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Component-based hurricane vulnerability model for mid/high-rise commercial residential buildings

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ABSTRACT

This paper focuses on the vulnerability of residential mid/high-rise buildings (MHRB) to hurricane-induced wind and wind-driven rain ingress, with a special emphasis on interior and contents damage. A component-based methodology utilizes the physics of rainwater ingress, distribution and propagation to provide the basis for the proposed MHRB risk assessment model. The model combines estimates of wind speed, impinging rain and surface run-off wind driven rain, envelope defects and breaches, interior water distribution and propagation, and component cost analyses to project envelope, interior and contents damage. The paper describes the model, verifies that it satisfies logical relationships to risk, and compares it against existing MHRB models. The new physics-based interior and contents vulnerability model should facilitate the evaluation of the cost effectiveness of mitigation measures.

1. Introduction

The focus of this paper is to increase the accuracy of an existing model that projects insured losses to residential housing from hurricane wind and impinging rain. Specifically, the prediction of interior and content damage via water ingress has been updated to incorporate the physics of water ingress and water propagation, as well as materials absorption. Content damage is defined as water damage to the components that can be carried away from the building, e.g., furniture, appliances, artwork, electronics and clothing. Whereas interior damage is the water damage to building interior components (ceiling, partitions, flooring, cabinets, and electrical components). These two loss categories can constitute more than 60 % of the total insured losses for a given hurricane event, and commonly exceed the losses due to direct physical damage of the building exterior and/or structural components [1]. Thus, interior and content loss modeling warrant significant attention to accuracy and the reduction of uncertainty. This study is currently limited to commercial residential (multi-family) mid/high-rise engineered buildings. Future work will extend these updates to other building classes such as single family residential.

Commercial residential mid/high-rise buildings (MHRB), typically greater than three stories, are engineered buildings and typically made of reinforcement concrete and/or steel, so damage to the main building structure due to wind effects and debris impacts is generally minor [2]. On the contrary, past hurricanes in Florida and elsewhere have shown the vulnerability of MHRB to envelope damage and cascading wind-driven rainwater ingress. Even for low intensity events, with minimal envelope damage, rainwater can leak through defects of the openings, especially sliding doors, resulting in damage to interior and contents [2]. For moderate to high

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intensity events, pressure and debris impact induced breaches of openings (doors and windows) can occur leading to extensive interior and contents damage. With the coastal population concentration [3] and billion-dollar hurricane-induced losses [4], there is a need for catastrophe models to accurately project the damage to building interior and contents in MHRB [5].

Catastrophe (cat) models that project losses to build infrastructure have four main components: a component which models the hazard, in our case hurricane wind; a component that categorizes the exposure into generic classes, in our case residential buildings; a component which models the effects of the hazard on the exposure to define vulnerability functions for each building class; and a component which utilizes outputs from the hazard, exposure and vulnerability components to quantify the actuarial risk in terms of economic damage and insured losses. Examples of cat models include [6–19].

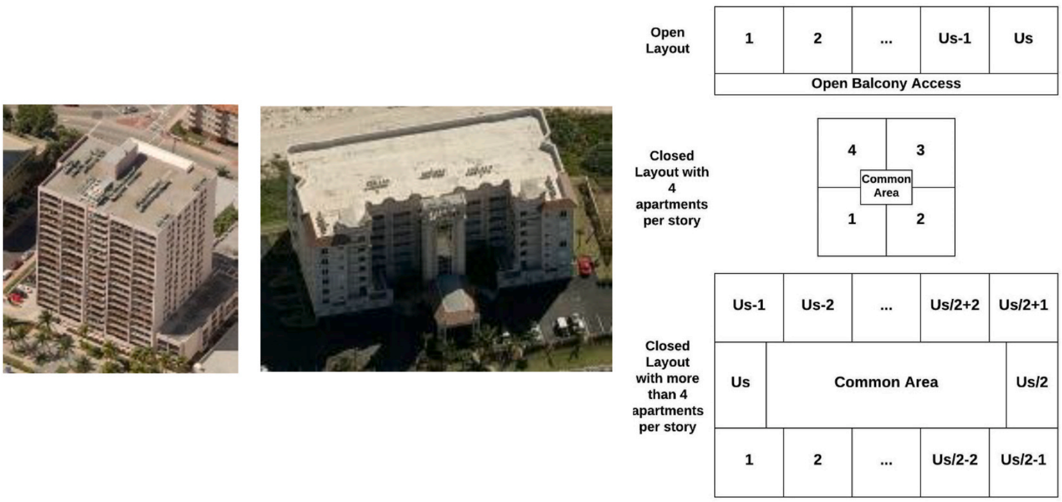
This paper focuses on the vulnerability component of a cat model for MHRB. State-of-the-art vulnerability models use engineering principles to project a building vulnerability through the prediction of physical damage to the external components of the structure and its envelope based on knowledge of wind-structure interaction and building component capacities [20–22]. These models are flexible and can assess the vulnerability of different classes of buildings [23–26]. Applied Research Associates (ARA) presented one of the first vulnerability assessment for MHRB [24], which provided the basis for the MH-HAZUS MHRB hurricane vulnerability model [27–29]. The generic building classes in MH-HAZUS include mid/high-rise commercial and residential buildings made of concrete, steel, and masonry.

The Florida Public Hurricane Loss Model is another cat model funded by the state of Florida to help with insurance regulation [26]. The FPHLM version 8.2 projects the losses of commercial residential buildings for both low-rise (CR-LRB) (1- to 3-story high) and mid/high-rise (CR-MHRB) [30]. To the best knowledge of the authors, the FPHLM vulnerability model for CR-LRB is the first model that uses the physics of water ingress and propagation, calibrated to physical test results, to estimate the interior and contents damage as a function of moisture contents of specific components [31]. By contrast, in the CR-MHRB vulnerability model, the damage to the interior is an empirical function of the height of accumulated water via ingress at each story, and the damage to the contents is an empirical function of the interior damage [2], same as in MH-HAZUS.

The authors combined the latest research from the FPHLM on exterior vulnerability of CR-MHRB [2] and on internal vulnerability of CR-LRB [31] to create a new MHRB vulnerability model which captures the physics of water ingress to produce more realistic estimates of damage to the interior and contents in MHRB. The research is funded by the Wind Hazard and Infrastructure Performance Center (WHIP–C) and the new MHRB model is referred to as the WHIP-MHRB model. The paper describes the model, which for different combinations of wind speeds and wind-driven rain, combines estimates of impinging and surface run-off wind driven rain, envelope defects and breaches, interior water ingress, distribution and propagation, and component cost analyses, to project envelope, interior and contents damage. Section 2 introduces resources leveraged by this study from the FPHLM. Section 3 describes the new interior and contents vulnerability model for MHRB. Section 4 shows results of the model. Section 5 shows that the model satisfies logical relationships to risk. Section 6 compares the model to other existing models.

2. Florida public hurricane loss model resources

Currently, the FPHLM MHRB vulnerability model estimates the interior damage as an empirical function of the height of accumulated water inside the building, and contents damage is estimated as another empirical function of interior damage. These functions are based on experience and judgment [2], and are not anchored into the physics of the problem. On the contrary, the FPHLM CR-LRB vulnerability model incorporates a new methodology which captures the physics of the water propagation and subsequent damage in



(a) (b) (c)

Fig. 1. Examples of closed (a) and open (b) MHRB and apartment unit distributions with apartment serial numbers (c).

low-rise buildings [31]. The authors leveraged resources from the FPHLM CR-LRB to develop the WHIP-MHRB vulnerability model. The improved WHIP-MHRB vulnerability model combines the external damage module from the FPHLM MHRB vulnerability model with the interior and contents damage modules of the FPHLM CR-LRB vulnerability model.

2.1. Mid/high-rise buildings characteristics

The developers of the FPHLM adopted a modular approach for modeling the vulnerability of MHRB [2]. The MHRB are defined as an aggregation of apartment units, and the total damage to the building is the aggregation of the damage to each apartment unit. The units can be corner or middle units depending on their positions in the floor plan. They can be distributed within two basic layout types: open building (apartment units are accessed externally) with at least 2 units per floor; and closed building (apartment units are accessed internally) with an even number of units per floor (4 or higher). Fig. 1 shows an example of the closed and open MHRB, and the possible layout of the units in each case. The schematics in Fig. 1c from top to bottom represent plan distribution of apartments in open buildings, closed buildings with four apartments per story, and closed buildings with more than four apartments per story. The authors define apartment numbers from 1 to Us (total number of apartments per story) for each apartment distribution shown in Fig. 1c.

2.2. MHRB exterior damage

The MHRB are engineered buildings, which suffer relatively minor structural damage during hurricane events [2]. Most of the external damage relates to breaches of the envelope, especially openings, so the MHRB vulnerability model only takes into account external damage to the openings (windows, entry doors, and sliding doors). The FPHLM has a library of vulnerability and breach matrices and curves of openings in apartment units, which provide the number of openings and corresponding breach areas as a function of wind speed, for corner or middle unit, located in high debris impact zone (1-4 stories), middle debris impact zone (5-7 stories), or low debris impact zone (8+ stories), in closed or open buildings [32,33]. The matrices give the probability distributions of the number of breached openings (for the case of vulnerability matrices) or breach areas (for the case of breach matrices) of windows, entry doors and sliders for different maximum wind speed intervals, while the curves give the expected values as a function of the wind speed. Damage to openings is a primary source of rain driven water ingress that damages interior and contents.

2.3. MHRB exterior defects

All buildings have defects due to defective installation of fenestration, poor maintenance, and aging. In addition, there might be gaps in the window-wall interface from window out of plane deformation in high winds. Sliding glass doors can admit lots of rainwater even when they don't break [2,34,35]. In the FPHLM CR-MHRB module, Pita et al. [2] defined the defect area of the openings (0.0026 ft^2 for window, 0.0258 ft^2 for door, 0.0237 ft^2 for slider) derived from ASHRAE [36]. Deficiency area estimates were assigned based on the average effective air leakage areas (Chapter 26, Table 1 (p. 26.15) in Ref. [36]).

2.4. Rain hazard simulation study

An accurate assessment of interior and content loss from water ingress necessarily begins with an accurate representation of rainfall during a hurricane, especially in MHRB where the main loss comes from the water-induced damage to the interior components. To that effect, a rain simulation study generates the total volume of wind-driven rain (WDR) during a hurricane as the sum of the wind-driven rain (WDR_1) accumulated prior to the occurrence of the maximum wind speed at the location of the building, and the wind-driven rain (WDR_2) accumulated from the time of maximum wind speed to the end of the hurricane [37]. The values of the simulations of WDR and WDR_2 are stored in a WDR matrix where each column of the matrix is the discretized probability distribution function of WDR as a function of the maximum 3 s actual terrain wind speed at 10-m height. In response to the rotation of the hurricanes during the simulations, the values of WDR_1 and WDR_2 are distributed in ratios α_i and β_j (i from 1 to 4, and j from 1 to 5) over the eight wind direction octants [38] where α_1 and β_1 are in the same octant. To be able to integrate the results of the rain study, which has a time component, into the FPHLM vulnerability model, which does not have a time component, the breaches of the openings are assumed to

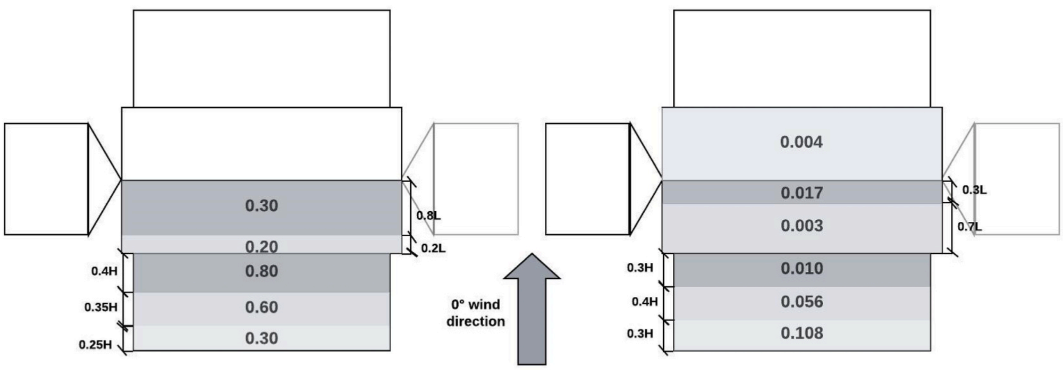


Fig. 2. RAF (left) and SRC (right) zonation plots given 0° wind direction for gable roof building.

take place at the time of occurrence of the maximum wind speed. In this manner, the only water ingress prior to maximum wind speed is through building defects, whereas after the maximum wind speed has been reached breaches provide the primary means of water ingress. Importantly, this means that the model does account for interior and content water damage even in cases where no breaches occur, which has been observed in field studies.

2.5. Water ingress

The rainwater penetration at a given location on a building façade includes the direct impinging rain and surface runoff rainwater which are characterized by the rain admittance factor (RAF) and surface runoff coefficient (SRC), respectively [39–41]. The RAF is the percentage of WDR that impinges on the building while the SRC is a normalized percentage of the WDR which runs-off on the façade. They are both wind direction dependant. Baheru et al. [42] produced zonation plots of RAF and SRC for different types of low-rise buildings at 0°, 45°, or 90° wind directions. Fig. 2 are RAF and SRC zonation plots for 0° wind direction for a building with a gable roof.

Johnson et al. [38] combined the rain hazard model [37] and the RAF and SRC research [42] to calculate the amount of water ingress from direct imping rain and surface runoff through defects and breaches of the façade of CR-LRB, for different wind directions. Section 3.3 describes how this research on CR-LRB was transferred to MHRB.

2.6. Interior and contents damage

Interior components include ceilings, partitions, floorings, cabinets, and utilities. There are five types of contents depending on their water absorption capacity and their location within common (accessible to anyone in the building) or private areas (i.e. apartment units) (the distinction between private and common areas is for insurance purposes, since condominium association policies only cover contents in common area). In private areas, there are water absorbent contents (WA), non-water absorbent contents (NA), and appliances (AP). There are also water absorbent (WA-CA) and non-water absorbent (NA-CA) contents in common areas.

Water damage to interior and contents depends on impinging rain, the means of water ingress, and the process that distributes entering water within the building interior. It is also a function of the materials that make up the interior and contents. For example, tile vs hardwood flooring may be the difference between a clean-up and a replacement. Recent experimental work has provided quantitative data as to water distribution within a building and material absorption. Raji et al. [43] studied the distribution of water ingress in a CR-LRB scale model. Silva de Abreu et al. [31] defined a water propagation path among the interior and contents components in the CR-LRB model, based on Raji et al. [43], coupled with water absorption capacities for these same interior and contents components. The results are estimates of the damage based on the moisture contents of these components. The physical damage ratios of the cabinets and electrical components are defined as an empirical weighted average of the damage ratios of the components they

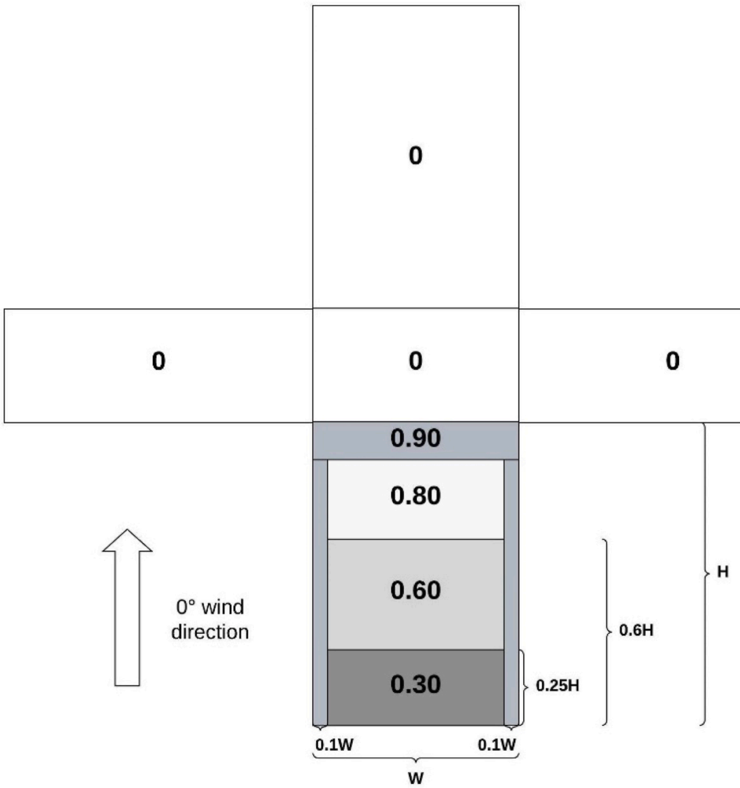


Fig. 3. RAF zonation plot given 0° wind direction.

are attached to.

The moisture contents is the accumulated water in a specific component divided by the sum of accumulated water and dry weight of the component. In the FPHLM CR-LRB module, Silva de Abreu et al. [31] defined the physical damage ratios of the ceiling and partitions made of gypsum boards and the flooring made of carpet based on a polynomial equation of the moisture contents. They also defined the damage ratios of the five types of contents as functions of the total amount of water accumulated in water absorbent contents or the total amount of water going through the non-absorbent contents. Section 3.4 and 3.5 explain how CR-LRB interior and contents damage model are incorporated into the WHIP-MHRB model.

3. WHIP-MHRB interior and contents vulnerability model

The research described above for CR-LRB water propagation and interior and contents damage is extended to the WHIP-MHRB model. The damage depends on a source of water ingress, a water propagation path, and the difference between the resulting moisture contents of a component and its acceptable water absorption capacity. The different steps involve the characterization of the WDR-structure interaction, the quantification of the water ingress, its propagation to the different interior and contents components, and percolation to lower stories, and finally the estimate of the resulting damage. The next sections describe these different steps.

3.1. Directional breach area of openings and exterior damage

The authors expanded the breach matrices (see section 2.2) into directional breach arrays, for each of eight possible wind directions (0°–315° in 45° intervals) which are incorporated in the probabilistic version of the WHIP-MHRB model detailed in section 4.2. For each combination of wind speed and wind direction, the numbers of damaged openings are saved in a multidimensional array D and the corresponding breach areas are saved in a multidimensional array DB. The WHIP-MHRB model assigns the arrays to each apartment unit based on its location in the floor plan and elevation of the building, and the wind direction. The physical damage ratios of the windows, doors and sliders in an apartment (DR_{ext}) are the number of damaged openings from D divided by the total number of openings in that apartment.

3.2. Rain-structure interaction

The WHIP-MHRB model extrapolates the zonation zones for CR-LRB to the case of MHRB and assigns the RAF and SRC to the components on the façade of each apartment unit based on the location of the unit in the zonation plot. Fig. 3 shows the RAF zonation plot for all façades given 0° wind direction. The plot includes building edge zones where the RAF values are set to 0.9 based on Straube and Burnett's [41] research on MHRB. The edge zones include the top floor and 0.1 times the width of the building on each side. The RAF's for the leeward and side units, as well as the flat roof, are zeroes where the rain does not directly impinge.

Fig. 4a shows the layout of a 6-story closed-layout building with 10 units per story. Fig. 4b is the elevation showing the RAF values for the units on the windward façade given 0° wind direction.

Fig. 4b displays the RAF values of windows and doors in unit 1 to unit 4 for each story where the upper value is RAF of windows and the lower value is RAF of doors in each cell. The units in the 1st story, 3rd story, and 5-6th stories are totally located in one zone, respectively. While for units in the 2nd story and 4th story, the openings span two zones where the RAF values are weighted averages based on the dimensions of the openings in the two zones (see Fig. 5a). The RAF values for the openings of the edge units are weighted

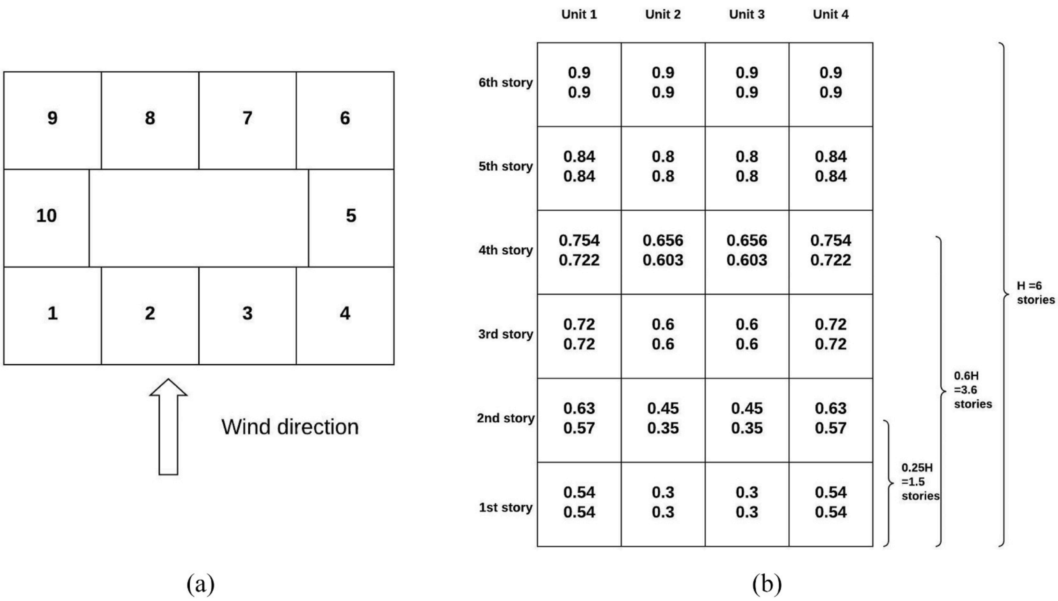


Fig. 4. Unit distribution in floor plan (a) and RAF zonation plot for windward façade given 0° wind direction (b).

averages based on the dimensions of the unit in the two zones (see Fig. 5b). The MHRB SRC values from the CR-LRB zonation plots for SRC are expanded in a similar way.

3.3. Water ingress

The authors extended to MHRB the method from Ref. [38] (sections 2.4 and 2.5). The premise is that WDR_1 water from both impinging rain and surface run-off ingresses into the building initially through defects only. Once breaches occur (at the time of maximum wind speed), WDR_2 water will ingress through both defects and breaches. The volumes of the direct impinging rain through defects and breaches of the openings in one unit at a given story are defined as:

$$WatDfDI = \sum_{i=W,D,S}\left(\sum_{j=1}^{4} AreaDefect_i \bullet WDR_1 \bullet \alpha_j \bullet floglaw \bullet RAF_{ij} + \sum_{j=1}^{5} AreaDefect_i \bullet survival_i \bullet WDR_2 \bullet \beta_j \bullet floglaw \bullet RAF_{ij}\right) \tag{1}$$

$$WatBrDI = \sum_{i=W,D,S}\sum_{j=1}^{5} AreaBreach_i \bullet WDR_2 \bullet \beta_j \bullet floglaw \bullet RAF_{ij} \tag{2}$$

where.

- *WatDfDI* and *WatBrDI* represent the volume of direct impinging rain through defects and breaches respectively.
- $AreaDefect_i$ and $AreaBreach_i$ are the defect area (see Ref. [2]) and breach area (selected from *DB* in square foot) of component i.
- $survival_i$ is the survival defect ratio equal to one minus breach area divided by total opening area.
- WDR_1 and WDR_2 are the amount (inch) of wind-driven rain before and after the breaches occur (see section 2.4).
- α_j and β_j are WDR distribution ratios (see section 2.4).
- *floglaw* is a height adjustment factor (see Ref. [38]). The WDR variation with height is assumed to be identical to the wind speed variation.
- RAF_{ij} is the rain admittance factor for component i and wind direction j.
- W, D, S represent the openings: windows, doors and sliders.

The volume of the surface runoff through defects and breaches of the openings in one unit are defined as:

$$WatDfSR = \sum_{i=W,D,S}\left(\sum_{j=1}^{4} AreaSR_{ij} \bullet WDR_1 \bullet \alpha_j \bullet floglaw \bullet SRC_{ij} + \sum_{j=1}^{5} AreaSR_{ij} \bullet survival_i \bullet WDR_2 \bullet \beta_j \bullet floglaw \bullet SRC_{ij}\right) \tag{3}$$

$$WatBrSR = \sum_{i=W,D,S}\sum_{j=1}^{5} AreaSR_{ij} \bullet WDR_2 \bullet \beta_j \bullet floglaw \bullet SRC_{ij} \tag{4}$$

where.

- *WatDfSR* and *WatBrSR* represent the volume of surface runoff through defects and breaches respectively.
- $AreaSR_{ij}$ is the reference surface runoff area of component i given wind direction octant j which equals to mean height of the story multiplied by length or height of component i when j is 1,3,5 or 2,4 respectively.
- SRC_{ij} is the surface runoff coefficient.
- W, D, S represent windows, doors and sliders.

3.4. Water distribution and propagation

In the WHIP-MHRB model 90 % of the aggregated water ingress, from equations (1)–(4), is distributed between partitions and flooring, in each apartment unit based on its location in the floor plan while the remaining 10 % propagates to the contents. The distribution between partitions and flooring is based on Raji et al.'s [43] tests (section 2.6) for light and moderate damage states. In the absence of actual data, the ratio propagated to the contents is determined based on common sense and engineering judgment. The

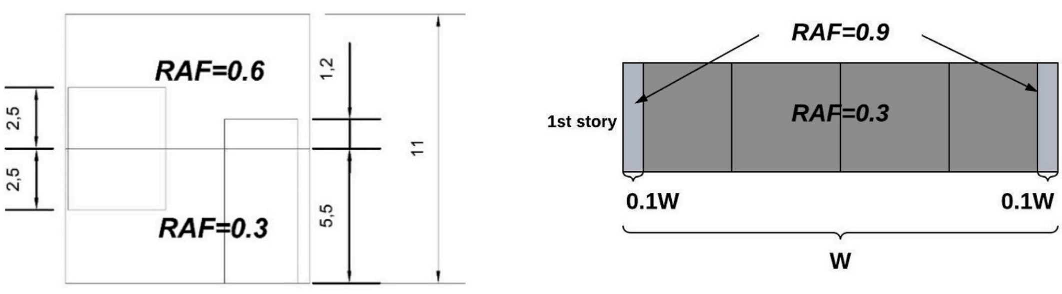


Fig. 5. Dimensions of the openings (a) and units (b) spanning two RAF zones.

results are two water distribution arrays representing the distribution of the water ingress between partitions and flooring in each unit for 8 angles between the wind direction and the direction perpendicular to the long side of the building (0°–315° wind direction with 45° interval). Each array is for the case before and after the breaches of openings occur. Table 1 is the partitions share of water intrusion through opening defects in closed building with 10 apartment units per story. The values in the table represent, for each unit, the fraction of the total amount of water ingress through defects, given a specific wind direction, that goes to partitions. For example, the first value, 0.24, in the table represents that given wind direction equal 0°, in the first unit, 24 % of 90 % of the water intrusion through opening defects propagates to partitions and the remaining 76 % goes to the flooring. The values in the blank cells are zero since for the given wind directions, the units are not on the windward side of the building.

Silva de Abreu et al. [31] proposed water absorption capacities for interior components and a water propagation path among the interior components and contents in the CR-LRB model. The WHIP-MHRB model expanded this water propagation path with the addition of a propagation path among separate but adjacent units. In an MHRB apartment unit, there are three sources of water intrusion during a hurricane: water ingress through defects and breaches of openings, water leak or percolation from upper unit, and water transmission from adjacent units. Fig. 6 defines the water propagation path and water propagation proportions including the percolation of excess water. The water intrusion propagates among the interior components and contents. 10 % of water intrusion through openings are transferred to the contents, and the other 90 % are transferred to partitions and flooring based on the values from the water propagation matrix. 36 % of the water transferred to partition is absorbed by partitions, 32 % percolates down to the flooring, and 32 % goes to the contents. The percolated water from the apartment unit above is absorbed by the ceiling, then the excess water after the component is saturated propagates to contents (40 %), flooring (20 %), and partitions (40 %). The contents water is distributed based on absorption percentages shown in Fig. 6. Excess water from partitions and contents transfers to the flooring. The model assumes either tile or carpet flooring. 10 % of excess water from flooring transfers to the flooring of adjacent apartment unit if it is not saturated, then the remaining water either percolates to the story below (20 % for ceramic tile flooring, and 70 % for carpet flooring) or escapes to the outside (80 % for ceramic tile flooring, and 30 % for carpet flooring).

3.5. Building damage

In the WHIP-MHRB model the physical damage ratios of interior components (DR_{int}), like ceiling and partitions made of gypsum boards and the flooring made of carpet, are defined with the same polynomial equation function of the moisture content used by Ref. [31], for the FPHLM CR-LRB model (see section 2.6).

The cost coefficient of a specific component represents the proportion of the cost of this component within the total building cost. A construction estimating tool widely used in the industry [1], provided the basis for the exterior cost coefficients (K_E) for the exterior components (windows, doors and sliders) and for the interior cost coefficients (K_I) for the interior components (ceiling, partitions, flooring, cabinets and electrical components). For insurance purposes, the model distinguishes between 1) apartment buildings (AB), with one owner, where the insurance policy covers all components in the building and 2) condominium buildings, with many different apartment unit owners, where the condominium association (CA) insurance policy covers only the external components and the interior components in the common areas. Eq. (5) and Eq. (6) define the cost coefficients for AB and CA. The exterior and interior cost coefficients depend on the ownership type, and all the variables that affect the building or condo association value (e.g. number of stories, building area and the existence or not of sliders).

$$K_{E,I_i} = \frac{cost\ of\ component\ i}{building\ value}, for\ AB \tag{5}$$

$$K_{E,I_i} = \frac{cost\ of\ component\ i}{condo\ association\ value}, for\ CA \tag{6}$$

These cost coefficients provide the means to translate the physical damage ratios for each component into monetary damage ratios, which can then be combined. Eq. (7) and Eq. (8) illustrate this process and show how the exterior and interior mean monetary damage ratios of an apartment unit ($\overline{DR_{ext}}(s,u)$ and $\overline{DR_{int}}(s,u)$) result from the summation of the damages in a given unit (u) on the story (s).

Table 1
Share of water intrusion through openings defects before breach occurs in closed building with 10 units per story, corresponding to partitions.

Unit	Wind direction							
	0°	45°	90°	135°	180°	225°	270°	315°
1	0.24	0.31	0.48	0.38				0.47
2	0.24	0.38						0.38
3	0.24	0.38						0.38
4	0.24	0.47				0.38	0.48	0.31
5						0.38	0.48	0.38
6				0.47	0.24	0.31	0.48	0.38
7				0.38	0.24	0.38		
8				0.38	0.24	0.38		
9		0.38	0.48	0.31	0.24	0.47		
10		0.38	0.48	0.38				

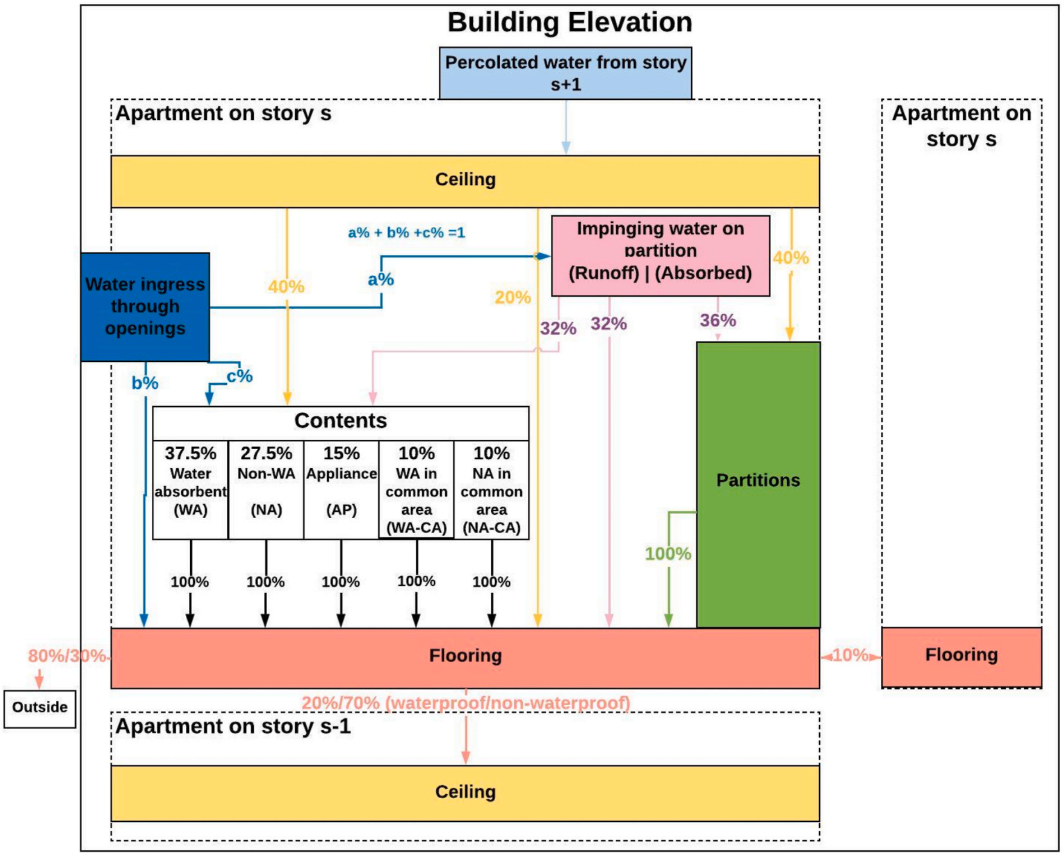


Fig. 6. Water propagation path and proportions.

$$\overline{DR_{ext}}(s,u) = \sum_{i=1}^{3} DR_{ext_i}(s,u) \bullet K_{E_i} \tag{7}$$

$$\overline{DR_{int}}(s,u) = \sum_{i=1}^{5} DR_{int_i}(s,u) \bullet K_{I_i} \tag{8}$$

where, $DR_{ext_i}(s,u)$ is the physical damage ratio of each type of opening including windows, door, and sliding door (defined as the number of damage openings divided by total number of openings in the apartment) in the apartment unit u and on the story s. $DR_{int_i}(s,u)$ is the physical damage ratio of each interior components including ceiling, partition, flooring, cabinets, and utilities in the apartment (defined in the previous section) in the apartment unit u and on the story s.

The monetary damage ratios of the overall building exterior and interior ($DR_{bldg,ext}$ and $DR_{bldg,int}$) are the average values of $\overline{DR_{ext}}$ and $\overline{DR_{int}}$ of all apartments in the building, respectively. The damage ratio of the building (DR_{bldg}) is the sum of the damage ratios of building exterior and interior.

$$DR_{bldg,ext} = \frac{1}{s \bullet u} \sum_{s=1}^{s_{max}} \sum_{u=1}^{u_{max}} \overline{DR_{ext}}(s,u) \tag{9}$$

$$DR_{bldg,int} = \frac{1}{s \bullet u} \sum_{s=1}^{s_{max}} \sum_{u=1}^{u_{max}} \overline{DR_{int}}(s,u) \tag{10}$$

$$DR_{bldg} = DR_{bldg,ext} + DR_{bldg,int} \tag{11}$$

The WHIP-MHRB model follows the same method used in Ref. [31] to assess the content losses. To compute the mean monetary damage ratio of the contents, cost participation factors were derived from a USACE report [44]. For WA the factor is 43 % (K_{WA}), for NA 45 % (K_{NA}), for AP 4 % (K_{AP}), for WA-CA 3 % ($K_{WA\text{-}CA}$), and for NA-CA 5 % ($K_{NA\text{-}CA}$). The mean damage ratio of the contents is the sum of the products of the damage ratio of each type of contents time their cost participation factors.

4. Results

The MHRB vulnerability model is primarily meant to be used for insurance purposes. In that context, there are two possible main scenarios regarding the characterization of MHRB. In areas like Florida, there is a very large variety of MHRB to achieve intentional architectural uniqueness, and it is therefore difficult to define a reasonable number of meaningful building classes that would cover the majority of the MHRB exposure. On the contrary, in other areas, like large urban environments with big and repetitive building complexes, for example in China, it is relatively easier to define relatively few building classes that will be representative of the majority of the building exposure. To address these two different scenarios, the MHRB vulnerability model has two different versions: the integrated vulnerability and actuarial model (VAM) and the probabilistic vulnerability model (PVM).

4.1. Vulnerability and actuarial version of the model

In the VAM version, the MHRB does not produce vulnerability outputs. The model is integrated within an actuarial model, and the vulnerability analysis is done “on the fly” for each policy within an insurance portfolio. The actuarial model reads policies from a commercial residential (CR) portfolio (for apartment building or condo association polices). For each policy, the model assigns missing exposure data (number of stories, building area, total number of units and number of units per story) based on statistical criteria. From hazard model outputs, the actuarial model assigns the corresponding maximum 3-sec gust wind speed at 10 m height over actual terrain (WS) to the policy, and proceeds with the vulnerability analysis as described in the previous sections.

For each policy of the portfolio, the model loops over 2 building layouts (open and closed), 2 flooring types (waterproof and non-waterproof), and 8 wind directions to produce $2 \times 2 \times 8$ damage ratio arrays for the building, contents, interior, and exterior. The resulting damage ratio arrays include 32 ($=2 \times 2 \times 8$) cells. Pita [45] derived proportions of open and closed MHRB, for different number of stories intervals (4–6, 6 to 9, and greater than 9) from a survey of MHRB in coastal and inland regions of Florida. The model uses these percentages of open and closed buildings to calculate a weighted average of the damage ratios corresponding to the 2 building layouts based on the location and number of stories of the building. The result is 16 damage ratios (for 8 wind directions and 2 possible flooring types), which are multiplied by the insurance limits resulting in the monetary losses for the overall building, its interior, its exterior, and its contents. From these 16 possible losses, the actuarial model calculates and outputs the mean and standard deviation for the losses of the building, contents, interior, and exterior for each policy in the portfolio.

4.2. Probabilistic vulnerability model

The PVM version of the MHRB vulnerability model is a stand-alone vulnerability model, which produces vulnerability outputs for different building classes of MHRB. These vulnerability outputs can then be used within actuarial models, to compute insured losses. The building classes for MHRB are defined based on key parameters of the MHRB exposure listed in Table 2.

At the heart of the PVM is a Monte Carlo simulation engine which runs simulations for combinations of maximum wind speeds (WS) and wind directions. The wind speeds vary in 2.2 m/s increments from 22.2 m/s to 110.2 m/s. The wind directions vary in 45° increments from 0 to 315°. In each simulation, the number of damaged openings and opening breach area are randomized based on directional breach array (see section 3.1) and the WDR_1 and WDR_2 are randomly selected from the WDR matrix based on the WS (see section 2.4). For each simulation, depending on the opening protection type, the model selects the appropriate breach matrix, from which the breach areas of the openings are randomly selected also as a function of WS. The water propagation proportions are randomly selected from Gaussian distributions with mean values shown in Fig. 6 with a 20 % coefficient of variation with similar assumptions as [31]. The cost participation factors for the contents are also randomly selected from Gaussian distributions with mean values shown in Section 3.5 and 20 % coefficient of variation.

The output of the WHIP-MHRB model includes wind and wind-driven rain vulnerability matrices and curves for overall building, its interior, its exterior and its contents for different building classes. The cells of a vulnerability matrix give the probability of having a damage ratio within a certain interval given that the hazard intensity is also within a certain interval. The vulnerability curves give the mean values of the probability distribution functions of damage for each hazard intensity interval (wind speed or wind driven rain).

5. Logical Relationships to Risk of PVM

The Florida Commission in the report of activities [46] lists some criteria to verify the logical relationship to risk for hurricane risk models. This section tests some of these criteria for the PVM, with the help of some comparative results from the PVM for different building classes, listed in Table 3 (in accordance with the building class characterization of Table 2). The interior (Int) vulnerability curves for these building classes are plotted in pairs in Figs. 7–9. Fig. 7 verifies that the vulnerabilities of the open buildings are larger

Table 2
Options of the parameters to define the building classes for the WHIP-MHRB model.

Parameter	Options		
Residency type	Apartment building (AB)	Condominium association (CA)	
Building layout	Open	Closed	
Number of units per story	2 to n (even), default 10	4 to n (even), default 10	
Number of stories	4 to 20		
Sliders	With (YSD)	Without (NSD)	
Window protection	Impact resistant (IR)	Shutter (YSh)	No shutter (NSh)
Flooring type	Ceramic tile (T)	Carpet (C)	Wood

Table 3
Benchmark building classes.

Residency type	Building layout	Number of Unit per story	Number of stories	Slider	Window protection	Flooring type
AB	Closed	8	8	NSD	NSh	C
AB	Open	8	8	NSD	NSh	C
AB	Closed	8	4	NSD	NSh	C
AB	Closed	8	15	NSD	NSh	C
AB	Closed	8	8	NSD	YSh	C
AB	Closed	8	8	NSD	IR	C

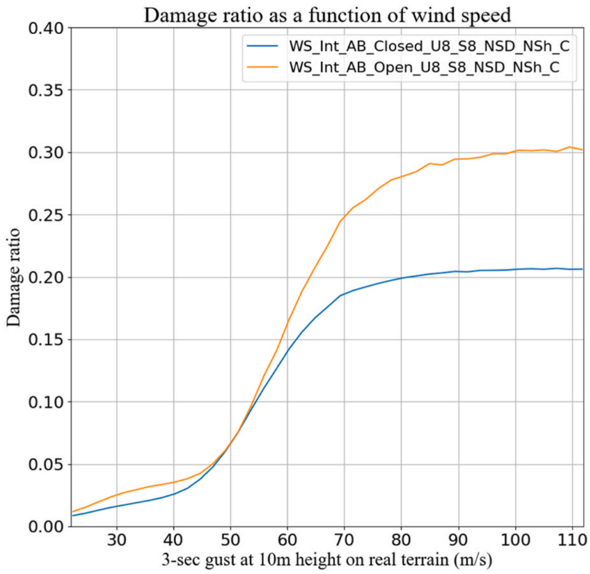


Fig. 7. Wind speed vulnerability curves of the interior: Closed (blue) versus Open (orange) layout.

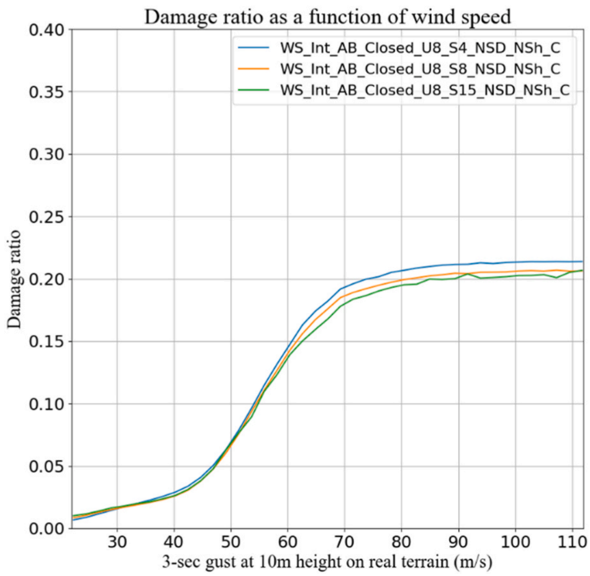


Fig. 8. Wind speed vulnerability curves of the interior: number of stories 4 (blue), 8 (orange), and 15 (green).

than the ones of the closed building due to the greater number of openings for open buildings. Fig. 8 shows that the vulnerability decreases slightly with an increase in the number of stories because the share of the interior and openings as a percentage of the total cost of the building decreases with increased number of stories. In Fig. 9, the vulnerability decreases with increased opening

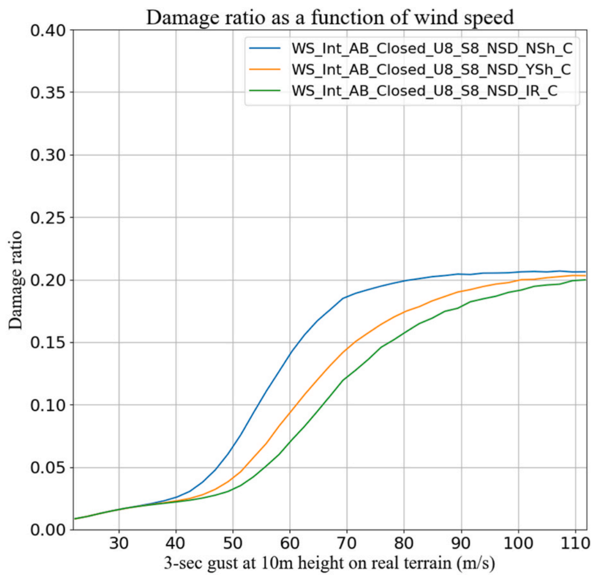


Fig. 9. Wind speed vulnerability curves of the interior: opening protection types NSh (blue), Ysh (orange), and IR (green).

protection. In all these cases, the vulnerability curves verify the logical relationships to risk. Note that the curves do not approach 100 % at high wind speeds, since the model assumes only interior components and openings can be damaged and the sum of the cost coefficients of these components is less than 1.

6. Comparisons against other models

Due to the scarcity of high-quality loss data for MHRB, it is difficult for any modeler to validate and calibrate WHIP-MHRB models against claim data. The MHRB module of the MH-HAZUS was developed primarily based on the experience and judgment with limited calibration [29]. The same is true of the VAM and PVM models described in this paper. Since the VAM of WHIP-MHRB model is an integrated vulnerability and actuarial model, only aggregated modeled portfolio losses could be compared against aggregated claim data if available, or against other model results. This section compares results from the VAM against the results of some existing models, extracted from the submission documents to the Florida Commission on Hurricane Loss Projection Methodology (FCHLPM).

In the case of the PVM of WHIP-MHRB model, this section compares the selected vulnerability curves from the PVM with those from the MH-HAZUS and FPHLM for similar building classes.

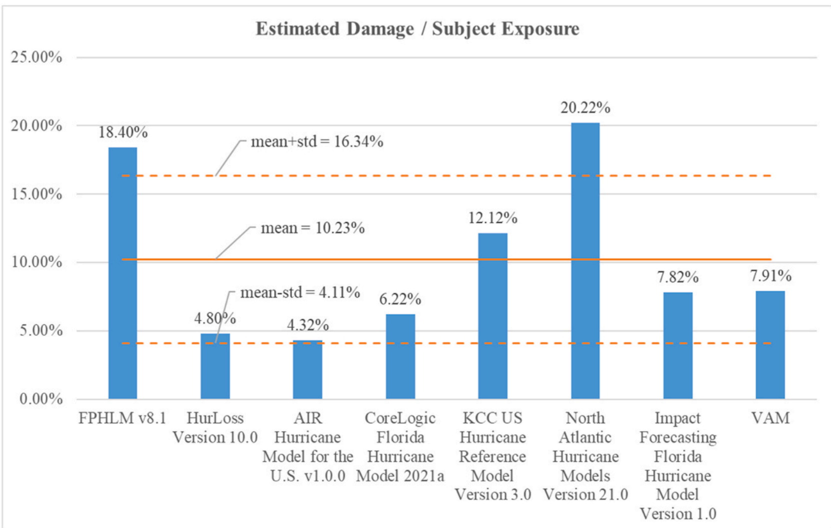


Fig. 10. FCHLPM Form V-1 concrete construction estimated damage/subject exposure.

6.1. Comparisons of VAM results against certified models for hypothetical event

The Report of Activities of the FCHLPM [46] model certification process requires the risk modelers submit a Form V-1. Form V-1 provides a hypothetical exposure of concrete buildings built in 1980 with 20 stories and 8 units per story. The windows have standard glass without shutters. These buildings are subjected to a hypothetical hurricane track distributed over 96 different ZIP codes in Florida. As part of the FCHPLM acceptability process, the modelers need to compute the damage in the different zip codes due to the hurricane and report the aggregated damages. Form V-1 for all the models certified by the FCHLPM are accessible on the website of the Commission.

The authors compared the VAM form V-1 results against the results from the other modelers for the year 2020, available on the FCHPLM website [11,47–51]. Fig. 10 shows the aggregated loss for Form V-1 for the VAM besides the results of other models. The mean value and standard deviation for these eight models are 10.23 %, and 6.12 % respectively. They are shown in Fig. 10 as solid and dashed lines respectively. The value of the VAM is 7.91 %, and it lies in the mid-range of the other models.

6.2. Comparison of vulnerability curves between PVM, FPHLM, and MH-HAZUS

The MH-HAZUS hurricane model is a component-based model like the PVM. For MHRB, the model assesses the losses due to the damage to exterior components (windows, doors, roofs, and walls) explicitly and to interior components (partitions, ceiling, mechanical, and electrical systems) implicitly based on a set of empirical functions. The exterior losses are functions of damage states of exterior components while the interior losses are functions of the accumulated water depth through damaged façade and wetted interior area due to roof damage. The content losses are assumed to be highly correlated with the damage to the building interior. The water depth due to fenestration damage, and roof damage is used to estimate the content loss [29]. The model sums the exterior losses and the interior losses as the building loss resulting in building loss functions. These building loss functions are buildings vulnerability curves (similar to the PVM curves), where the mean damage ratio of the building is a function of peak gust wind speed at 10 m height over open terrain. The MH-HAZUS library includes building and contents loss function for 5-story and 8-story engineered residential buildings for open terrain (with little or no debris impact) and suburban terrain (with debris impact). For purpose of comparison, the MH-HAZUS wind speeds are converted from open terrain to suburban terrain based on wind speed conversion factors provided by FEMA [29], assuming that MHRB's are predominantly a feature of suburban exposure.

Fig. 11 compares the building vulnerability curves of the PVM (mean and mean plus and minus one standard deviation, which can be as high as 6.7 %) and MH-HAZUS for the cases of 5-story and 8-story apartment buildings with key parameters listed in Table 4. There are marked differences between the two models. As expected, debris impact in the MH-HAZUS model makes a large difference, and the model with limited debris impact is below the PVM curves for most of the low to moderate wind speed range, while the model with debris impact is above the PVM curves at moderate to high wind speeds. The PVM vulnerability curves are higher than both MH-HAZUS curves at low to moderate wind speeds because the PVM models the rainwater penetration through the defects of the openings, even in the absence of damage. On the other hand, for high wind speeds, the PVM curves are lower than both MH-AZUS curves because the amount of water intrusion in the PVM model is not enough to cause the complete destruction of the internal components, and external damage is limited to openings. Moreover, the MH-HAZUS model appears to be more sensitive to number of stories than the PVM model.

Fig. 12 (vulnerability of contents) compares the contents vulnerability curves (mean and mean plus and minus one standard deviation, up to 18 % at high wind speeds) of the PVM and MH-HAZUS for the same cases of 5-story and 8-story buildings. The results for content damage are similar to the building damage. The PVM curves are bracketed by the MH-HAZU curves. At low wind speeds (about 25 m/s to 60 m/s) the PVM curves are above the MH-HAZUS curves, while at higher wind speeds the MH-HAZUS has more content damage.

Fig. 13 compares a building vulnerability curve from the FPHLM and the PVM for a 20-story building [30]. In the case of the PVM the figure shows the mean and mean plus and minus one standard deviation. The building class corresponds to a closed layout, 20-story building, with 8 units per story, standard glass without shutter, and carpet floor. The FPHLM MHRB module estimates the interior damage ratio as a function of the height of the accumulated WDR, in a way similar to MH-HAZUS. Fig. 13 for the case of the VAM already showed that the FPHLM is one of the models with higher loss prediction. In this case the FPHLM model is clearly more vulnerable than the PVM, except at low wind speeds where the PVM captures better the damage due to water penetration through defects.

Fig. 14 compares the contents vulnerability curves from the FPHLM and the PVM for the same 20-story buildings [30]. The FPHLM MHRB module assumes the damage ratio of the contents is a function of the damage ratio of the building interior based on experience and judgment. In this case, the two models coincidently produce very similar results even though the two models use different approaches to estimate content damage in MHRB.

7. Conclusions

This paper describes a novel component-based methodology to estimate the damage to mid/high-rise buildings (MHRB), especially the damage to building interior and contents, during hurricane events. A modular approach reduces the MHRB to a combination of apartments units and the model uses the physics of the damage processes from wind and water penetration including damage to openings, rainwater ingress, distribution and propagation, and damage to interior and contents. The resulting model has two versions: a combined hurricane risk model which integrates the vulnerability model into the actuarial model (VAM) to produce portfolio analysis "on the fly" and a probabilistic vulnerability model (PVM) which produces a library of vulnerability matrices and curves for different building classes.

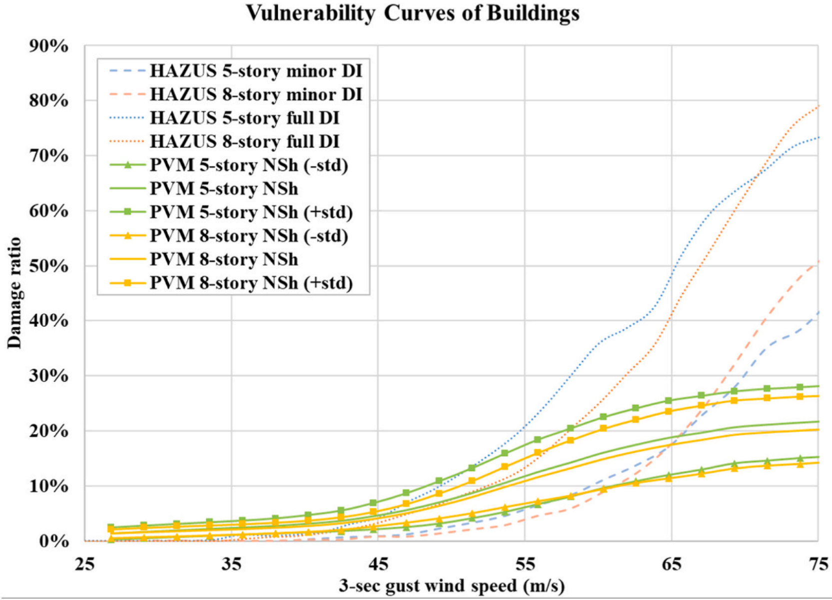


Fig. 11. Comparison of vulnerability curves of buildings between PVM and HAZUS model.

Table 4
Key parameters for vulnerability curves from the HAZUS model and PVM.

Parameters	MH-HAZUS hurricane model	PVM
Layout	Closed	Closed
Number of stories	5 or 8	5 or 8
Number of units	8	8
Glass of windows	single pane tempered glass	Standard glass without shutter (NSh)
Roof Deck	Concrete	–
Roof Cover	Built-up roof cover	–
Glazing area ratio	33 %	20 %
Slider	Without slider	Without slider
Floor type	unknown	Carpet
Debris impact (DI)	Full (suburban) or minor (open terrain)	Full

One of the main issues in the development of MHRB models is the lack of high-quality insurance claim data for validation. As an alternative, the paper verified that the model satisfies the logical relationships to risk. In addition, comparisons of the new model against established available models either proprietary or public, show that the new WHIP-MHRB model results are within the range of other models, which ensures the credibility of the model, at least against other models. The new model tends to predict higher losses at low speeds due to water ingress even in the absence of breaches, and tends to predict lower losses, capped at the interior losses, at higher wind speeds.

Due to the physics-based nature of the model for both exterior and interior damage, it lends itself very well to the possible incorporation of different mitigation features for the openings, interior, and contents components. As such, it is an effective tool to test the cost-effectiveness of different mitigation measures.

The results depend on a large measure on the accuracy of the representation of the different water impact and propagation processes, and the material properties of the different components. Epistemic uncertainty in these variables propagates into the overall model uncertainty. The current model uses results from tests and research on low-rise buildings, including on rain admittance factor, surface runoff coefficients, estimates of water ingress, its distribution and propagation. Results of future tests specific to MHRB for different dimensions, geometry, structure and construction materials could be easily incorporated in the vulnerability model. Other areas of possible improvements include damage to electrical components and other utilities, and cost estimates. As more data becomes available and more research leads to a better understanding of these processes, the uncertainty of the results can be reduced.

CRediT authorship contribution statement

Zhuoxuan Wei: Conceptualization, Formal analysis, Investigation, Writing - original draft. **Jean-Paul Pinelli:** Funding acquisition, Supervision, Writing - original draft, Writing - review & editing. **Kurtis Gurley:** Supervision, Writing - review & editing.

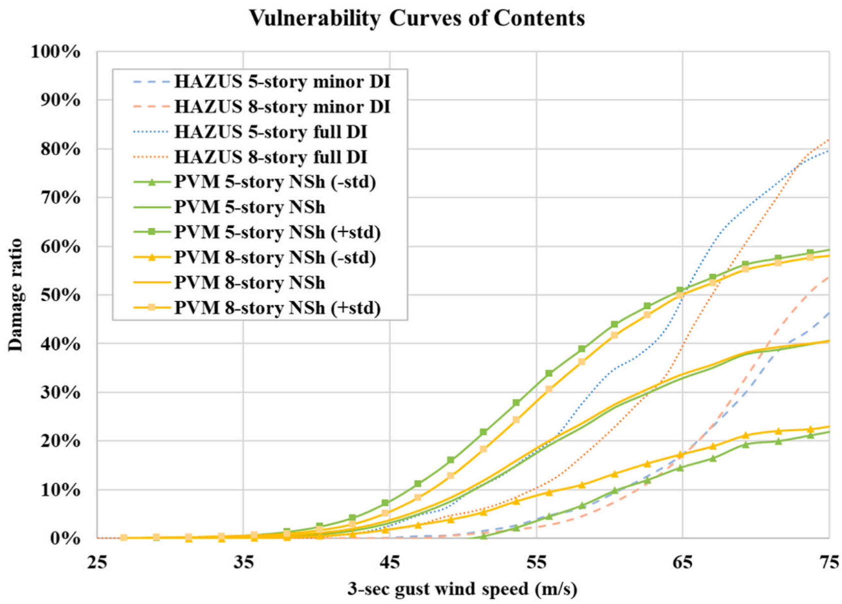


Fig. 12. Comparison of vulnerability curves of contents between PVM and HAZUS model.

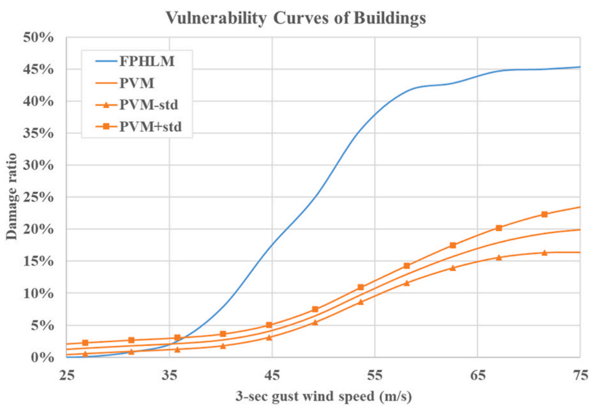


Fig. 13. Comparison of building vulnerability curves between PVM and FPHLM.

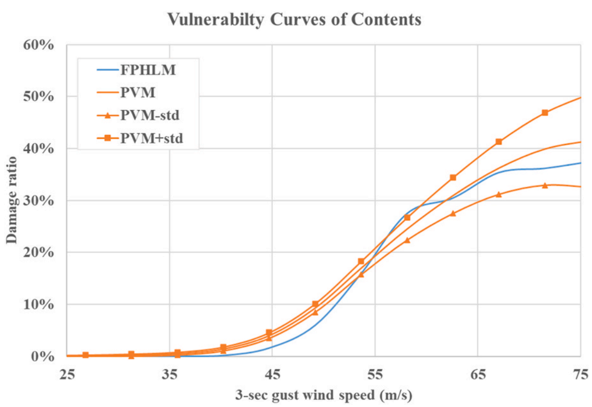


Fig. 14. Comparison of contents vulnerability curves between PVM and FPHLM.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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References

[1] R.S. Means, Square Foot Costs, 2012.
[2] G.L. Pita, J.P. Pinelli, K. Gurley, J. Weekes, S. Cocke, S. Hamid, Hurricane vulnerability model for mid/high-rise residential buildings, Wind Struct. 23 (5) (Nov. 2016) 449–464, https://doi.org/10.12989/WAS.2016.23.5.449.
[3] R.A. Pielke, J. Gratz, C.W. Landsea, D. Collins, M.A. Saunders, R. Musulin, Normalized hurricane damage in the United States: 1900–2005, Nat. Hazards Rev. 9 (1) (Feb. 2008) 29–42, 10.1061/(ASCE)1527-6988(2008)9:1(29)/ASSET/F9BDE35D-036A-41DA-A2A1-13CFCF09A714/ASSETS/IMAGES/MEDIUM/D4.TIF.GIF.
[4] NOAA, Hurricane Costs, 2022. https://coast.noaa.gov/states/fast-facts/hurricane-costs.html. (Accessed 14 June 2023).
[5] J.P. Pinelli, G. Pita, K. Gurley, B. Torkian, S. Hamid, C. Subramanian, Damage characterization: application to Florida public hurricane loss model, Nat. Hazards Rev. (2011), https://doi.org/10.1061/(ASCE)NH.1527-6996.0000051.
[6] Z. Huang, D. V Rosowsky, P.R. Sparks, Long-term hurricane risk assessment and expected damage to residential structures, Reliab. Eng. Syst. Saf. 74 (2001) 239–249 [Online]. Available: www.elsevier.com/locate/ress. (Accessed 14 June 2023).
[7] A. Hatzikyriakou, N. Lin, Impact of performance interdependencies on structural vulnerability: a systems perspective of storm surge risk to coastal residential communities, Reliab. Eng. Syst. Saf. 158 (2016) 106–116, https://doi.org/10.1016/j.ress.2016.10.011.
[8] L. Ma, V. Christou, P. Bocchini, Framework for probabilistic simulation of power transmission network performance under hurricanes, Reliab. Eng. Syst. Saf. 217 (2021), 108072, https://doi.org/10.1016/j.ress.2021.108072.
[9] W. Dong, Engineering models for catastrophe risk and their application to insurance, Earthq. Eng. Eng. Vib. 1 (2002) 145–151, https://doi.org/10.1007/s11803-002-0018-9.
[10] H.C. Shah, W. Dong, A. Chen, A. Risk, T. Solutions, Evolution of seismic risk management for insurance over the past 30 years, Earthq. Eng. Eng. Vib. 17 (1) (2018) 11–18, https://doi.org/10.1007/s11803-018-0421-5.
[11] RMS (Risk Management Solutions), North Atlantic hurricane models [Online]. Available: http://www.rms.com/, 2021.
[12] E. Michel-Kerjan, et al., Catastrophe risk models for evaluating Disaster risk reduction investments in developing countries, Risk Anal. 33 (6) (2013), https://doi.org/10.1111/j.1539-6924.2012.01928.x.
[13] S.C. Chian, A complementary engineering-based building damage estimation for earthquakes in catastrophe modeling, International Journal of Disaster Risk Science 7 (1) (Mar. 2016) 88–107, https://doi.org/10.1007/S13753-016-0078-5/TABLES/10.
[14] G. Biasi, M. Eeri, M.S. Mohammed, D.H. Sanders, Earthquake damage estimations: ShakeCast case study on Nevada bridges, Earthq. Spectra 33 (1) (2017) 45–62, https://doi.org/10.1193/121815EQS185M.
[15] M. Barbato, F. Petrini, V.U. Unnikrishnan, M. Ciampoli, Performance-based hurricane engineering (PBHE) framework, Struct. Saf. 45 (Nov. 2013) 24–35, https://doi.org/10.1016/J.STRUSAFE.2013.07.002.
[16] L. Ma, P. Bocchini, V. Christou, Fragility models of electrical conductors in power transmission networks subjected to hurricanes, Struct. Saf. 82 (Jan. 2020), 101890, https://doi.org/10.1016/J.STRUSAFE.2019.101890.
[17] A.U. Abdelhady, S.M.J. Spence, J. McCormick, Risk and fragility assessment of residential wooden buildings subject to hurricane winds, Struct. Saf. 94 (Jan. 2022), 102137, https://doi.org/10.1016/J.STRUSAFE.2021.102137.
[18] M.L. Hernández, M.L. Carreño, L. Castillo, Methodologies and tools of risk management: hurricane risk index (HRi), Int. J. Disaster Risk Reduc. 31 (Oct. 2018) 926–937, https://doi.org/10.1016/j.ijdrr.2018.08.006.
[19] J.A. de Bruijn, et al., Using rapid damage observations for Bayesian updating of hurricane vulnerability functions: a case study of Hurricane Dorian using social media, Int. J. Disaster Risk Reduc. 72 (Apr. 2022), https://doi.org/10.1016/j.ijdrr.2022.102839.
[20] G.L. Pita, J.P. Pinelli, K.R. Gurley, S. Hamid, Hurricane vulnerability modeling: development and future trends, J. Wind Eng. Ind. Aerod. 114 (Mar. 2013) 96–105, https://doi.org/10.1016/J.JWEIA.2012.12.004.
[21] G. Pita, J.-P. Pinelli, K. Gurley, J. Mitrani-Reiser, State of the art of hurricane vulnerability estimation methods: a review, Nat. Hazards Rev. 16 (2) (Aug. 2014), 04014022, https://doi.org/10.1061/(ASCE)NH.1527-6996.0000153.
[22] G.L. Pita, Foundation and development of natural catastrophe modeling, Nat. Hazards Rev. 23 (4) (Aug. 2022), 04022025, https://doi.org/10.1061/(ASCE)NH.1527-6996.0000567.
[23] ARA (Applied Research Associates), Development of loss relativities for wind resistive features of residential structures [Online]. Available: https://www.floir.com/siteDocuments/LossRelativitiesSingleFamilyResidential.pdf, 2002. (Accessed 14 June 2023).
[24] ARA (Applied Research Associates), Development of loss relativities for wind resistive features for residential buildings with five or more units [Online]. Available: https://www.floir.com/siteDocuments/2002ARADevelopmentofLossRelativitiesforWindResistiveFeaturesforResidentialBuildingswithFiveorMoreUnits.pdf, 2002. (Accessed 14 June 2023).
[25] P.J. Vickery, P.F. Skerlj, J. Lin, L.A. TwisdaleJr, M.A. Young, F.M. Lavelle, HAZUS-MH hurricane model methodology. II: damage and loss estimation, Nat. Hazards Rev. 7 (2) (May 2006) 94–103, 10.1061/(ASCE)1527-6988(2006)7:2(94).
[26] J.P. Pinelli, K.R. Gurley, C.S. Subramanian, S.S. Hamid, G.L. Pita, Validation of a probabilistic model for hurricane insurance loss projections in Florida, Reliab. Eng. Syst. Saf. 93 (12) (Dec. 2008), https://doi.org/10.1016/J.RESS.2008.03.017, 1896–1905.
[27] P.J. Schneider, B.A. Schauer, M. Asce, HAZUS—its development and its future, Nat. Hazards Rev. 7 (2) (May 2006) 40–44, 10.1061/(ASCE)1527-6988(2006)7:2(40).
[28] FEMA, "hazus 5.1 hurricane model user guidance," [Online]. Available: https://www.fema.gov/sites/default/files/documents/fema_hazus-5.1-hurricane-model-user-guidance.pdf, 2022. (Accessed 14 June 2023).

[29] FEMA, Hazus Hurricane Model Technical Manual Hazus 5.1, 2022 [Online]. Available: https://www.fema.gov/sites/default/files/documents/fema_hazus-hurricane-model-technical-manual-5-1.pdf. (Accessed 14 June 2023).
[30] FPHLM, Florida Public Hurricane Loss Model 8.2 (2023) [Online]. Available: https://fphlm.cs.fiu.edu/files/wind_certification/v8.2Submission/. (Accessed 15 June 2023).
[31] R.V. Silva de Abreu, J.P. Pinelli, F. Raji, I. Zisis, Testing and modeling of hurricane wind-driven rain water ingress, propagation, and subsequent interior damage in residential buildings, J. Wind Eng. Ind. Aerod. 207 (Dec. 2020), 104427, https://doi.org/10.1016/J.JWEIA.2020.104427.
[32] J. Weekes, J. Balderrama, K. Gurley, J.-P. Pinelli, G. Pita, S. Hamid, Physical Damage Modeling of Commercial-Residential Structures in Hurricane Winds, Eleventh American Conference on Wind Engineering, 2009.
[33] J.E.C. Weekes, PREDICTING THE VULNERABILITY OF TYPICAL COMMERCIAL AND SINGLE FAMILY RESIDENTIAL BUILDINGS TO HURRICANE DAMAGE, 2014 [Online]. Available: https://www.proquest.com/openview/4bf5682d76eb57cc18b0a0ab296eeca0/1?pq-origsite=gscholar&cbl=18750. (Accessed 15 June 2023).
[34] A.G. Chowdhury, G.T. Bitsuamlak, T.-C. Fu, P. Kawade, Study on roof vents subjected to simulated hurricane effects, Nat. Hazards Rev. 12 (4) (Nov. 2011) 158–165, 10.1061/(ASCE)NH.1527-6996.0000039/ASSET/E186BFB2-B7F7-4878-94D6-E082DC55C718/ASSETS/IMAGES/LARGE/11.JPG.
[35] M. Mullens, B. Hoekstra, I. Nahmens, F. Martinez, Water intrusion in central Florida homes during hurricane jeanne in september 2004 [Online]. Available: http://www.ba-pirc.org/pubs/deliverables/WaterIntrusionReport8-21-06.pdf, 2006. (Accessed 14 June 2023).
[36] ASHRAE, ASHRAE Fundamentals Handbook, 2001 [Online]. Available: https://sovathrothsama.files.wordpress.com/2016/03/ashrae-hvac-2001-fundamentals-handbook.pdf. (Accessed 14 June 2023).
[37] G. Pita, et al., Assessment of hurricane-induced internal damage to low-rise buildings in the Florida Public Hurricane Loss Model, J. Wind Eng. Ind. Aerod. 104 (106) (2012) 76–87, https://doi.org/10.1016/j.jweia.2012.03.023.
[38] T. Johnson, et al., Simulation of rain penetration and associated damage in buildings within a hurricane vulnerability model, Nat. Hazards Rev. 19 (2) (Mar. 2018), 04018004, https://doi.org/10.1061/(ASCE)NH.1527-6996.0000288.
[39] T. Baheru, A.G. Chowdhury, J.P. Pinelli, G. Bitsuamlak, Distribution of wind-driven rain deposition on low-rise buildings: direct impinging raindrops versus surface runoff, J. Wind Eng. Ind. Aerod. 133 (Oct. 2014) 27–38, https://doi.org/10.1016/J.JWEIA.2014.06.023.
[40] B. Blocken, J. Carmeliet, A simplified numerical model for rainwater runoff on building facades: possibilities and limitations, Build. Environ. 53 (2012) 59–73, https://doi.org/10.1016/j.buildenv.2012.01.010.
[41] J. Straube, E.F.P. Burnett, Simplified Prediction of Driving Rain Deposition Simplified Prediction of Driving Rain on Buildings, 2000 [Online]. Available: https://www.researchgate.net/publication/247524319.
[42] T. Baheru, A.G. Chowdhury, J.-P. Pinelli, Estimation of wind-driven rain intrusion through building envelope defects and breaches during tropical cyclones, Nat. Hazards Rev. 16 (2) (May 2015), 04014023, 10.1061/(ASCE)NH.1527-6996.0000158/ASSET/287E1E7D-74F5-4A33-AE3E-78F3D4654BD3/ASSETS/IMAGES/LARGE/FIGURE15.JPG.
[43] F. Raji, I. Zisis, J.P. Pinelli, Experimental investigation of wind-driven rain propagation in a building interior, J. Struct. Eng. 146 (7) (Apr. 2020), 04020114, https://doi.org/10.1061/(ASCE)ST.1943-541X.0002670.
[44] USACE, "us army corps of engineers New Orleans district final report DEPTH-DAMAGE relationships for structures, contents, and vehicles and CONTENT-TO-STRUCTURE value ratios (csvr) in support of the DONALDSONVILLE to the gulf, Louisiana, feasibility study," [Online]. Available: https://www.mvn.usace.army.mil/Portals/56/docs/PD/Donaldsv-Gulf.pdf, 2006. (Accessed 15 June 2023).
[45] Pita, G. L. (2012). *Hurricane vulnerability of commercial-residential buildings* [Doctoral dissertation, Florida Institute of Technology].
[46] FCHLPM, Hurricane Standards Report of Activities as of November 1, 2021 Florida Commission on Hurricane Loss Projection Methodology, 2021 [Online]. Available: www.sbafla.com/methodology.
[47] AIR (AIR Worldwide Corporation), Standards of the Florida Commission on Hurricane Loss Projection Methodology, 2021 [Online]. Available: www.air-worldwide.com/Legal/Trademarks/. (Accessed 14 June 2023).
[48] ARA (Applied Research Associates), HurLoss Version 10.0 Florida Commission on Hurricane Loss Projection Methodology 2019 Hurricane Standards, 2021, 10.0.
[49] KCC (karen clark & company), "KCC US hurricane reference model version 3.0," [Online]. Available: https://fchlpm.sbafla.com/media/f2whpnfi/kcc19_submissiondocument_210503.pdf, 2021. (Accessed 14 June 2023).
[50] IF (Impact Forecasting), Impact forecasting Florida hurricane model version 1.0 ELEMENTS version 15.0 [Online]. Available: https://www.aon.com/impactforecasting/, 2021.
[51] CoreLogic, Florida hurricane model 2021a A component of the CoreLogic north atlantic hurricane model in risk quantification and engineering TM v21 Florida commission on hurricane loss projection methodology [Online]. Available: https://fchlpm.sbafla.com/media/dkjpurbv/fchlpm_corelogic2019_30april2021.pdf, 2021. (Accessed 14 June 2023).