Hurricane Damage Prediction Model for Residential Structures

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Abstract: The paper reports progress in the development of a practical probabilistic model for the estimation of expected annual damage induced by hurricane winds in residential structures. The estimation of the damage is accomplished in several steps. First, basic damage modes for components of specific building types are defined. Second, the damage modes are combined in possible damage states, whose probabilities of occurrence are calculated as functions of wind speeds from Monte Carlo simulations conducted on engineering numerical models of typical houses. The paper describes the conceptual framework for the proposed model, and illustrates its application for a specific building type with hypothetical probabilistic input. Actual probabilistic input must be based on laboratory studies, postdamage surveys, insurance claims data, engineering analyses and judgment, and Monte Carlo simulation methods. The proposed component-based model is flexible and transparent. It is therefore capable of being readily scrutinized. The model can be used in conjunction with historical loss data, to which it can readily be calibrated.

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Introduction

Within the United States, windstorms are one of the costliest natural hazards, far outpacing earthquakes in total damage (Landsea et al. 1999). For example, the $22 billion insured losses of Hurricane Andrew exceeded by about $7 billion the insured losses of the Northridge California Earthquake. A recent analysis of windstorm damage for the United States East and Gulf coasts by Pielke and Landsea (1998) suggests that the average annual economic loss could be about $5 billion. This agrees closely with National Oceanic and Atmospheric Administration estimates of $84 billion dollars in hurricane related damage since 1980. According to statistics published by the Munich Re Group for the year 2001, windstorms were responsible worldwide for 55% of the $36 billion in economic losses and 88% of the $11.5 billion in insured losses due to all natural disasters combined. Similar percentages were recorded for the United States (*Topics–Annual Review* 2002). Over half of the hurricane-related damage in the United States occurs in the state of Florida, which has $1.5 trillion in existing building stock currently exposed to potential hurricane devastation. With approximately 85% of the rapidly increasing population situated on or near the 1,900 km of coastline, Florida losses will continue to mount in proportion to coastal population density. It is therefore critical for the state of Florida, and the insurance industry operating in that state, to be able to estimate expected losses due to hurricanes and their measure of dispersion. For this reason the Florida Department of Insurance asked a group of researchers to develop a public hurricane loss projection model. This paper describes a model for the estimation of the damage to residential buildings due to hurricane or severe storms.

Although a number of commercial loss projection models have been developed, only a handful of studies are available in the public domain to predict damage for hurricane prone areas. Boswell et al. (1999) attempted to predict the public costs of emergency management and recovery, without taking into account losses to individual homeowners. In 1985, Berke et al. (1995) presented a computer system simulating economical and social losses caused by hurricane disasters, and a Vulnerability Assessment and Mapping System (Berk et al. 1984) enabled the

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user to consider various types of hurricanes with varying surge, wind pattern and point of landfall. This information is of some interest, but it is not directly applicable to residential construction in Florida.

Most studies for residential losses use postdisaster investigations (FEMA 1993) or available claim data to fit damage versus wind speed vulnerability curves. For example, a relationship between home damage from insurance data and wind speed was proposed for Typhoons Mireille and Flo (Mitsuta et al. 1996). A study by Holmes (1996) presents the vulnerability curve for a fully engineered building with strength assumed to have lognormal distribution, but clearly indicates the need for more thorough postdisaster investigations to better define damage prediction models. A method for predicting the percentage of damage within an area as a function of wind speed and various other parameters was presented by Sill and Kozlowski (1997). The proposed method was intended to move away from curve fitting schemes, but its practical value is hampered by insufficient clarity and transparency. Huang et al. (2001) presented a risk assessment strategy based on an analytical expression for the vulnerability curve. The expression is obtained by regression techniques from insurance claim data for hurricane Andrew. Khanduri and Morrow (2003) also presented a similar method of assessment of vulnerability and a methodology to translate a known vulnerability curves from one region to another region. Although such approaches are simple, they are highly dependent on the type of construction and construction practices common to the areas represented in the claim data. Recent changes in building codes or construction practices cannot be adequately reflected by Huang et al.'s vulnerability curve. In addition, damage curves obtained by regression from observed data can be misleading, because very often, as was the case for hurricane Andrew, few reliable wind speed data are available. In addition, damage curves regressed from observed data do not adequately represent the influence of primary storm characteristics such as central pressure, forward velocity, radius of maximum wind, the amount of rain, duration, and other secondary parameters such as demand surge and preparedness.

In contrast, a component approach explicitly accounts for both the resistance capacity of the various building components and the load effects produced by wind events to predict damage at various wind speeds. In the component approach the resistance capacity of a building can be broken down into the resistance capacity of its components and the connections between them. Damage to the structure occurs when the load effects from wind or flying debris are greater than the component's capacity to resist them. Once the strength capacities, load demands, and load path(s) are identified and modeled, the vulnerability of a structure at various wind speeds can be estimated. Estimates are affected by uncertainties regarding on one hand the behavior and strength of the various components and, on the other, the load effects produced by hurricane winds. A hurricane wind damage prediction model that incorporates a time-stepping component approach is being implemented for the FEMA HAZUS project (Lavelle et al. 2003).

The purpose of this paper is to present and illustrate the principle of a probabilistic component approach to the prediction of wind-induced damage and of corresponding repair/replacement costs. Our approach makes use of probabilistic information on combinations of damage states. The latter consist of combinations of basic damage modes, determined by engineering judgment, postdisaster observations, laboratory experiments on component capacity, and/or analysis.

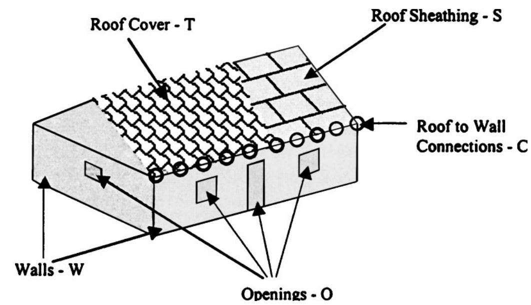

FIG. 1. Components of single family home

The next section discusses basic damage modes. We then consider combined damage states and the derivation of their probabilistic characteristics. Once this is done it is possible to estimate repair/replacement costs associated with building damage induced by windstorms. Such costs are referred to as wind-induced building damage, or for short damage. Note that we will occasionally refer to some types of damage in a physical, as opposed to a monetary sense. For example, we will refer to the physical damage of, say, shingles. We will omit the adjective "physical" and refer to physical damage more briefly as damage whenever the context is sufficiently clear that no confusion can result from this use. The calculation of damage ratios (repair/replacement costs) allows the estimation of building vulnerabilities. In a wind engineering context we will define vulnerability as a measure of the susceptibility to damage, expressed as a function of the wind speed. Finally, we discuss and illustrate the estimation of expected damage for groups of buildings, including regional expected annual damage, and expected damage induced by a hurricane event. Uncertainties associated with such estimates will be dealt with in a subsequent paper. A companion team of researchers for this project is developing the wind field model that will provide this damage model with the probabilities of occurrence of various wind speeds (Powell et al. 2003), thus allowing the estimation of annualized insurable loss. Development of the wind field model is not a part of this paper, and will be the subject of a forthcoming separate document.

Basic Damage Modes

This research is currently focused on typical residential low-rise structures of different types, including manufactured homes, that make up the overwhelming bulk of the Florida building stock. For purposes of illustration, the paper presents the approach for a building belonging to a specified type: an unreinforced masonry house with timber gable roof covered with shingles. Its most vulnerable types of components are shown in Fig. 1. They correspond to the following five significant basic damage modes: (1) breakage of openings (O); (2) loss of shingles (T); (3) loss of roof or gable end sheathing (S); (4) roof to wall connection damage (C); and (5) masonry wall damage (W). For a specified wind speed v the building will either not experience damage, or experience several of these five basic damage modes. Some damage modes are independent of each other (e.g., loss of shingles and breakage of openings); others are not (e.g., given that the building has experienced window breakage, the probability of its losing sheathing increases)

The model is further refined by dividing each basic damage mode into several subdamage modes (e.g., $O_i, i=0,1,2,3$) ac-

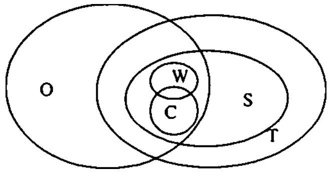

FIG. 2. Venn diagram for basic damage modes of masonry home

cording to the degree of damage: no damage, light, moderate, or heavy damage. For example, we can define O_0 as zero loss of opening (no damage), O_1 as loss of less than 25% of openings (light), O_2 as loss of 25–50% of openings (moderate), and O_3 as loss of in excess of 50% of openings (heavy). Subdamage modes can similarly be defined for the other basic damage modes, denoted by $T_j, S_k, C_l, W_m, (j,k,l,m = 0,1,2,3)$. The subdamage modes corresponding to a damage mode must be so defined that they are mutually exclusive. For example, the union of the subevents O_i $(i=1,2,3)$ is equal to the event O, and the sum of their probabilities is equal to the probability of O: $P(O)=P(O_1)+P(O_2)+P(O_3)$. For each damage mode the probability of event "no damage" $(i=0)$ is unity minus the sum of the probabilities of the three subdamage modes $(i=1,2,3)$.

The choice of basic damage modes is in general determined by practical considerations such as the type of structure, the format of the requisite probabilistic information and the extent to which it is available, the need for keeping the model reasonably simple, and the requisite accuracy of the loss estimation. The basic damage modes need not be consistent from one structural type to the next. The methodology described in this paper is independent of the basic damage modes being considered in the calculations.

Combined Damage States

Varying levels of damage to different components characterize windstorm damage to a structure. We shall refer to these combinations of damage modes as combined damage states. Since the resulting combined damage states require not only set-theoretical but also architectural and structural engineering scrutiny, it is appropriate to use an engineering approach to their definition. The damage states being considered must satisfy the following requirements:

1. They must be combinations of the damage modes described previously.
2. They must be chosen with a view to enabling damage estimates to be made correctly, in the sense that no possible damage state is omitted, and no double or multiple counting of damage states occurs.
3. They must make sense from an architectural and structural engineering point of view. For example, for a building covered by conventional sheathing, it may be assumed that wall damage will not occur without some loss of sheathing. Similarly, although shingle and opening failures do not necessarily cause roof-to-wall connection damage, it is reasonable to assume that no roof to wall connection damage will occur without some shingle loss and opening breakage.

The relations between basic damage modes are represented in the Venn diagram of Fig. 2. The partial or total overlap of the basic damage modes is based on engineering judgment and the findings in post damage studies. Associated with the basic damage modes O, T, S, W, and C are events—combined damage states—whose union represents the total damage universe shown in Fig. 2. Combined damage states can similarly be considered that involve subdamage modes. Fig. 3 shows the Venn diagrams associated with various possible damage outcomes. We consider the events associated with the occurrence of the following combinations of subdamage modes:

1. *Event 1.* O_0T_0 (no damage). See hatched area in Fig. 3(a). Since it is assumed that all damage involves first some opening breakage and/or shingle loss, the lack of both of these is equivalent to no structural damage. Although minor contents damage could occur due to roof and openings leaks.
2. *Events 2, 3, 4.* O_iT_0 (opening failure and no shingle loss) $-i=1,2,3$. See hatched area in Fig. 3(b). Recall that each area O_i is a subset of the set O; for convenience this is not shown in any of the graphs of Fig. 3. The probabilities of these substates will help to estimate the cost of repair of homes that have only opening failures.
3. *Event 5, 6, 7.* $O_0T_jS_0$ (shingle failure and no opening or sheathing loss) $-i=1,2,3$. See hatched area in Fig. 3(c). The probabilities of these substates will help to estimate the cost of repair of homes that have only roof cover failures (e.g., homes with effectively boarded openings and strong garage doors).
4. *Events 8–16.* $O_iT_jS_0$ (opening and shingle failure and no sheathing loss) $-i,j=1,2,3$. See hatched area in Fig. 3(d).
5. *Events 17–25.* $O_0T_jS_k$ (shingle and sheathing failure and no opening failure) $-j,k=1,2,3$. See hatched area in Fig. 3(e).
6. *Events 26–52.* $O_iT_jS_kW_0C_0$ (opening, shingle and sheathing loss, and no wall and connection failure) $-i,j,k=1,2,3$. See hatched area in Fig. 3(f).
7. *Events 53–133.* $O_iT_jS_kC_lW_0$ (opening, shingle, sheathing and connection failure, and no wall failure). See hatched area in Fig. 3(g).
8. *Events 134–214.* $O_iT_jS_kW_mC_0$ $-i,j,k,m=1,2,3$ (opening, shingle, sheathing and wall failure, but no connection failure). See hatched area in Fig. 3(h).
9. *Events 215–457.* $O_iT_jS_kC_lW_m$ $-i,j,k,l,m=1,2,3$ (opening, shingle, sheathing, wall, and connection failure). See hatched area in Fig. 3(i).

There are a total of 457 damage state events. However, not all of these events are of interest from a damage estimation point of view. Engineering considerations allow the elimination of a number of events. There are several scenarios:

1. When roof cover damage (T) and sheathing damage (S) occur at the same time, the damaged area of the roof cover must be equal to or larger than the damaged area of sheathing. We can therefore eliminate all the damage states which pertain to damaged area of roof cover smaller than the damaged area of sheathing, i.e., eliminate events that contain T_jS_k when $j<k$.
2. When roof cover damage (T) or sheathing damage (S) or opening damage (O) occur together with wall damage (W) or connection damage (C), the level of damage for T or S or O should be larger than for W or C. That is, there is only a small probability that a wall would suffer heavy damage while the roof cover has suffered light damage. Thus we can eliminate all the damage states which contain lower levels of roof covering damage and decking damage and opening damage than wall damage and connection damage, i.e., eliminate events containing O_i, T_j, S_k, W_m, and C_n when $i,j,k<m,n$. In particular, when severe wall damage and severe roof to wall connection damage occur together, the whole structure collapses. So if roof to wall connection and wall damage are both heavy (i.e., if W_3 and C_3 occur), the

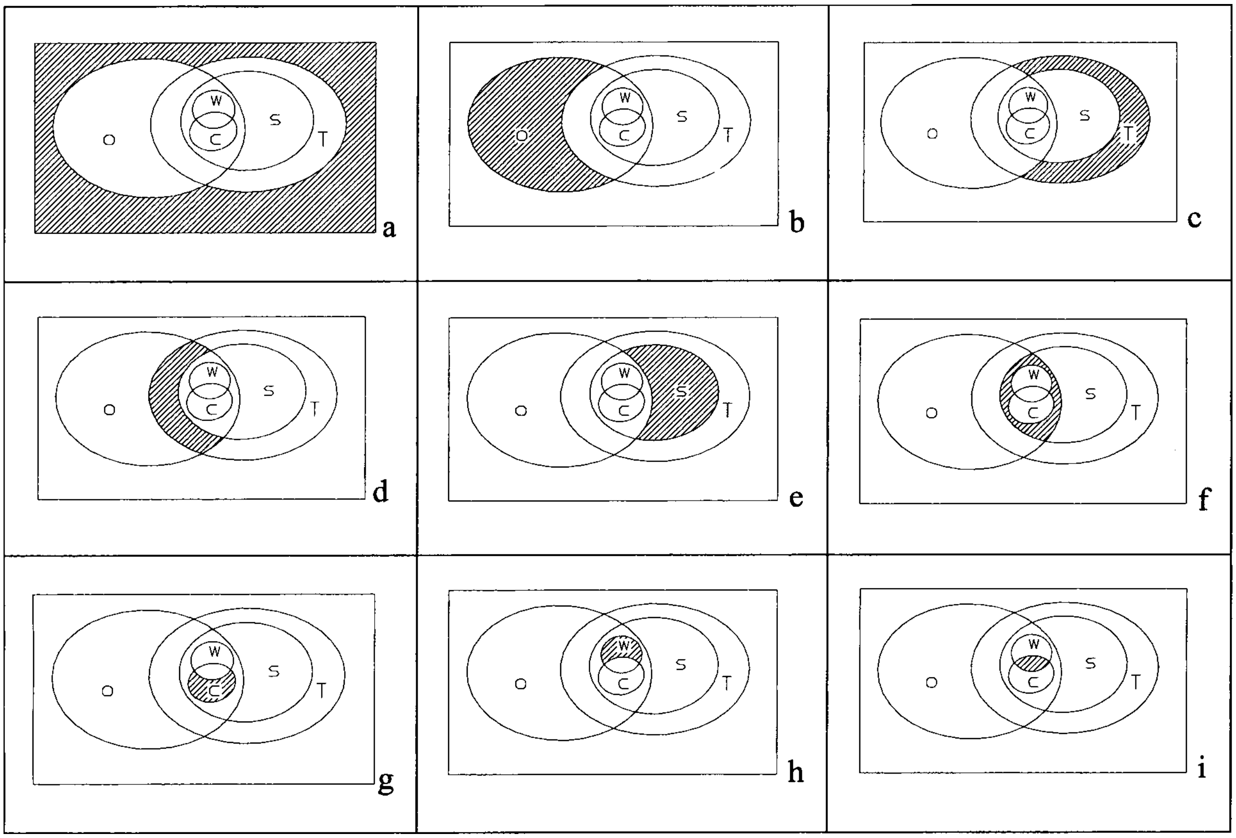

FIG. 3. Venn diagrams of combined damage states (subsets of Fig. 2)

only significant damage event will be $O_3T_3S_3W_3C_3$, so that we can eliminate all events $O_iT_jS_kW_3C_3$ for which $i,j,k=1,2$.

These engineering considerations allow the elimination of between 230 and 326 damage states, leaving 131–227 possible damage combinations, depending on the interpretation of the above criteria. The final number will be defined based on the simulations. Note from Fig. 2 that, for any specified wind speed, any two distinct damage states are mutually exclusive. For example, a structure cannot experience both the state $O_iT_jS_kW_0C_0$ and the state $O_iT_jS_kW_0C_1$.

Calculation of Damage Matrices

The determination of values for the probabilities of occurrence of the basic damage modes and the combined damage state events rely upon the use of a component-based Monte Carlo simulation engine. The simulation relates estimated probabilistic strength capacities of building components to 3 s average gust wind speeds through a detailed wind and structural engineering analysis that includes effects of wind-borne missiles. Details of the Monte Carlo simulation are given in Cope et al. (2003). The approach has similarities to that proposed by Lavelle et al. (2003), but differs in that the wind speeds needed for the damage matrices are deterministic values. Lavelle et al. (2003) use an explicit time stepping method to account for the life cycle of a structure during a wind event, while the model in this study expresses damage as conditional upon deterministic peak 3 s gusts. The wind field model developers determine separately the probabilities of occurrence of these 3 s gusts. Thus, a stochastic wind field model is not a necessary component for the determination of damage probabilities conditioned upon wind speed.

The correlation or dependence between damage to different components is embedded implicitly in the engineering simulation. The simulation models the load paths and physical sequence of damage during a hurricane so that, for example, the amount of roof sheathing damage is correlated to the amount of opening damage through the corresponding increase in internal pressure.

A possible resulting damage mode matrix, for the example of Fig. 1, is shown in Table 1. The simulations yield estimates of probabilities that a building of a specified type will experience damage (subdamage) modes of various kinds, conditional on wind speeds belonging to 5 m/s intervals centered on values of ν varying from 40 to 70 m/s. Table 1 states that for ν in the interval $57.5\ \text{m/s} < \nu \leq 62.5\ \text{m/s}$, $P(T_2|60\ \text{m/s}) = 50\%$ is the probability that a building will experience moderate shingle damage, and $P(S_3|60\ \text{m/s}) = 10\%$ is the probability that the building will experience heavy roof sheathing damage. To simplify the notation we may omit the notation "$|\nu$" in all subsequent developments, that is, we will use the shorthand notation $P(x)$ in lieu of $P(x|\nu)$.

The probabilities listed in Table 1 are not used directly in the final damage estimate, as explained in the next section. They are used as an intermediate step to validate and calibrate the Monte Carlo simulation engine, through comparisons with other estimates from other sources. These sources include: laboratory tests (e.g., Cunningham 1993, Baskaran and Dutt 1995); postdisaster observations of damage, duly accounting for the fact that reported damage includes damage due to effects other than wind (for example storm surge); and engineering judgment needed to supplement or interpolate between sparse data.

The final damage estimation will be calculated from a table of

Table 1. Probabilities of Occurrence of Subdamage Modes $O_{i,}T_{j,}S_{k,}C_{l,}W_m$ Conditional on Wind Speed Intervals; Intermediate Output to Be Used for Validation with Observed Data

ν(m/s)	40	45	50	55	60	65	70
$P(O_1 \| \nu)$	4%	6%	10%	5%	5%	5%	0%
$P(O_2 \| \nu)$	1%	4%	30%	40%	35%	20%	10%
$P(O_3 \| \nu)$	0%	0%	10%	40%	60%	75%	90%
$P(T_1 \| \nu)$	4%	2%	1%	2%	0%	0%	0%
$P(T_2 \| \nu)$	1%	5%	15%	35%	50%	40%	30%
$P(T_3 \| \nu)$	0%	2%	4%	10%	40%	60%	70%
$P(S_1 \| \nu)$	0%	1%	7%	20%	10%	10%	10%
$P(S_2 \| \nu)$	0%	0%	3%	10%	30%	30%	30%
$P(S_3 \| \nu)$	0%	0%	0%	0%	10%	40%	60%
$P(C_1 \| \nu)$	0%	0%	6%	15%	20%	10%	10%
$P(C_2 \| \nu)$	0%	0%	4%	10%	10%	20%	10%
$P(C_3 \| \nu)$	0%	0%	0%	0.8%	10%	40%	80%
$P(W_1 \| \nu)$	0%	0%	4%	10%	10%	10%	10%
$P(W_2 \| \nu)$	0%	0%	3%	14%	10%	20%	10%
$P(W_3 \| \nu)$	0%	0%	0%	1.5%	23%	40%	80%

combined damage states, which is a more detailed display of the possible damage modes in various combinations. An example of a combined damage states matrix is shown in Table 2, where the table has been compressed by using the variable indices i,j,k,l,m. When the table is expanded for the various combinations of $i,j,k,l,m=0,1,2,3$, and the impossible or unlikely combinations are removed, as discussed earlier, the resulting probabilities of the 227 combined damage states are displayed. The wind field model will come into play when the results of the simulation are used to calculate annualized damage probabilities, as discussed in the following sections.

Damage Estimation

Consider a residential community consisting of total number of n homes of different structural types m in a zone with specified surrounding terrain conditions. Assume that the probabilities of occurrence of each of the damage states, e.g., $P(O_3T_2S_1W_0C_0)$, are estimated conditional upon wind speed, through engineering simulations, as shown in Table 2 for each of the m structural types. Assume that the repair/replacement cost ratio, referred to as damage ratio (DR_i) for each possible damage state (DS_i) listed in Table 2, e.g., $O_3T_2S_1W_0C_0$, is obtained from insurance adjusters or construction estimation manuals.

In fact, it is not reasonable to expect that a different damage ratio can be assigned to each of the possible 227 damage states combinations. Rather, the many combinations will be associated with a handful of damage cost ratios, from 0 to 100% in increments of, for example, 10%. For example, 67 states, say, may all lead to 20% damage ratio, 43 states may lead to 30% damage ratio, 19 states may lead to 40% damage ratio, and so forth. The simplification inherent in this observation is to be incorporated into the estimation procedure, and will require the consideration of different cost, field, and construction variables.

The probable expected damage, expressed as a percentage, can be estimated as follows:

Step 1

The mean damage for a structure of type m in the zone subjected to a wind speed in the interval $\{\nu-\Delta\nu/2,\nu+\Delta\nu/2\}$ m/s is the sum of all the possible damage ratio corresponding to the damage states listed in Table 2 for speed ν in that interval multiplied by their probabilities of occurrence. This mean damage is traditionally referred to as the vulnerability of the structural type at a given wind speed. For example, for $\nu=60$ m/s, $\Delta\nu=10$ m/s, the following equation results:

$$
\begin{aligned}
\text{mean\_damage}_{(\text{type } m|60\text{ m/s})} \\
&= \big[P\big(O_3T_2S_1W_0C_0|60\text{ m/s}-5\text{ m/s}<\nu<60\text{ m/s} \\
&\quad +5\text{ m/s},\text{type } m\big)^{*}\mathrm{DR}\big(O_3T_2S_1W_0C_0\big) \\
&\quad +\big[P\big(O_3T_2S_2W_0C_0|60\text{ m/s}-5\text{ m/s}<\nu<60\text{ m/s} \\
&\quad +5\text{ m/s},\text{type } m\big)^{*}\mathrm{DR}\big(O_3T_2S_2W_0C_0\big)+\ldots\big]+\ldots \\
&= \sum_i P\big(\mathrm{DS}_i|60\text{ m/s},\text{type}_m\big)^{*}\mathrm{DR}\big(\mathrm{DS}_i\big) \qquad (1)
\end{aligned}
$$

summed over all damage states DS_i.
In Eq. (1), $\mathrm{DR}(O_3T_2S_1W_0C_0)$ denotes the repair cost corresponding to damage state $O_3T_2S_1W_0C_0$ as a percentage (or damage ratio) of the building replacement value, and $\mathrm{DR}(\mathrm{DS}_i)$ is similarly defined.

In assigning the repair cost, the procedure needs to incorporate the fact that the combined repair cost of components cannot exceed the replacement cost of the facility. In practice, the combined repair costs taper off to reach the replacement cost. Moreover, if the repair cost of the combined structure exceeds 70–80% of the replacement value of the building, it might be considered economical to demolish the building. For this case the cost of demolishing and removal of debris must be used in the estimates.

Table 2. Sample of Simulated Probabilities of Combined Damage States, Conditional on Wind Speed Intervals; To be Used for Damage Calculations

ν(m/s)	40	45	50	55	60	65	70
$P(O_0T_0)$	90.25%	81.90%	38.00%	6.00%	0.00%	0.00%	0.00%
$P(O_iT_0)$	4.75%	9.10%	40.00%	54.00%	20.00%	0.00%	0.00%
$P(O_0T_jS_0)$	4.75%	7.60%	10.00%	3.70%	0.00%	0.00%	0.00%
$P(O_0T_jS_k)$	0.00%	0.50%	0.50%	0.30%	0.00%	0.00%	0.00%
$P(O_iT_jS_0)$	0.25%	0.40%	2.00%	6.30%	30.00%	20.00%	0.00%
$P(O_iT_jS_kW_0C_0)$	0.00%	0.50%	0.50%	0.33%	1.00%	10.00%	0.00%
$P(O_iT_jS_kC_lW_0)$	0.00%	0.00%	3.00%	3.87%	6.00%	0.00%	0.00%
$P(O_iT_jS_kW_mC_0)$	0.00%	0.00%	0.00%	3.57%	9.00%	0.00%	0.00%
$P(O_iT_jS_kC_lW_m)$	0.00%	0.00%	6.00%	21.93%	34.00%	70.00%	100.00%

Step 2

An expression similar to Eq. (1) applies to each of the wind speeds. The plot of the mean damages versus wind speed for each structural type *m*, will be a vulnerability curve for that particular type *m*. Assume the probability of occurrence of a storm with a peak 3 s gust wind speed within the interval $\{\nu-\Delta\nu/2, \nu+\Delta\nu/2\}$ m/s is $P(\nu)=p(\nu)\Delta\nu$, where $p(\nu)$ is the probability density function of the largest yearly wind speed (such information will be provided by the associated probabilistic wind field development team). The mean annual damage equation for a particular structure type *m* is

$$\text{annual\_mean\_damage}_{\text{type } m} = \sum_{\text{windspeed } i} \text{mean\_damage}_{(\text{type } m|V_i)} * P\left(V_i - \Delta\nu/2 < \nu < V_i + \Delta\nu/2\right) \quad (2)$$

Step 3

The damages for types $m=1,2,\ldots$ are multiplied by the respective relative frequency of those types in the building population of the community. The mean annual damage equation becomes

$$\text{annual\_mean\_damage} = \sum_{\text{Bldgtype } i} \text{annual\_mean\_damage}_{\text{type } i} * P(\text{type } i) \quad (3)$$

In Eq. (3), the $P(\text{type } i)$ is obtained through an exposure study reported by Zhang (2003) and Pinelli et al. (2003).

Step 4

The total expected damage to buildings for a particular community is the damage calculated by using Eq. (3) times the total number *n* of houses in the zone. Multiplication of this latter result by the average value of a home in that area yields the mean annual monetary damage. Alternatively, if dealing with a portfolio where the values of each house in the portfolio is known, the mean annual damage [Eq. (3)] for one house can be multiplied by the sum of the values of all the houses insured in that area. The process is repeated for each zone, and the results for each community are added to obtain the expected hurricane-induced annual damage to buildings for the entire state.

The above Eqs. (1)–(3) can also be combined to compute the probability of occurrence of different levels of damage ratio for the community (DR_i) as follows:

$$P\left(\text{DR}_l\right) = \sum_{V_j} \sum_{\text{types}_k} \left[P\left(\text{DR}_l|\text{type}_k, V_j\right) * P\left(V_j\right) * P\left(\text{type}_k\right)\right] \quad (4)$$

where $P(\text{DR}_l|\text{type}_j, V_k) = \Sigma\ P(\text{DS}_i|\text{type}_j, V_k)$ for all damage states DS_i with the same damage ratio DR_l

Uncertainties

The example presented here is only for illustration. Since the purpose of this paper is to present the conceptual framework of the methodology used for damage computation, a detailed discussion of the uncertainties involved will be the focus of a followup paper. We confine ourselves here to briefly discussing the different sources of uncertainty and how they could affect the model.

A first source of uncertainty resides in the selection of the types of structural models for the simulations. The building population in Florida is comprised of a wide variety of residential buildings of different structural types. Surveys of the building stock in the principal Florida counties have yielded detailed statistics of the building population in the main urban centers of Florida (Pinelli et al. 2003, Zhang 2003). On the basis of this information, structural models are being selected that are representative of a significant portion of the Florida building stock. The uncertainty involved in extrapolating the results of a few structural models to the entire building population needs to be estimated.

Some critical issues regarding cost uncertainties must also be addressed. There is often significant overlap between repair costs, due to uncertainties in the correspondence between actual physical damage and cost projection. For example, whether or not the window opening in a wall is damaged, a repair of the wall might include the removal and replacement of the openings, or for cases such as shingles and walls, the entire wall and shingles might have to be replaced for the sake of consistency and esthetic appearance, regardless of the level of physical damage. In addition, it is difficult to capture the uncertainty in risk adjuster loss estimation, which is very large at low damage levels and tapers off at higher than 50% damage. It must also be pointed out that the engineering simulations involve only the structural elements described before. The damage to mechanical, electrical, plumbing, and kitchen installations as well as the damage to internal partitions and other elements is not simulated. However, this damage is an integral part of the building damage for insurance purposes. Its estimate will add another layer of uncertainty.

Also, although the simulation of contents damage is not addressed in this paper, it will be in the final version of the model. Since this part of the damage is highly dependent on the rain intensity of the hurricane and the fact that a house might experience leaks even without envelope breach, estimate of contents damage also involve a lot of uncertainty.

Another primary source of uncertainty pertains to the properties or parameter inputs into the Monte Carlo simulations. The size of these uncertainties will depend on the information sources available for strength of components, the variability of construction techniques, and quality among houses and regions of the state, materials used, effects of aging, load path assumptions, and other considerations. For example, very little data are available to quantify the relation between load and capacity of asphalt shingles, but significant information is available for sheathing capacity as a function of material type, nailing patterns, and so forth. Such uncertainties can be reflected within the probabilistic model assigned to the various component capacities, and a total probability of damage — or at least a measure of its mean and variability — that can then be used in the estimation of the cost.

A considerable contributor to uncertainty is inherent in the relation between a given wind speed and resultant forces in the building envelope. The pressure coefficients assigned to various building zones in the American Society of Civil Engineers 7 standards are designed to envelope multiple directions and worst-case scenarios, and are not necessarily appropriate to represent snapshots of real physical loads. Wind tunnel data are available to define these coefficients more realistically for only a small handful of structural shapes. These uncertainties need to be estimated and incorporated within the Monte Carlo simulation model along with the structural capacity uncertainty discussed above. Cope et al. (2003) give a brief description of the wind loading scheme developed for this model.

The estimates of the wind speed itself involve a significant degree of uncertainty that affects the final damage estimate. As noted earlier, the probabilistic wind model, including the uncertainties associated with it, is being developed in parallel with the effort reported here (Powell et al. 2003).

Sensitivity studies are being conducted to define the influence of the different parameters on the outputs of the models and to identify the most critical sources of uncertainty. The model and the simulation will also be validated and calibrated against available claim data from insurance companies.

Conclusions

This paper presents a probabilistic framework for the estimation of annual damages due to windstorms in the state of Florida. The framework assures that no type of damage is counted more than once, all significant types of possible wind damage are accounted for in the calculations, and interactions between various types of damage are included implicitly in the simulations relating wind speed to damage. The costs are calculated by accounting for the dependence between various damage modes (e.g., window breakage and roof uplift). The damage is modeled as a stepwise process, as damage to openings gives sudden rise to increases of internal pressures, and sudden collapse of the roof results in immediate damage to walls. The paper also discusses the use of damage matrices for the estimation of expected damage due to a windstorm event, and of expected annual damage, both at a specified location and over a larger geographical area. The framework developed in the paper is illustrated for the case of five basic damage modes. Work is near completion on the application of the framework to the various types of residential structures most common in Florida, including masonry and wood wall structures, various roof types, and manufactured homes.

A key ingredient of the proposed procedure is the development of a Monte Carlo simulation approach that relates probabilistic strength capacities of building components subjected to wind action through a detailed aerodynamic and structural engineering analysis. Work is also in progress on quantifying the uncertainties in loss calculations, based on uncertainties in the estimation of probability matrices, hurricane wind speeds, structural behavior, component properties and costs, and building population. Work is in progress on the probabilistic wind field model. Preliminary predictions of annual vulnerability are planned once such development is completed.

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