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Hurricane vulnerability model for mid/high-rise residential buildings

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Abstract. Catastrophe models appraise the natural risk of the built-infrastructure simulating the interaction of its exposure and vulnerability with a hazard. Because of unique configurations and reduced number, mid/high-rise buildings present singular challenges to the assessment of their damage vulnerability. This paper presents a novel approach to estimate the vulnerability of mid/high-rise buildings (MHB) which is used in the Florida Public Hurricane Loss Model, a catastrophe model developed for the state of Florida. The MHB vulnerability approach considers the wind pressure hazard exerted over the building's height as well as accompanying rain. The approach assesses separately the damages caused by wind, debris impact, and water intrusion on building models discretized into typical apartment units. Hurricane-induced water intrusion is predicted combining the estimates of impinging rain with breach and pre-existing building defect size estimates. Damage is aggregated apartment-by-apartment and story-by-story, and accounts for vertical water propagation. The approach enables the vulnerability modeling of regular and complex building geometries in the Florida exposure and elsewhere.

Keywords: mid/high rise buildings vulnerability; interior damage; impinging rain; cyclone risk

1. Introduction

The eastern United States and several other coastal areas around the world are highly vulnerable to the impact of tropical cyclones due to their concentration of population and infrastructure, and their economic dependence on coastal resources and tourism. This is especially true of large urban coastal areas, like Miami and Tampa in the case of the United States, where the increasing population density resulted in the construction of large numbers of mid/high-rise buildings (MHB) which may be highly susceptible to hurricane damage. To ensure the economic viability of coastal areas and to enhance the safety of their inhabitants, it is imperative to foster hazard-resilient sustainable coastal communities. An important component of this process is to

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gain a good understanding of the cyclone risk to which the built-environment is subjected. This knowledge will allow decision makers and planners to put in place proper economic instruments and to develop risk mitigation strategies.

Catastrophe models advance the above objective as they are indispensable tools to estimate natural risk and help in the development of mitigation policies. The challenge for modelers is to develop credible models that assess hazard risk with acceptable uncertainty and are able to analyze varying site and building conditions. MHB cannot be classified in generic types of similar geometrical configurations. Therefore, a versatile vulnerability assessment methodology is required to deal with their unique configurations. This paper introduces the methodology developed for the Florida Public Hurricane Loss Model (FPHLM) to analyze the vulnerability of MHB subjected to the hurricane-induced wind, debris impact, and rain.

2. Natural risk estimation, catastrophe models, and building vulnerability assessment

Natural risk estimation measures the probable loss severity that the observed or hypothesized occurrence of hazards may cause on the infrastructure. As such, this discipline provides crucial decision information to government institutions and public firms that oversee buildings subjected to natural threats. The methodologies to evaluate natural risk have progressed from simple actuarially based approaches to the more complex probabilistic simulation approach commonly adopted today (e.g., Grossi and Kunreuther 2005, Pita, Pinelli *et al.* 2013). The complexity of the tools to assess natural risk has accompanied that development.

The most advanced tools to assess natural risk nowadays are the so-called catastrophe models. These perform three main operations: (1) identification of hazard and exposure, (2) quantification of the severity of consequences arising from the conjunction of hazard and exposure, and (3) assessment of the frequencies with which those several consequences are likely to occur. Catastrophe models have a tripartite structure: hazard estimation, building vulnerability, and exposure characterization.

Traditionally, the catastrophe models deal with well-defined sets of building typologies which share similar construction attributes. Each typology represents a class of buildings which might include up to hundreds of thousand if not millions of buildings. For example, single family one story masonry buildings, with gable roof, shingles, and no shutters. As such, a relatively small number of vulnerability functions can statistically represent the wind vulnerability of the entire building population of a region. However, if the characteristics are very diverse preventing that the buildings are grouped under a common class, the statistical validity of the vulnerability functions comes into question. The classification of mid/high-rise residential buildings falls under this case as these are neither homogeneous nor numerous as to define uniform building classes. As a result a new methodology, as the one described herein, needs to be put in place to assess the vulnerability of these buildings.

3. The Florida Public Hurricane loss model

The FPHLM is a catastrophe model funded and commissioned by the state of Florida to aid in insurance rate making, and to provide an independent tool to compare against proprietary models.

The model has been certified uninterruptedly since 2006 by the Florida Commission on Hurricane Loss Projection Methodology undergoing extensive testing, validation, and external review (FCHLPM 2013). Since its inception, the FPHLM has proved to be a valuable model to project insurance losses (for example, the State uses the model to do stress tests on insurance companies) and to evaluate mitigation strategies for residential homes (Hamid, Pinelli *et al.* 2011, Pinelli, Pita *et al.* 2011).

The source code is proprietary, but it is the first state-owned model to predict insured hurricane losses with an open rationale. All the assumptions and methodologies underlying the model are published and available to the public. The FPHLM estimates the risk of portfolios of residential insurance policies, for the state, Counties, or other territories with metrics such as: annual expected losses, probable maximum losses, and value at risk. The model also performs scenario analyses. Once a land-falling hurricane track, size and maximum wind speed are known, the model can estimate losses to the insured exposure or portfolio of policies. More detailed information on the characteristics of the FPHLM can be found elsewhere (Hamid, Pinelli *et al.* 2011, Pinelli, Pita *et al*. 2011, Hamid, Kibria *et al.* 2010).

The methodology presented herein to estimate the vulnerability of mid/high-rise buildings considers wind and rain related building damage. A surge damage component is currently in development under a separate contract with the sponsor and will be presented in a separate paper.

4. Description of the exposure component

As noted earlier, a catastrophe model consists of three components: hazards, vulnerability and exposure. The FPHLM is split in three independent programs according to the characteristics of the exposure:

- for personal residential (PR) single family homes, composed of 1 or 2 story site built or manufactured homes;
- for low-rise commercial residential buildings (LRB), composed of 1 to 3 story low-rise, predominantly apartment buildings;
- for a mid/high-rise commercial residential buildings (MHB), composed of 4 stories and higher, predominantly condominium buildings (Fig. 1).

Each of these three programs share the same hazard component, but have unique vulnerability and actuarial components.

The exposure of PR and LRB buildings can be adequately described by several common typologies of similar geometry, use-type, and materials. Consequently, a similar simulation approach to assess the vulnerability of the typologies can be used. In contrast, the MHB cannot be reduced to a few typologies (Pita 2012). Moreover, the MHB are engineered structures that usually sustain few structural failures during a windstorm, but are subject to damage via water ingress through their cladding and breached openings.

It would not be realistic to instantiate the MHB inventory with a few representative building classes, because it would misrepresent the majority of such existing buildings. For instance, there is a wide variety of steel-frame structure building shapes and configurations. These different shapes lead to very different wind-loading scenarios and therefore different vulnerabilities. Equally important, the amount of MHB in the Florida inventory is at least an order of magnitude smaller than that of PR or LRB. It is therefore not feasible to average the losses over a very large number of buildings and compensate small differences between buildings. On the contrary, the inventory consists of relatively few buildings with unique geometries.

This paper presents a novel modular approach to model the vulnerability of MHB that circumvents these difficulties. The approach discretizes individual buildings into typical individual units, assesses separately their exterior damage due to wind and debris impact, their interior damage due to water intrusion, and aggregates the damage from each unit to estimate the overall building vulnerability.

Since the modular vulnerability assessment is performed individually with every MHB in a portfolio, the methodology does not generate building vulnerability curves where damage is a function of wind speeds measure located at 10 meters height. Instead, this methodology considers the wind profile that the building experiences over its height for a given synthetic or historical hurricane.

4.1 Apartment unit types

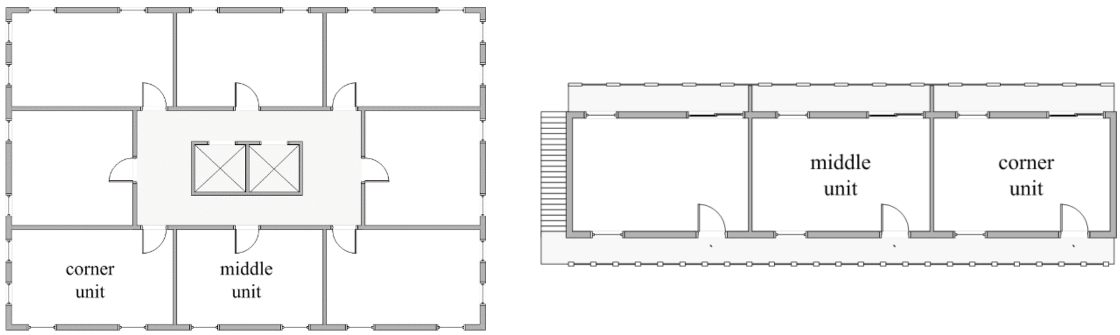
In an extensive survey conducted on the Florida building stock, the MHB exhibited a large architectural variety (Pita, Pinelli *et al*. 2008, Pita 2012). For the purposes of wind vulnerability estimation, the buildings were classified as open or closed configuration buildings. The buildings whose units are accessed through external corridors with the circulation core (elevator and/or stairs) located in the exterior of the building are called “open buildings”. Conversely, buildings whose units are accessed internally are termed “closed buildings” (Fig. 1). A survey of public aerial imagery supplied the percentages of buildings in coastal and inland zip codes that have closed and open configurations, stratified by building height (Table 1).

(a) closed building configuration (b) closed building configuration

Fig. 1 Typical MHB building configurations Source: Windows Live Maps®

Table 1 Percentage of open and closed buildings by number of stories. From Pita (2012)

Number of stories	Coastal zip codes		Inland zip codes	
	Closed	Open	Closed	Open
4 – 6	43	57	87	13
7 – 9	54	46	65	35
> 9	84	16	96	4



(a) closed building configuration (a) closed building configuration

Fig. 2 Diagrams of MHB in the model with middle and corner apartment types shown

Units located in the middle of a closed building have only one wall exposed to wind while those located in an open building have two. Apartments located in the corners of a closed building have two exposed walls, while those in the corners of open buildings have three exterior walls (Fig. 2). These are referred to in the model as "middle" and "corner" units. Corner units are subjected to the higher wind pressures that are present along the edges of the building, compared to the middle units, which are located within lower pressure zones at the center of the wall area.

In addition to the building configuration and the position of the unit in the base plan, the units are defined by four other features: the unit area, the story on which the unit is located (influencing wind speed and the debris potential hazard), the presence or not of a balcony which implies the presence or not of a sliding door, and opening protection.

A common base area of 105 m^2 is assigned in the model to all units based on the results of the surveys. The story on which a unit is located is an indicator of the likelihood of debris damage to openings (Jain 2015). Consequently, the buildings have been divided vertically in three debris zones: Zone 1: 1st – 3rd story (maximum impact potential); Zone 2: 4th – 7th story (medium impact potential) and, Zone 3: 8th + stories (least impact potential). The last feature of the description of unit models is the opening protection: windows and sliders can have either normal glass (NG), with or without aluminum shutters, or impact resistant glass (IR). Doors are either standard or impact resistant. If the glass type or the presence of shutters is not specified in the portfolio database, the algorithm probabilistically assigns it using the year built and the hurricane zone as indicators.

Table 2 Typical MHB apartment unit models

Opening Type	Unit type	Quantity*	Dimensions [m]	Total openings area [m^2]
Windows	Corner/Closed	6 (7)	1.5 × 1.2	11 (13)
	Corner / Open	7 (8)	1.5 × 1.2	13 (14)
	Middle / Closed	3 (4)	1.5 × 1.2	5 (7)
	Middle / Open	4 (5)	1.5 × 1.2	7 (9)
Entry Door	All	1	0.9 × 2	1.8
Sliding Door (none)	All	1(0)	1.5 × 2	3 (0)

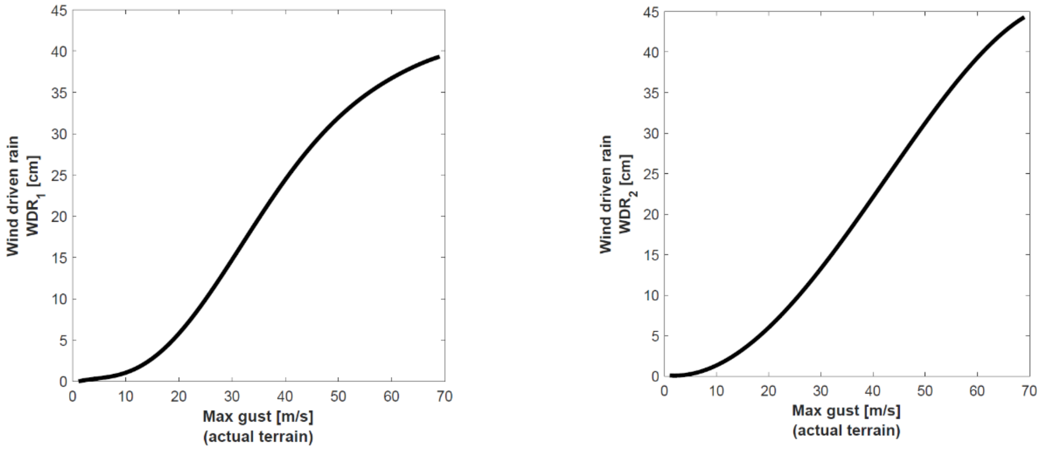
*values in parentheses indicate quantity when no sliding door is present

As a result of this classification scheme, 156 MHB different unit models were developed in version 6.1 of the FPHLM, corresponding to different combinations of building layout (open or closed), floor location (corner or middle unit), opening protection (impact resistant, aluminum shuttered or not protected), and story height (zones 1 to 3). Each model can have one sliding door (i.e., with a balcony), or no sliding door. In the latter case, the number of windows is increased. Further classification details of the models are summarized in Table 2.

5. Hazard model

The FPHLM hurricane hazard wind model is based on the last 114 years of hurricane data (Powell, Soukup *et al*. 2005). The model provides simulations of vertical wind speed profiles at any particular location using the terrain conversion methodology described in Vickery, Wadhera *et al.* (2009). This methodology is a modification of the log wind profile and has been validated against dropsonde data.

In addition, a separate probabilistic hurricane rain model was developed which generates estimates of accumulated wind-driven rain as a function of maximum wind speed during a hurricane (Pita, Pinelli *et al.* 2012, Pita 2012). For every simulated storm, the rain model computes two complementary accumulated amounts of wind driven impinging rain at each location, WDR_1 and WDR_2 from the wind-driven rain considered flowing through a vertical plane. WDR_1 is the wind-driven rain accumulated between the beginning of the storm and the moment when the maximum wind speed occurs. WDR_2 is the remaining wind-driven rain accumulated until the end of the storm. Fig. 3 shows the simulated mean value of WDR_1 and WDR_2 as a function of the storm maximum wind speed. Both WDR_1 and WDR_2 are assumed to have the same variation with height as the wind speed, since the wind driven rain is a linear function of the horizontal wind speed (Straube and Burnett 2000, Blocken and Carmeliet 2010).



(a) WDR_1 (b) WDR_2

Fig. 3 Mean accumulated impinging rain functions

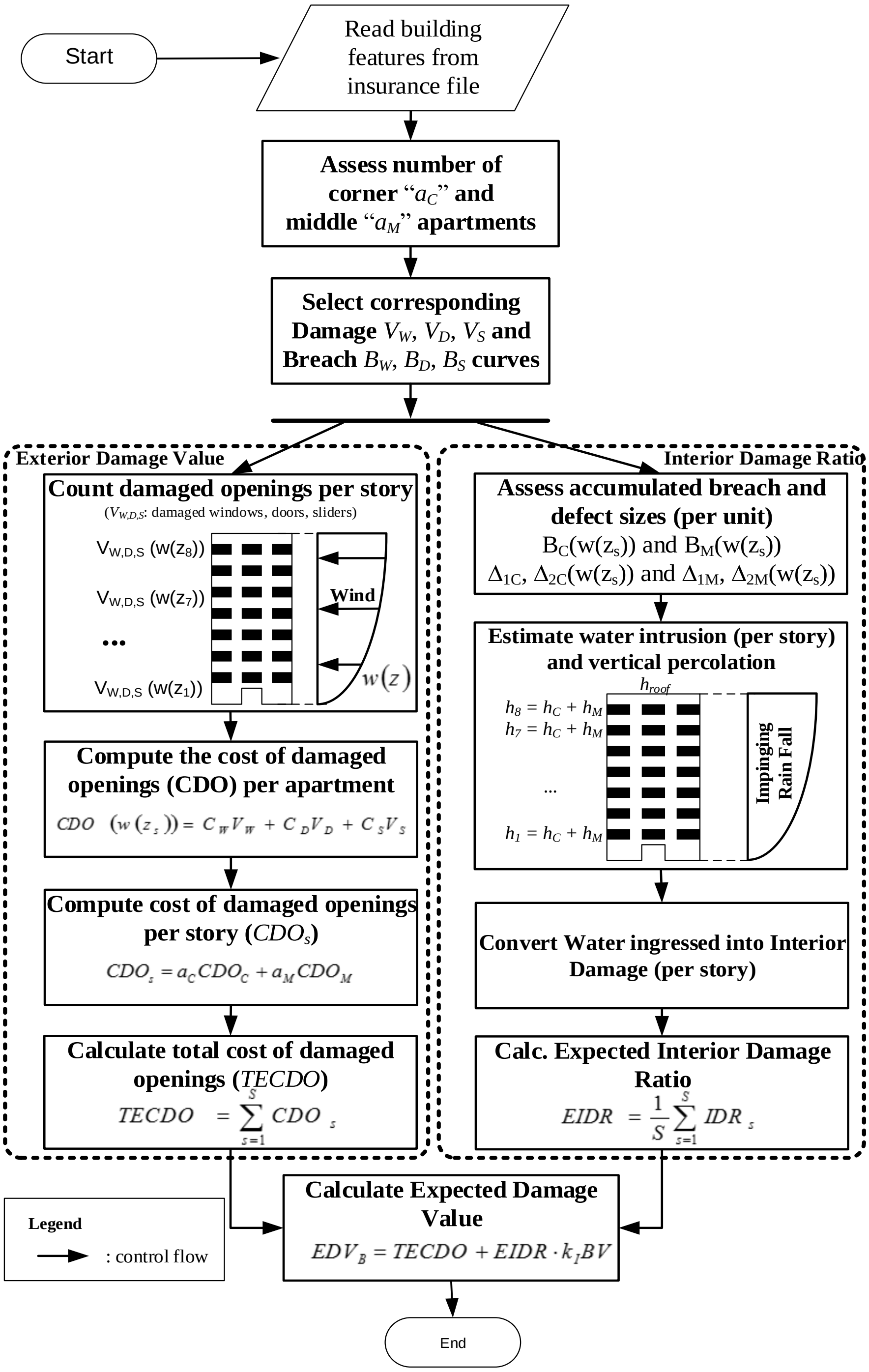


Fig. 4 Hurricane vulnerability assessment of a MHB

6. Vulnerability model

Provided the hurricane wind and rain estimates from the hazard model, the vulnerability model performs three main tasks: (1) it estimates and appraises the physical damage to exterior components of buildings; (2) it assesses the interior and utilities damage caused by water that ingresses through exterior damage and defects; (3) it combines the exterior and interior damage to estimate the building and contents vulnerabilities. The complete vulnerability model is described in Pita (2012). The methodology for assessing the overall vulnerability of a MHB is summarized in Fig. and explained, along with its terminology, in the coming sections.

4.1 Exterior damage assessment

The MHB have engineered steel and/or concrete structures which are not expected to suffer significant structural damage from hurricane winds. Most external wind damage in MHB consists in the failure of non-structural components, especially openings. Hence, historically the vast majority of financial loss is associated with fenestration damage and the cascading interior damage that results from rainwater intrusion (e.g., Mileti 1999). For example, Fig. 5 shows a MHB in Satellite Beach, Florida, after it was damaged by Hurricane Jeanne in 2004. Although the building appears to have suffered only minimal structural damage, it did suffer extensive interior damage due to breach of the envelope, and as a consequence the owners chose to tear it down rather than repair it.

Structural damage is also not emphasized in the model because the damage caused by storm surge is not currently accounted for in the model (although it will be in a future version of the model), and much of the structural damage of MHB, even building collapse, is often associated with surge-induced erosion and scouring of the foundations. Moreover, the intentionally unique nature of many mid-high rise buildings renders the modeling of a 'typical façade' and its potential vulnerability an intractable problem. What these structures do have in common, however, are individual living units with windows, doors, defects, and vulnerability to rain water intrusion damage which are considered in the model.

Fig. 5 MHB damaged by Hurricane Jeanne in 2004

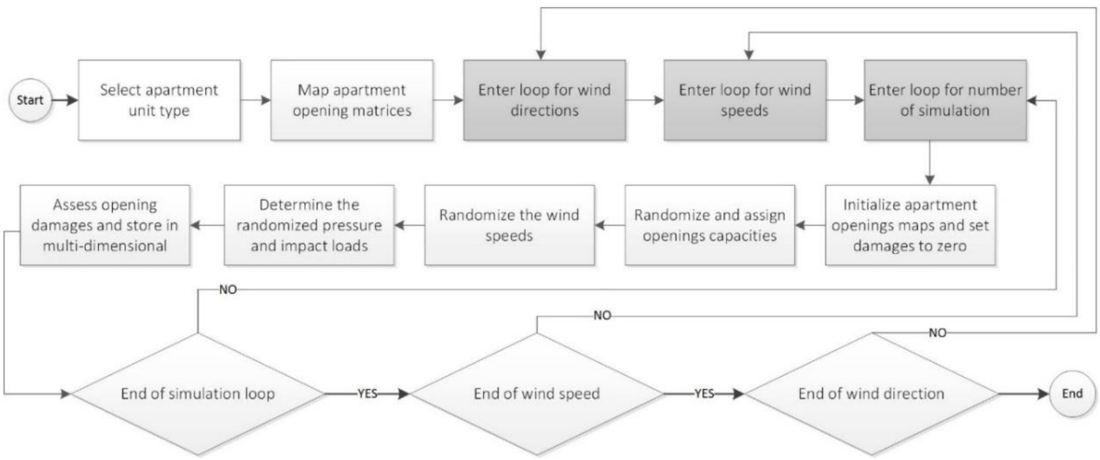
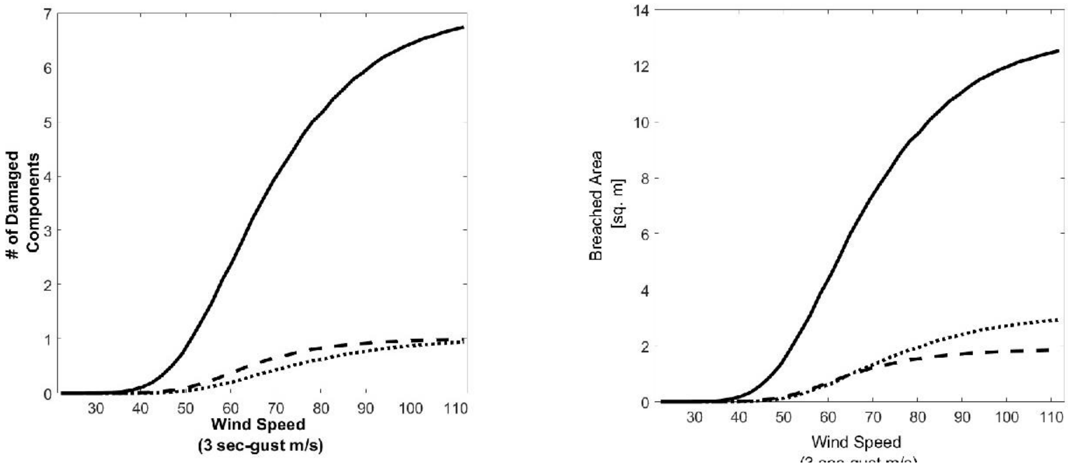


Fig. 6 Monte Carlo simulation process for generating opening damage matrices

Therefore, the vulnerability model focuses on the apartment unit rather than the building. The approach developed simulates the interaction of wind with façade components: windows, entry doors, and sliding glass doors. The flowchart in Fig. 6 summarizes the procedure to assess the external damage sustained by the facades of the MHB apartment models.

The methodology consists of a series of Monte Carlo simulations (Weekes, Balderrama *et al.* 2009, Weekes 2014), where each unit is subjected to peak 3-sec gust wind speeds that increase from 22 to 112 m/s with 2 m/s increments. The wind direction is varied around the perimeter of the apartment model from 0 degree to 315 in 45 degree increments. Each wind speed and direction are accompanied by 2,000 simulations, where the capacity of each modeled exterior component is randomly assigned from an appropriate distribution. The library of capacity distributions was based upon a combination of literature, laboratory testing, post-damage surveys, and manufacturer ratings. Building components which in any given simulation instance are not damaged by pressure are subsequently checked for debris damage. Lower units are assigned a higher probability to debris impact than higher units. The algorithm records the damage in each component and a new simulation instance is started. The completed simulation sequence yields a four dimensional damage array delineating wind speed, wind direction, modeled component, and simulation number.

The damage arrays are next turned into vulnerability curves of openings and curves of breached opening area, for each unit type. The vulnerability curves of windows, entry doors, and sliders (V_W, V_D, V_S) express the accumulated number of damaged (cracked or breached) openings of each kind as a function of the wind speed. The breach curves for the same components (B_W, B_D, B_S) express the accumulated area of breached openings as a function of the wind speed. In the case of breached components the resulting gap (assumed to be equal to the area of the opening) is used to compute the amount of water that ingresses the building model in the simulation. For the damaged but not breached windows the pane is cracked due to impact and will require replacement, but does not result in a significant source of water intrusion. Fig. 7 shows sample opening vulnerability curves and breach curves of a corner unit in an open layout building, in the high debris impact zone, with slider and shutter protection.



(a) Number of damaged openings. windows (-),doors(…), and sliders (--)

(b) breached area windows (-),doors(…), and sliders (--)

Fig. 7 Functions to estimate exterior damage of building units for a corner/open apartment with slider in the high debris impact zone with shutters

6.2 Exterior damage cost

The curves described in the previous section are used in the model to estimate the exterior loss according to the flowchart in Fig. 4. First, the catastrophe model loads an insurance portfolio dataset and initiates the hurricane simulation. For each policy in the insurance portfolio, the program reads the building information including: number of stories, number of units if available, and its location. Next it assigns a wind speed profile congruent with the building location. If the number of stories and/or the number of units are unavailable, these are assigned, together with the type of layout (open or closed), based on the statistics for that region from the exposure survey.

The descriptor of building configuration (i.e., open, closed) and the number of apartments determine the number, debris zone, and types of corner and middle units needed to load the corresponding opening vulnerability and breach curves (i.e., curves V_W, V_D, V_S and curves B_W, B_D, B_S introduced previously).

The vulnerability curves, combined with the wind speed value at the height z_i of every story, $W(z_i)$, supply the number of openings damaged at each story, which are then assigned a replacement cost, $C_{W,D,S}$. The result is a cost estimate of the damage sustained by the openings at each story (CDO_s), which is then accumulated over all the stories to get the total expected cost of damage to the openings (*TECDO*).

The replacement costs $C_{W,D,S}$ are based on a survey of glazing companies throughout Florida and contractors interviews. In most cases, the complete opening assemble will be replaced regardless of the severity of damage, due to Florida building code regulations and liability issues.

Façade defects and deficiencies

Existing defects and deficiencies are the other sources of water intrusion that the methodology considers, particularly at lower wind speeds where physical exterior damage is minor. Typical defects are window sills, doorway thresholds, wall cracks, cladding poorly caulked, electrical outlets and panel boxes, inadequately caulked windows, dryer vents, door thresholds, plumbing and ventilation ducts. The areas of these deficiencies are accounted for by computing an average deficiency per opening (based on the values from ASHRAE (2001)), estimating the total deficiency area per story, and estimating how the total deficiency area is replaced by opening breach damage. Each opening is associated with an average deficiency area: for window (δ_W), entry door (δ_{ED}) and sliding door (δ_{SD}). For example, the area of deficiencies in a unit due to windows is $\delta_W n_w$ where n_w is the number of windows per apartment. When a opening is breached, the water infiltration that was computed through say, an undamaged window sill defect, is now estimated through the breach opening. The total area of openings deficiencies per unit Δ_1 is computed as

$$\Delta_1 = \delta_W n_W + \delta_D n_D + \delta_S n_S \tag{1}$$

The decreased areas of deficiencies (Δ_2) in a given apartment due to the increasing size of breaches (due to wind pressure and debris impacts) is computed as

$$\Delta_2(W(z_i)) = \delta_W n_W (1 - D_W) + \delta_D n_D (1 - D_D) + \delta_S n_S (1 - D_S) \tag{2}$$

where D_W, D_{ED}, D_S are the percentages of broken windows, entry door, and sliding door respectively.

The accumulated areas of defects and breaches at each story for both corner and middle units are a function of the number of corner and middle apartment units, a_C and a_M.

6.4 Estimation of impinging rain

The accumulated free field wind driven rain quantities WDR_1 and WDR_2 are estimated as a function of the maximum 3-second gust at 10 m at the building location. The variation of horizontal rain with height is then assumed to follow the same variation as the wind speed. A rain admittance factor (*RAF*) (Straube and Burnett 2000) relates the wind driven rain in the free wind field to the actual wind driven impinging rain that comes into contact with the building (Pita, Pinelli *et al*. 2012).

Impinging rain is considered to only affect the windward face of the building, but the wind changes direction as the hurricane progresses, so defects and breaches reported on windward sides of the building may not always be subject to direct impinging rain. A reduction factor (f_{sim}) is required to take into account the fact that a defect or a breach may not be on the windward side of the storm for the entire duration of a storm and as such is not subjected to the full amount of accumulated impinging rain. A runoff factor f_{run} is also included which accounts for water that runs down the face of the buildings from higher stories and is forced into defects or breaches below. The value of f_{sim} and f_{run} are currently set at 0.5 and 1.4 based on engineering judgment and limited validation sources (e.g., Blocken and Carmeliet 2012).

6.5 Interior damage assessment

The interior of the building includes all the elements which are attached to it, for example, partitions, internal doors, carpets, and kitchen cabinets, electrical, mechanical and plumbing utilities. The interior damage is represented in two stages in the methodology: the first occurs as a direct result of impinging rain through the breaches and defects in the exterior façade, and the second occurs as a consequence of the interior water propagation from higher to lower units.

The methodology currently does not model the time history of damage accumulation, consequently the breaches are assumed to occur on average, at the moment when the maximum wind gust happens. For each corner or middle unit, all the opening breach areas (from the external damage simulations) add up to an area $B(s)$. The opening defects add up to an area Δ_1 which is reduced to Δ_2 if breaches occur. The mean height $h(s)$ of water that ingresses at a particular story s, is defined as the aggregated volume of water which enters in each apartment through defects before ($WDR_1 \cdot \Delta_1$) and after ($WDR_2 \cdot \Delta_2$) the breaches occur, and through the breaches caused by wind pressure and debris ($WDR_2 \cdot B$), divided by the floor area

$$h(s) = f_{run} \cdot f_{sim} \cdot RAF \cdot \left(\frac{W(z_i)}{W(10)}\right) \cdot \left[a_c \cdot \left(\frac{WDR_1 \Delta_{1c}}{A_b} + \frac{WDR_2 \cdot (B_c(s) + \Delta_{2c}(s))}{A_b} \right) + \right.$$
$$\left. + a_M \cdot \left(\frac{WDR_1 \Delta_{1M}}{A_b} + \frac{WDR_2 \cdot (B_M(s) + \Delta_{2M}(s))}{A_b} \right) \right] \quad (3)$$

where A_b is the average base area of a single unit. $W(z_i)$ is the wind speed at the height z_i of story (s) and $W(10)$ is the 10m wind speed reference height (at story 3). For the sake of simplicity the computation of defects is not represented in the flow chart of Fig. 4.

As part of the interior damage assessment, a scheme for modeling vertical water propagation between floors was implemented. The algorithm computes the total water height per story ingressed and propagates a percentage of that water down to the story below. In addition, water penetration through possible roof cover damage as well as roof defects or ventilation ducts can happen in the upper floor, which then trickles down to the lower stories. Therefore, an additional volume of water penetration is modeled at the upper story. At present, assuming concrete slab floors, 10% of the water which ingresses per story is assumed to percolate to the floor directly below. This factor is subject to change when data becomes available for validation.

Lastly, a bi-linear expression based on engineering judgment transforms the water height in each story to interior damage ratio per story IDR_s (Eq. (4)). The threshold value t_{id} sets the critical water height (assumed as 1 inch) that represents complete interior damage.

$$IDR_s = \begin{cases} \frac{1}{t_{id}} h(s) \times 100 & h(s) < t_{id} \\ 100\% & h(s) \geq t_{id} \end{cases} \quad (4)$$

Assuming that each story has a similar interior insured value, the aggregation of all the interior damage ratios divided by the total number of stories S represents the expected interior damage ratio (*EIDR*) for the whole building.

7. Actuarial model

7.1 Overall expected damage value assessment for building and contents

In order to estimate the total interior damage, the *EIDR* is multiplied by the value of the building interior (as defined in section 6.5), which is taken to be a percentage k_I of the total building value (BV). The insured value or insured limit is used as a proxy for the building value. The cost coefficient of interior damage $k_{I,}$ is computed considering the plan size of the building, the type of layout (open or closed), and the number of stories (R.S. Means 2010). The values of k_I also differ for apartment buildings and condos in that for apartment buildings k_I is the ratio of the total building interior value over the entire buildings value, whereas for condominiums k_I is defined as the common areas interior value over the total building value. More details on the costing structure can be found in Pita (2012).

Finally, the aggregation of the exterior and interior damage costs produces the total expected damage value (EDV_B). The rate of damage to contents is assumed to be the same as the rate of damage to building interior (contents are elements inside but not attached to the building, like furniture, appliances, rugs, etc.). Therefore, the expected content damage value (EDV_C) is the product of the *EIDR* by the contents value. The insured value or insured limit of contents is used as a proxy for the contents value.

7.2 Condominium and rental units' damage assessment

Given the modular approach of the methodology, it is naturally applicable to the estimation of the damage to individual living units, whether these are rental units or condominium units. Since it is assumed that the rate of interior damage is uniform throughout a story *s*, the expected damage values to an apartment unit ($EUDV_B$) and its contents ($EUDV_C$) are the product of the *EIDR(s)* for that story by the interior and contents values of the apartment unit. The insured value or insured limit for the apartment unit and its contents are used as a proxy for their values.

7.3 Actuarial metrics

The actuarial component calculates expected insured losses for building and contents by applying policy deductible and limits. Specifically, this component estimates the annual average loss (AAL) and the probable maximum loss (PML) either for the entire state or for a given region (Hamid, Kibria *et al.* 2010, Gulati, George *et al*. 2014). In the case of mid-high rise building which are predominantly condominium buildings, there is no time related expenses on the condo association insurance policies.

8. Validation

As a part of a catastrophe model, the methodology presented herein is not meant to represent any particular building but to statistically characterize portfolios of several thousands of insured properties. The statistical validity of the damage estimates can only be tested against many large insurance portfolios across several hurricanes. Unfortunately, the scarcity of available insurance claim data does not currently allow a meaningful validation of the model. Nonetheless, the authors have access to a few portfolios of insurance claims from Hurricane Wilma which passed through southern Florida in 2005. Table 3 shows a comparison of the actual versus modeled loss for two portfolios. Although the individual differences between modeled and observed losses are large, yet taken together they approximate a smaller difference which is encouraging. Moreover, these are very small portfolios which show that the model is fully operative, but more meaningful validation will depend on the availability in the future of more and larger portfolios for a large enough number of events.

9. Model contributions, limitations and future work

The model presented here includes several unique contributions which advance the sciences of building vulnerability modeling and natural risk analysis. First, at the heart of the model is a per-unit vulnerability assessment approach rather than a per-building approach, which accounts for the possible layouts of the units in a MHB. This provides the flexibility needed to statistically address the large variability of MHB typologies. Second, the vulnerability model captures the openings' damage typical of MHB by taking into account both the decreasing susceptibility to missile impact and the variation of wind speed with height. Third, the interior damage is modeled using a detailed model of rain intrusion through both defects and breaches coupled with an interior water propagation model.

The model is applicable only to portfolios of large (i.e., at least hundreds) numbers of MHB and is not intended to analyze individual MHBs. Currently, the model addresses only wind damage. The authors are currently developing a model for surge damage which will be combined with the wind model.

Future work includes better estimates of the rain admittance factor and the variation of surface run-off for high rise buildings, as well as the refinement of the interior damage mechanisms that take into account water penetration and water percolation. The authors are also currently working on modeling of wind effects on typical balcony glass hand-railing systems used in mid-high rise buildings. Finally, the future availability of a sufficiently large number of claim data will facilitate the calibration and validation of the model.

10. Conclusions

The proposed modular approach is well suited to assess the vulnerability of buildings with large variability such as MHBs, typical of these building all around the world, which cannot be reduced to a few typical cases. The constitutive apartment units of a MHB share common vulnerabilities that can be more easily typified. These buildings can then be represented as an aggregation of a few types of units, and the model has the capability of adapting to different building configurations. The modular approach is also well adapted to the intricacies of insurance policies for apartment and condominium buildings, as well as for their individual apartment units.

Table 3 Actual vs. Modeled Building Losses (hurricane Wilma 2005)

Company	Actual	Modeled	Difference
A	$ 2,752,816	$ 398,737	-86%
B	$ 8,072,374	$ 12,187,650	51%

The results of running the model on a few portfolios are encouraging. In order for a model like the FPHLM to take full advantage of its modeling capabilities, insurance companies around the world should ensure that they collect more detailed information on their insured MHB, including, the number of stories, number of apartment units per story, and type of facade cladding.

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