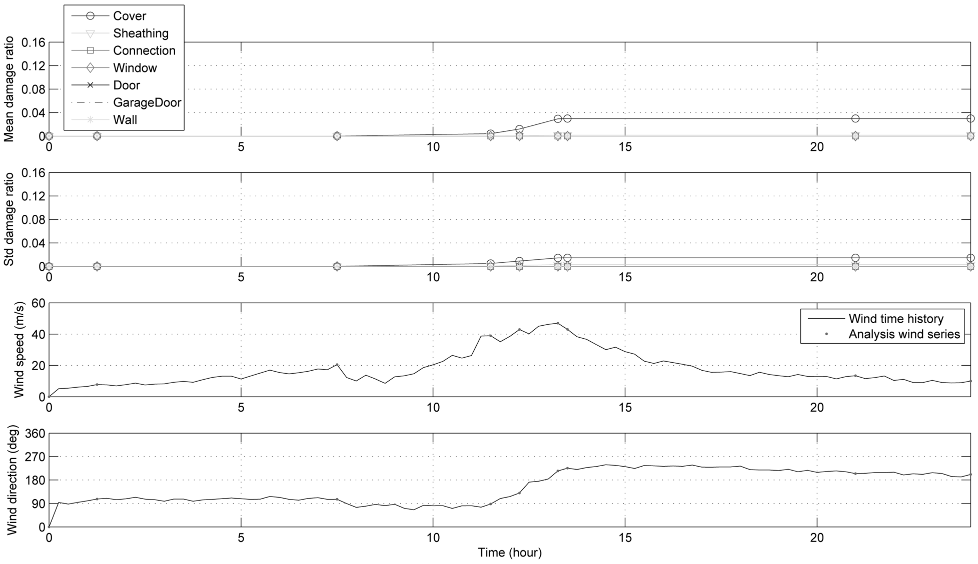


Fig. 9 Same as in Fig. 8, but ignoring debris damage effects

Table 4 Comparison of the estimated wind damage condition of the residential development in Sarasota County, Florida (Fig. 7), during the passage of Hurricane Charley, by time series and maximum wind analyses, respectively

Mean damage (in %) (Std of damage (in %))		Cover	Sheathing	Connection	Window	Door	Garage door	Wall
Cumulative wind damage (Charley wind history)	with debris	3.09 (1.59)	0.27 (0.48)	0.00 (0.00)	4.47 (6.00)	5.22 (15.57)	0.22 (4.72)	0.00 (0.00)
	without debris	2.97 (1.44)	0.15 (0.29)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)
Maximum wind damage (47 m/s at 215 deg)	with debris	2.41 (1.34)	0.24 (0.47)	0.00 (0.00)	3.71 (5.22)	3.35 (12.51)	0.11 (3.34)	0.00 (0.00)
	without debris	2.33 (1.32)	0.12 (0.26)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)

5. Conclusions

Windborne debris is a major cause of wind damage to residential areas. A time-dependent structural vulnerability assessment methodology is developed that accounts for debris impact damage to building envelopes as well as the ‘chain reaction’ failure mechanism it induces by interacting with wind pressure damage. Examples are given to demonstrate the use of the methodology to predict the cumulative wind damage to residential developments during storm passage. Applications of the methodology to annual wind damage estimation are also discussed.

The interaction between pressure damage and debris damage is modeled by integrating a debris risk analysis methodology and a component-based pressure damage model. The former is an extension of Lin and Vanmarcke (2008) debris risk model for general structural vulnerability analysis (Lin, *et al*. 2010). The component-based pressure damage model is developed based on the engineering component of the Florida Public Hurricane Loss Projection (FPHLP) model (Gurley, *et al*. 2005). The use of the integrated vulnerability model in instantaneous wind damage analysis and time series analysis are presented, respectively. In time series analysis, it is much more efficient to apply the maximum wind velocity in each wind direction segment, rather than that in each time interval, of the wind time history.

The underlying physical mechanism of pressure-debris interaction is internal pressurization. In our current vulnerability model, a simple methodology (see Gurley, *et al*. 2005) is used to adjust the internal pressure when opening damage occurs. Research is needed to validate and, perhaps, further improve the internal pressure estimation method.

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