Vulnerability of mid-high rise commercial-residential buildings in the Florida Public Hurricane Loss Model

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ABSTRACT: In its first stage the Florida Public Hurricane Loss Model (FPHLM) was developed to predict expected losses due to hurricane activity and to evaluate mitigation measures for single-family residential buildings. The FPHLM was certified by the state of Florida, and was recently extended to include commercial-residential buildings, classified as low rise (1 to 3 stories) and mid-high rise structures (4 or more stories). The challenges that these types of buildings present led the research team, composed of experts in the field of atmospheric science, civil engineering, actuarial and computer science, to create new approaches for both cases. In this paper the method to calculate the vulnerabilities of mid-high rise buildings is described and the preliminary results are introduced. Unlike single-family residential buildings, mid-high rise buildings have a high variability not reducible to a few typical cases. To deal with this problem a modular approach is proposed that estimates the vulnerabilities of individual apartment units. The modules cover most usual apartment types, and are combined to represent whole buildings. Thus, buildings with any number of stories or units per floor can be modeled by aggregating the corresponding damage per unit.

1 INTRODUCTION

Complex public and private issues such as safety enforcement, hurricane losses predictions, damage mitigation and the insurance ratemaking regulation, among others, made the use of catastrophe models attractive and necessary. Furthermore, experience has shown that the use of catastrophe models is an improvement over econometric estimations based on historical losses only (Watson and Johnson, 2004). Along the line of those improvements the Florida Public Hurricane Loss Model (FPHLM) has been at the forefront in the endeavor of preparing for and protecting from hurricane activity in the state of Florida. The model was developed and is maintained by a multidisciplinary team composed of engineers and scientists mainly from Florida International University (FIU), Florida Institute of Technology (FIT), the University of Florida (UF), Florida State University (FSU), and the National Oceanographic and Atmospheric Administration (NOAA).

The FPHLM dealt in its first stage with residential buildings only (Pinelli et al 2003, Powell 2005, Chen et al 2004, Pinelli et al 2004, Pinelli et al 2006, Pinelli et al 2007) and has recently been extended to include commercial-residential buildings that house a non-negligible share of the population in urban areas. This building stock has been divided, following a recent study by Pita et al. (2008), into low rise buildings (1-3 stories) and mid-high rise buildings (4+ stories).

This paper deals specifically with the modeling approach to predict the damage in mid-high rise buildings. The considerable dimensional variability of these buildings is a challenge to modelers. In particular, it is not practical to define a reasonable number of typical buildings representative of the entire building stock. That circumstance led the engineers to a new modular approach, whereby the buildings' individual apartments are modeled, and the building vulnerability as an aggregation of apartment vulnerabilities.

Hurricane-induced damage to buildings has two components: exterior damage caused mainly by wind pressure and debris missiles (Minor 1994), and interior damage mostly produced by wind-driven rainfall entering the building.

Probabilistic envelope damage of individual apartment models is assessed through Monte Carlo simulations carried out for increasing 3-sec peak-gust wind speeds and debris impacts. This exterior damage information is summarized in vulnerability curves. To estimate interior damage, the amount of wind-driven rainfall ingress is computed. Finally the aggregation of all exterior and interior damage accounts for the total expected damage to the building. The preliminary results of this ongoing research are shown and discussed in this paper.

2 MID-HIGH RISE BUILDINGS SURVEY

Although previous surveys of Florida's single-family residential buildings have been performed (Intrarisk 2002, Zhang 2003), the authors of this paper have carried out one of the first attempts to describe the mid-high rise buildings' constructive features using information from property appraiser's databases all over the state of Florida. This information is essential to identify the most representative cases that are worth being modeled. Even though the results have been shown elsewhere (Pita et al. 2008), a summary is reproduced here to describe the mid-high rise models selection process.

The importance of any building type in the building stock is related to both its quantity and its value (Pielke and Landsea, 1998, 2008). Figure 1 shows a comparison of the relatives quantity and value of low-rise (LR-C) and mid-high rise (MH-R) buildings among condominiums (data for apartment buildings is incomplete).

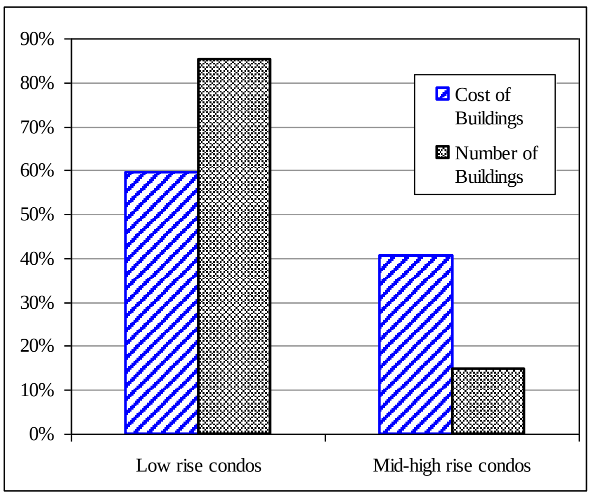

Figure 1: Relative exposure value compared to relative no. of buildings for all condos (from Pita et al. 2008)

From this chart it is evident why the mid-high rise buildings need to be modeled: despite the fact that they are few in number, they are very significant in dollar value.

Table 1: Exterior Walls -Mid/High rise (Pita et al. 2008)

County	Wood	CB	Other
Pinellas	2%	98%	-
Brevard	1%	98%	1%
Lee	-	99%	1%

Regarding constructive features, based on the available information in selected counties, the predominant exterior wall is concrete block, (Table 1), and the most common roof type is the flat roof (Table 2). The distribution of number of stories (in Palm Beach, Pinellas, Brevard and Lee County) is shown in Figure 2 while Table 3 shows the year built distribution.

Table 2: Roof Type - Mid/High rise (Pita et al. 2008)

County	Gable/Hip	Flat
Brevard	24%	76%
Lee	44%	56%

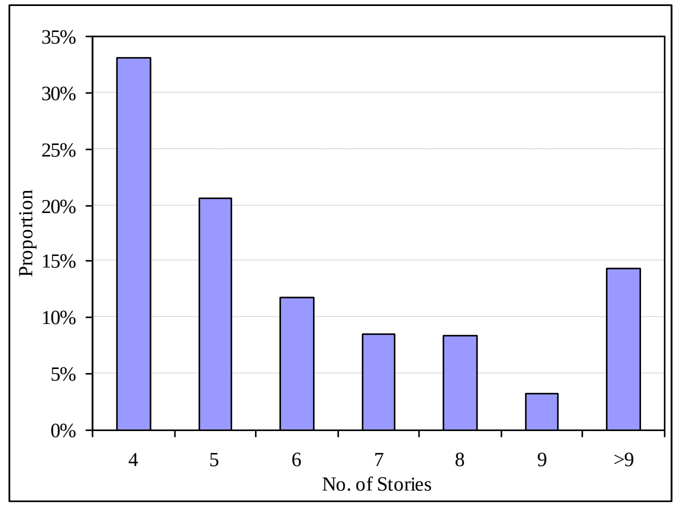

Figure 2: No. Stories relative percentage average – Mid-high rise. (from Pita et al. 2008)

Table 3: Year Built – Mid-High Rise (Pita et al. 2008)

County	Pre - 1970	1971-1983	1984-1992	1993-2002	2003-2007
Palm Beach	6%	46%	40%	7%	1%
Pinellas	9%	54%	14%	12%	11%
Brevard	2%	34%	31%	23%	10%
Lee	3%	42%	15%	24%	16%

The survey (Pita et al 2008) reveals that mid-high rise buildings have a substantial variability due to the combination of factors that include number of stories, geometrical dimensions, type of façade materials, and number of apartments per floor. Due to the importance of mid-high rise buildings, a vulnerability approach different from that of low-rise buildings is necessary.

3 MODELING STRATEGIES

3.1 *Unit types*

The survey results confirm that a modular approach based on modeling individual apartment units instead of whole buildings is appropriate. The unit types are chosen to reflect the cases more frequently found in Florida. There are at least 6 factors that make apartments different; they are: the building general layout, the position of the apartment in the base plan of the building, the unit square footage, the type of exterior wall, the story height of the apartment, related to the debris potential hazard, and finally the opening types.

The apartment location in the building layout is critical for its wind vulnerability. There are at least two crucial locations: "middle units" and "corner units" (Figure 3). The modeling approach needs to consider these two positions as they have different wind loads applied to them. An apartment's wind vulnerability also depends on how many of the apartment walls belong to the exterior façade of the building. In this study two different arrangements are modeled: "open buildings" and "closed buildings" (Figure 4). An open building is one with an exterior corridor to access the apartments. "Closed buildings" are those with apartments accessed from the interior of the building.

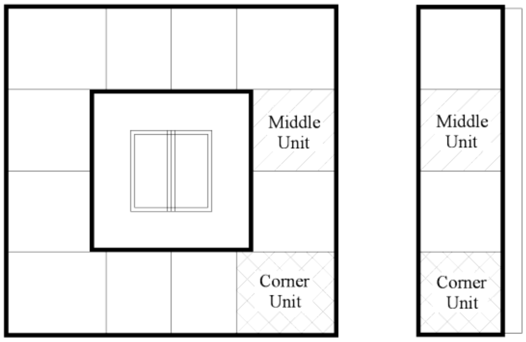

Figure 3: Closed and open building plan views with middle and corner apartment types.

Middle units in open buildings have two opposite walls that belong to the exterior façades, while in closed buildings they have only one. Corner units have three and two walls that belong to the exterior façade in open and closed buildings respectively (Figure 3). Regarding this topic the authors are currently carrying out a survey to determine the prevalence of open and closed buildings in coastal vs. inland areas (postal zip codes).

The area of exterior walls subjected to external wind pressure is related to the apartment base area. The data shows that 1000, 1500 and 2000 sqf are typical sizes of apartment units representative of common buildings' base areas. An additional key feature is the wall material or cladding, and its cover. Different materials show different porosity and thus different water penetration tolerance.

Figure 4: Closed and Open buildings respectively (From Windows Live Maps®)

The height of an apartment unit with respect to the ground is also a key factor for its vulnerability to debris impact. Debris damage decreases with height. To this end the buildings were divided in three zones; Zone 1: for 1st – 3rd story; Zone 2: for 4th – 7th story and, Zone 3 for 8th + stories. The intensity of the debris impact model decreases from zone 1 to 3.

Finally the opening's features have an important influence on both exterior and interior damage. Impact resisting glass, conventional windows/sliders and shutter-protected openings are modeled.

In summary, the apartment characteristics that are currently included in the modeling are:

a) Building layout: Open / Closed
b) Unit position in the base plan: Middle / Corner
c) Unit area: 1,000 / 1,500 / 2,000 sqf
d) Exterior wall: Stucco on masonry
e) Unit height in building: Zone 1 / Zone 2 / Zone 3 for debris zones
f) Shutters / no shutters / Impact resisting win dows

If all the aforementioned factors are combined, there are at least 108 cases to be modeled. The approach allows the total damage assessment of most buildings by aggregating the right combination of apartment models.

3.2 *Number of openings*

The openings are constituted by windows, entry doors and sliding doors. Their dimensions and quantity per apartment type are outlined in Table 4. All windows and sliding doors face the exterior of the building while the entry door only faces the exterior in the case of open buildings.

Table 4: Opening dimensions

Opening Type	Unit Type	Quantity	Dimensions [ft]
Windows	Corner / Closed	5	5 x 4
	Corner / Open	8	5 x 4
	Middle / Closed	2	5 x 4
	Middle / Open	5	5 x 4
Entry Door	All	1	8 x 4
Sliding Door	All	1	8 x 8

3.3 *Exterior Damage assessment*

For each apartment type, the exterior damage is assessed through Monte Carlo simulations. The models are subjected to increasing wind speeds, different wind angles and debris impact. For a given wind speed, the pressures on a model façade are calculated based on ASCE 7-05. Pressures are transformed into loads and the performance of all openings, wall cover and cladding are assessed. The strength of each component is assigned according to probability distributions; these are defined based on manufacturers data, test results (Weekes et al 2008), and engineering judgment. For a given wind speed, all components' strength distributions are sampled to compare capacity and demand. If damage occurs to one of the components, a window for example, the program records the information onto a damage matrix and then all internal pressure coefficients are recalculated and loads redistributed. All components that were undamaged in the previous step are rechecked under the new load scenario, before moving to the next sampling or run.

Consequently the simulations produce a damage matrix for each apartment type model. Damage matrices relate each component's physical damage for a given wind speed and wind angle. A 4-dimensional tensor is therefore produced. See Eqn. (1).

$$DM = DM(\text{Runs, Components,}\ldots \ldots\text{, Wind speeds, Wind angles}) \quad (1)$$

4 ASSESSMENT OF APARTMENT VULNERABILITY

4.1 *Exterior Vulnerability assessment*

The vulnerability is defined as the susceptibility to damage from hazards (Godschalk 1991) or degree of loss resulting from a potential damaging phenomenon (UN, 1992). For this work the vulnerability is defined as the relationship between the damage ratio to the 3-sec gust wind speed, where damage ratio is defined as the cost to replace the damaged components over the total cost of the new apartment. This particular damage definition is used to make the physical damage compatible with the insurance industry definition.

Vulnerabilities for each model are computed by first translating the physical damage recorded in the damage matrices into damage ratios. All component damages for each wind speed and angle are priced, including labor and material costs. Thus the total repair cost is available for each unit and it is then normalized by dividing it by the total cost of the apartment. The process is repeated for all wind speeds and wind angles.

The damage matrices are then transformed into vulnerability matrices. The columns of these matrices represent the different wind speeds from 50 mph to 250 mph in 5 mph increments. These are 3-s gust wind speeds at any given height. The rows of the matrices correspond to damage ratios (DR) in 2% increments up to 20%, and then in 4% increments up to 100%. The cells of a vulnerability matrix for a particular unit type represent the conditional probability of a given damage ratio occurring at a given wind speed.

The vulnerability curve is constructed from the vulnerability matrix. The vulnerability curve for any apartment unit type is the plot of the mean or average damage ratio vs. wind speed. The exterior envelope vulnerability curves for different apartments are shown in Figure 5. It is apparent from the graph that units in open buildings are more vulnerable than in closed buildings and that corner units are more vulnerable than middle units.

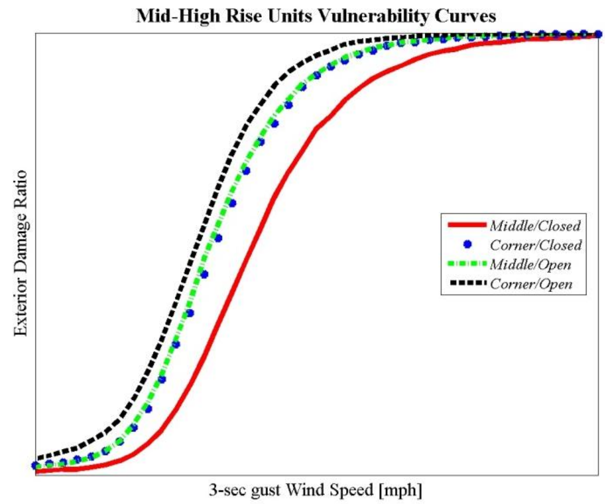

Figure 5: Vulnerability curves for all 4 types of apartments – Concrete block walls – standard glass – Stucco.

4.2 *Interior damage assessment*

The main cause for damage inside the buildings is water intrusion. At low wind speeds the water gets into the building through cracks in the walls, wiring outlets, flashings, windows sealing, etc. At high wind speeds, the water enters through the breaches in the openings and cladding produced by wind and debris. In order to estimate the amount of water that enters into an apartment in both cases, it is necessary to assess the initial permeability that the apartment has to water leakage and to assess the overall breach size produced in the envelope by wind and debris at high speeds.

For low wind speeds, the inclusion of information on the subjacent defects, due to either poor workmanship or to aging, that allow water to come into an apartment is currently under development. An equivalent permeability will be included in the program that will allow water leakage at low wind speeds. It is noteworthy though that water entering at low speeds is frequent in buildings in Florida so a consideration of this factor is important.

For high wind speeds, a set of four physical vulnerability curves were derived from the damage matrices for windows, slider, entry door and walls, for each apartment type, that relate the 3-sec gust wind speeds with the breaches' square footage (Figure 6). The window breach size cannot be retrieved from the damage matrices since these do not express the openings' physical damage as an area but as "damaged" or "undamaged". Therefore if an opening is damaged, a breach expressed as a percentage of the opening size is assigned through sampling of a probability function (Table 5). Wall damage is expressed as a percentage of the wall area in the damage matrix so a probability sampling is not necessary. Consequently, a set of curves for each opening with the expected breach size in square feet as a function of wind speed is produced for each apartment type model. These will be used later to assess the amount of water that entered the apartment.

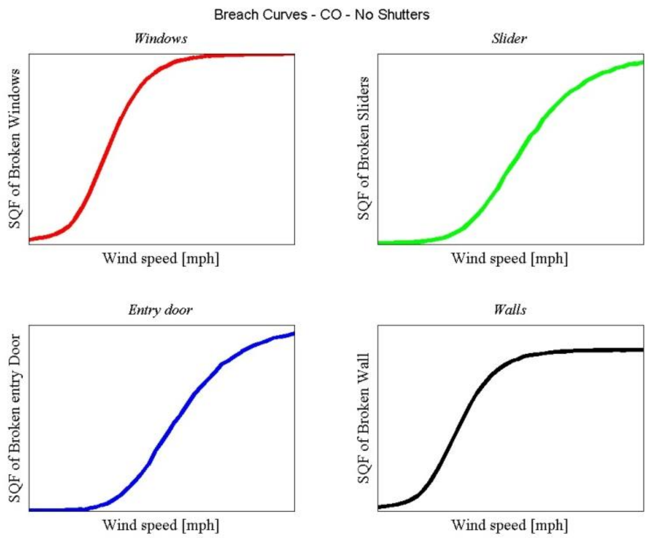

Figure 6: Fragility curves for windows, slider, entry door and exterior wall for a given apartment type

The difference between the physical vulnerability curves of Figure 6 and the damage ratio vulnerability curves of Figure 5 lies in the fact that the first relate the physical damage of one component in the form of the breach size to wind speed while the second refers to the all-inclusive damage of components expressed as cost damage ratio to wind speed.

Table 5: Breach probability distributions

Opening Type	Breach due to debris	Breach due to debris
Windows	N(0.1, √.0005)	N(0.5, √0.001)
Entry Door	N(0.05, √.0005)	N(0.3, √0.001)
Sliding Door	N(0.05, √.0005)	N(0.3, √0.001)

4.3 *Wind-driven rainfall*

The meteorology team simulates thousands of years of hurricane activity producing wind field profiles for every postal zip code centroid. The wind field is a three dimensional field that delivers the variation of wind speed with height for each latitude/longitude coordinates of a zip code centroid. In addition to the wind speed information the FPHLM meteorological team is developing a rain model that delivers the rainfall rate and rain duration at every zip code centroid.

To estimate the amount of water that gets into an apartment, three pieces of information are needed, first a rain model, second a way to compute the amount of rain that hits the exterior wall and finally an estimation of the breach size per story. The amount of rain impinging on the vertical face of the building is computed using a chart that relates the vertical rainfall rate and wind speed inputs with the impinging rain on the vertical face of the building (Figure 7).

The chart was developed using a simplified approach to account for the effect that wind has on the rain drop trajectories. The authors are currently refining these relationships.

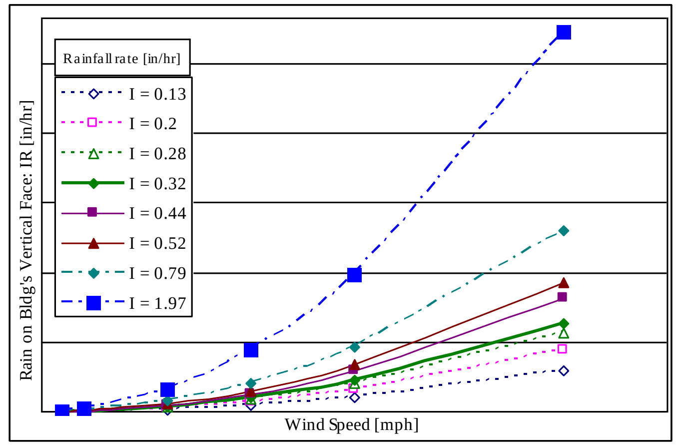

Figure 7: Wind-driven horizontal rain

5 COMPUTATION OF DAMAGE FOR A GIVEN BUILDING

5.1 *Aggregation of Exterior and Interior Damage*

Unlike the single-family home loss model where interior and exterior damage was aggregated inside the vulnerability module, the aggregation for mid-high rise buildings is performed outside that module due to the interior damage propagation. The modular approach produces independent assessments of exterior damage for each unit. To the contrary, the interior water damage can spread from unit to units and trigger damage far from its source. So the interior damage is treated in two stages; the first part is the one that occurs as a direct result of the exterior damage and the second part the one that occurs as a consequence of the interior damage propagation. In the latter case, the overall dimensions and the number of apartments per story and their size must be taken into account.

The separate modeling of exterior and interior damage as presented here is also well suited to deal with the insurance issue of different insurance coverage for apartment and condo buildings. Apartment buildings are those buildings owned by a person or company which rents the apartments to tenants. In this case the building insurance policy covers the exterior of the building, the interior of both common areas and units, the contents of the common areas and selected unit contents like appliances. On the other hand, the apartments in condo buildings are owned by the individuals that either live in them or rent them to a third party whilst the building is administered by a condo association. In this case, the building policy covers the building exterior and the interior plus contents of the common areas only. In both cases the tenant or unit owner belongings are not covered by the building policy.

5.2 *Cost analysis*

For mid-high rise buildings the definition of what constitutes the interior and contents of an apartment or even a building depends on the type of ownership as explained above. When computing the total loss, it is necessary to understand how interior and exterior components contribute to the total insured value of the building. To that purpose many different Florida building floor plans were investigated and a cost analysis was performed considering that they could be either apartment buildings or condo buildings. The cost participation coefficients represent an approximate distribution of exterior and interior value as a share of the total insured value for apartment and condo buildings' units. The coefficients will be used later to weight the expected exterior and interior damage ratios. For the exterior proportion of the damage in apartment buildings' units, the factor is called k^{AB}_E while for condo buildings it is called k^{CB}_E. The interior portion of the damage is simply 1 minus the corresponding coefficient.

5.3 *Mid-High rise buildings detailed damage estimation*

This section shows how the exterior and interior damage are calculated. See Figure 8.

The program reads the information on the building and its location for every policy in the insurance portfolio and then assigns a wind speed profile to it based on its location. Next the algorithm calculates the number of corner and middle units per floor. At the same time the vulnerability curves for all types of apartment units and the corresponding components' physical vulnerability curves are selected.

Vulnerability curves are aggregated for each story and weighted by the relative proportion of middle and corner units. See Eqn. 2,

$$V_A(W_0) = \frac{a_C V_C + a_M V_M}{a_C + a_M} \quad (2)$$

where V_A is the aggregated exterior vulnerability per story, W_0 is the wind speed value that is a function of height, a_C and a_M are the number of middle and corner units and V_C and V_M are the vulnerability curves for middle and corner units respectively as seen in Figure 5. The wind speed value at every story is used to get from the aggregated vulnerability V_A the value of the exterior damage ratio of each story EDR, i.e.

$$EDR_s(\text{story}) = f\left[V_A(W_0),\ W_0(\text{height})\right] \quad (3)$$

Thus a vector of exterior damage ratio for each story is built. The expected exterior damage ratio vector (EEDR) for the entire building becomes:

$$EEDR = \frac{1}{\#\,\text{Stories}} \sum_{i=1}^{n} V_A(W_i) \quad (4)$$

For the interior damage estimation the process is similar. From the wind profile, the corresponding wind speed, W_0, is calculated at each story. For a given story (see Figure 8) and its corresponding wind speed, the value of the expected breach size for windows, entry door, slider door and walls is retrieved from the set of 4 breach curves (Figure 6). The breach size of each component is added to get the average breach size per story. The next step is that of estimating the amount of water that, for the hurricane considered, could get into a particular story with a given breach size. The meteorology component provides the amount of rainfall rain and the estimated duration of the hurricane-driven rain in that particular zip code; the chart in Figure 7 estimates the impinging rain onto the building façades from the aforementioned information. Thus with the impinging rain and the expected breach size at a floor, it is possible to get an estimate of the amount of water that would have entered that particular floor.

Empirical curves based, at present, on engineering judgment, transform the water content in each story to interior damage ratio. Also an empirical scheme for vertical propagation of interior damage was implemented (to be further refined in the future). So the final product of the interior damage assessment is the Expected Interior Damage Ratio (EIDR). See Eqn. 5:

$$EIDR = \frac{1}{\#\,\text{Stories}} \left[\sum_{i=1}^{n} IDR(W_i) + \sum_{i=1}^{n} IDR_{VERT}(W_i) \right] \quad (5)$$

where $IDR(W_i)$ is the interior damage vector, $IDR_{VERT}(W_i)$ is the interior damage propagation vector; both vectors are expressed as a percentage.

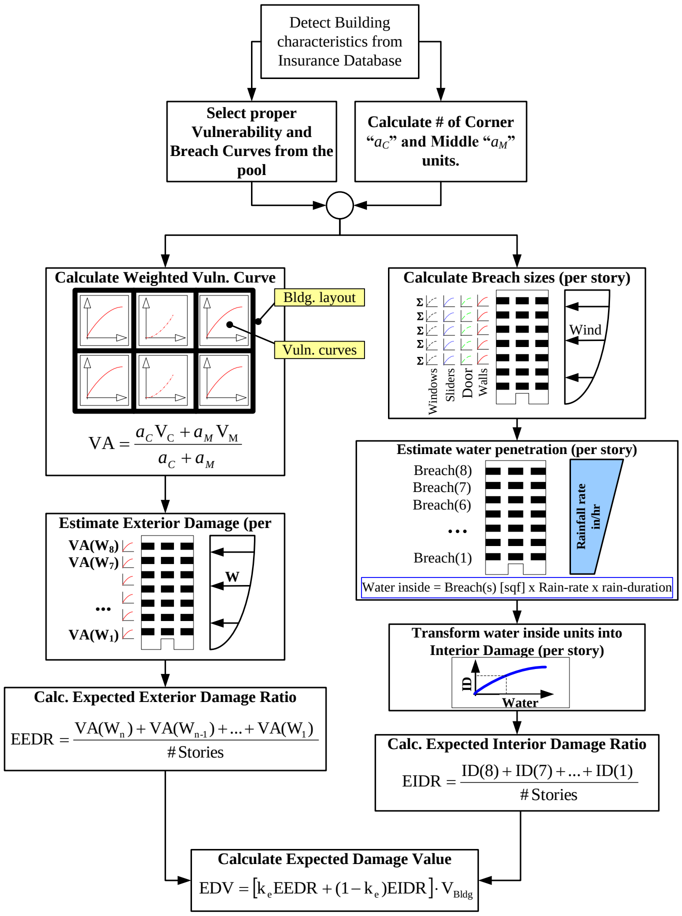

Figure 8: Exterior and Interior damage assessment

At this point of the process, the algorithm has computed expected damages, both exterior (EEDR) and interior (EIDR), for the particular building of the policy under study. Depending on the building type and the building value, the dollar value of the damage is attained by using either one of equations 6 or 7, for apartments or condo buildings respectively. In these equations, it is assumed that the rate of damage for the interior is the same for all portions of the interior of the building.

$$EDV_j^B = \left(k_E^{AB} EEDR + (k_E^{AB} - 1) \cdot EIDR\right) \cdot V_{AB} \quad \textbf{(6)}$$

$$EDV_j^B = \left(k_E^{CB} EEDR + (k_E^{CB} - 1) \cdot EIDR\right) \cdot V_{CB} \quad \textbf{(7)}$$

where EDV_j^B is the Expected Damage Value, expressed in dollars for building "j", and V_{AB} and V_{CB} are the insured values of the apartment or condo building respectively.

The procedure that was described heretofore takes place for every single policy of every insurance company. Also every single insurance company database is subjected to multiple hurricanes. Thus the process repeats thousands of times. Once the procedure has finished for all possible cases then the algorithm calculates the expected annual loss, which is the average loss over all the years included in the simulations.

5.4 *Mid-High rise buildings loss estimation model overall structure.*

An outline of all the components mentioned up to this point working together clarifies the functioning of the loss model as a whole; the complete loss model is depicted in the simplified flowchart of Figure 9.

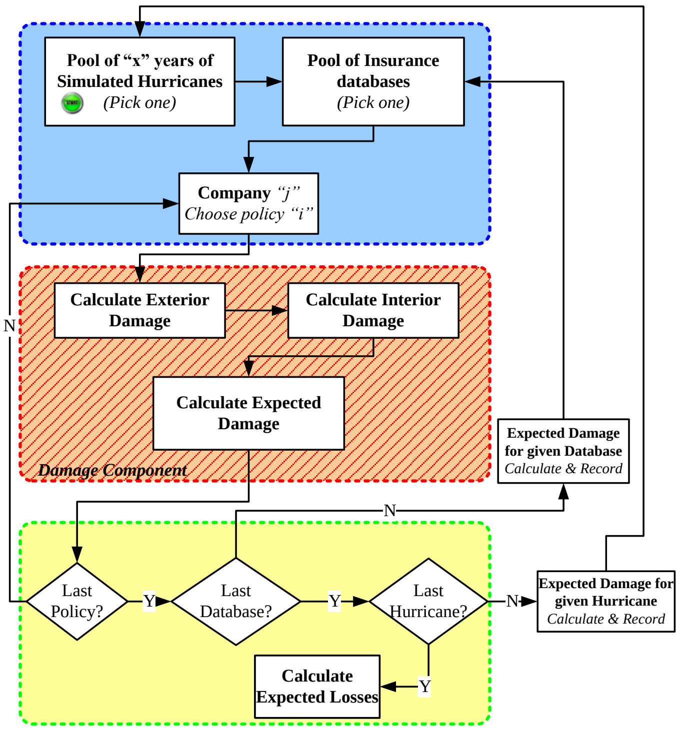

Figure 9: Flowchart of the overall mid-high rise model

The loss model organization is depicted in Figure 9; all components described in this paper are summarized in the middle dashed rectangle-area. The first hurricane of the simulation is selected and the corresponding wind velocity is assigned to every zip code in the state. Then the building database is selected and the algorithm uploads all buildings one by one. For each building the algorithm calculates the exterior damage as a result of wind speed and the interior damage as a result of water intrusion. Both exterior and interior damage are aggregated and transformed to a dollar value loss. The process is repeated until the last building database is finished and also until the last hurricane has been considered. At the end of the process the algorithm applies all the actuarial rules and calculates the expected loss.

6 VALIDATION

At present the model is a work in progress so the validation has not been finalized. The challenge is that all components of the model, i.e. atmospheric, engineering, and actuarial, need to be validate independently and then a validation of all components working together is also necessary. These validations are dependent on the availability of reliable insurance data.

7 CONCLUSIONS

The overall structure of the FPHLM for commercial-residential mid-high rise buildings has been presented and discussed.

The adopted modular approach is well suited for the large variability of this kind of buildings, which cannot be reduced to a few typical cases. On the contrary, the apartment units share common vulnerabilities that can be more easily typified. Any building can then be seen as an aggregation of a few types of units, and the model has the capability of adapting to different building patterns. The modular approach is also well adapted to the intricacies of insurance policies for apartment and condo buildings.

Major challenges of the technique include: the development of hurricane rain models and of realistic interior damage mechanisms that take into account water penetration and water propagation; and, the validation of the model based on actual insurance claim data.

8 ACKNOWLEDGMENTS

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