HAZUS-MH Hurricane Model Methodology. II: Damage and Loss Estimation

Peter J. Vickery[1]; Peter F. Skerlj[2]; Jason Lin[3]; Lawrence A. Twisdale Jr.[4]; Michael A. Young[5]; and Francis M. Lavelle[6]

Abstract: An overview of the damage and loss models used in the HAZUS-MH Hurricane Model is presented. These models represent the last two of five major component models used in HAZUS for the prediction of damage and loss to buildings subjected to hurricanes. The damage and loss models have been validated using damage data collected during poststorm damage surveys and insurance loss data. The HAZUS Hurricane Model represents an advance in the state of the art over most hurricane loss prediction models, in that it estimates wind induced loads, building response, damage, and then loss, rather than simply using historical loss data to model loss as a function of wind speed. A mitigation example is presented that shows the expected reductions in losses achieved by strengthening the roof of a building and adding window protection.

DOI: 10.1061/(ASCE)1527-6988(2006)7:2(94)

CE Database subject headings: Hurricanes; Models; Damage; Estimation; Predictions.

Introduction

This paper presents an overview of the development and validation of the models used to generate the fast running damage and loss functions used in the HAZUS-MH Hurricane Model (HM). The damage and loss models represent the last two of five key component models used in the HAZUS HM. The overall approach taken in the development of the HAZUS HM is described in Fig. 1. The first three model components (hurricane hazard model, terrain model, and the wind load/debris models) are discussed in the companion paper (Vickery et al. 2003).

The physical damage to a building subjected to hurricane winds is modeled using an engineering-based load and resistance approach, where once the wind-induced loads acting on a building are computed, the physical damage model to the building is estimated in terms of failure of building envelope components. The load and resistance approach used to develop the HAZUS HM incorporates the effects of progressive failures and internal pressures, and it inherently incorporates many of the duration effects associated with the changes in wind speed and direction which accompany hurricane winds.

Losses are estimated from the building damage states using empirical cost estimation techniques for building repair and replacement. Contents loss is based on an empirical model that relates contents damage to building envelope performance. The building, contents, and loss of use components have been validated with insurance loss data, wherever possible. The load-resistance-damage-loss methodology used in the HAZUS HM provides the framework needed to reliably examine the effect of mitigation in a quantitative manner, through the modeling of building components with increased resistances, and assessing the reduction in the hurricane induced damage and loss.

[1]IntraRisk, Applied Research Associates, Raleigh, NC 27615 (corresponding author). E-mail: pvickery@ara.com

[2]Partner Re, Zurich, Switzerland.

[3]Risk Management Solutions, Newark, CA.

[4]IntraRisk, Applied Research Associates, Raleigh, NC 27615.

[5]Risk Management Solutions, Newark, CA.

[6]IntraRisk, Applied Research Associates, Raleigh, NC 27615.

Note. Discussion open until October 1, 2006. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on June 28, 2004; approved on July 6, 2005. This paper is part of the ***Natural Hazards Review***, Vol. 7, No. 2, May 1, 2006. ©ASCE, ISSN 1527-6988/2006/2-94–103/$25.00.

Damage Model

In the HAZUS HM, the physical damage modeling approach focuses on the damage to exterior components and cladding, including windows, roof cover, roof deck, joint failures, and wall failures (for wood frame and masonry walls). Frame failure is considered only for manufactured houses and the failure of entire roofs on residential buildings and some low rise commercial buildings. The emphasis on modeling component and cladding failures, together with a limited effort toward the modeling of frame failures, is consistent with the failure modes observed in most buildings during poststorm damage investigations.

The model uses a load and resistance methodology to estimate damage to a structure subjected to hurricane winds. Geometric representations of representative buildings were developed describing one- and two-story single-family dwellings, one-, two-, three-, and four story multifamily dwellings, manufactured houses, preengineered metal buildings, low rise retail buildings, industrial buildings, and high rise buildings. Example model building geometries used to develop the HM are shown in Fig. 2. Statistical models defining the resistance of the building components used in the HAZUS HM have been developed using results from laboratory test data, engineering analyses coupled with laboratory data, and in some cases engineering judgment. All assumptions as to the component resistances used in the model are documented in the technical manual which will accompany the

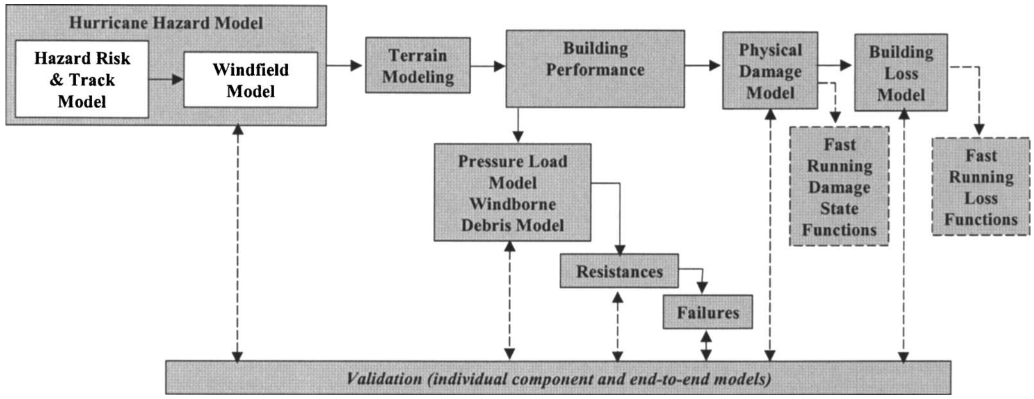

Fig. 1. Overview of approach used to develop damage and loss functions for HAZUS

HAZUS HM software. Resistances are assigned to each of the components that can fail in a given simulation. Examples of the building components modeled are roof cover, roof sheathing, roof trusses, metal panels, window, doors, and walls.

Model buildings were developed where, for any building type in a given storm, the wind speed and direction produced by a model hurricane are computed at 15 min intervals, and the wind loads on all building components are estimated using the directionally dependent pressure coefficients described in the companion paper (Vickery et al. 2003). At the same time, the probability of a missile impact is computed using the missile impact models described in the same paper. Once all the wind loads have been computed for a given time step, the loads are compared to the sampled component resistances. Following the computation of the pressure-induced failures of windows and doors, the computation of damage by missile impact is performed. If a window, door, or

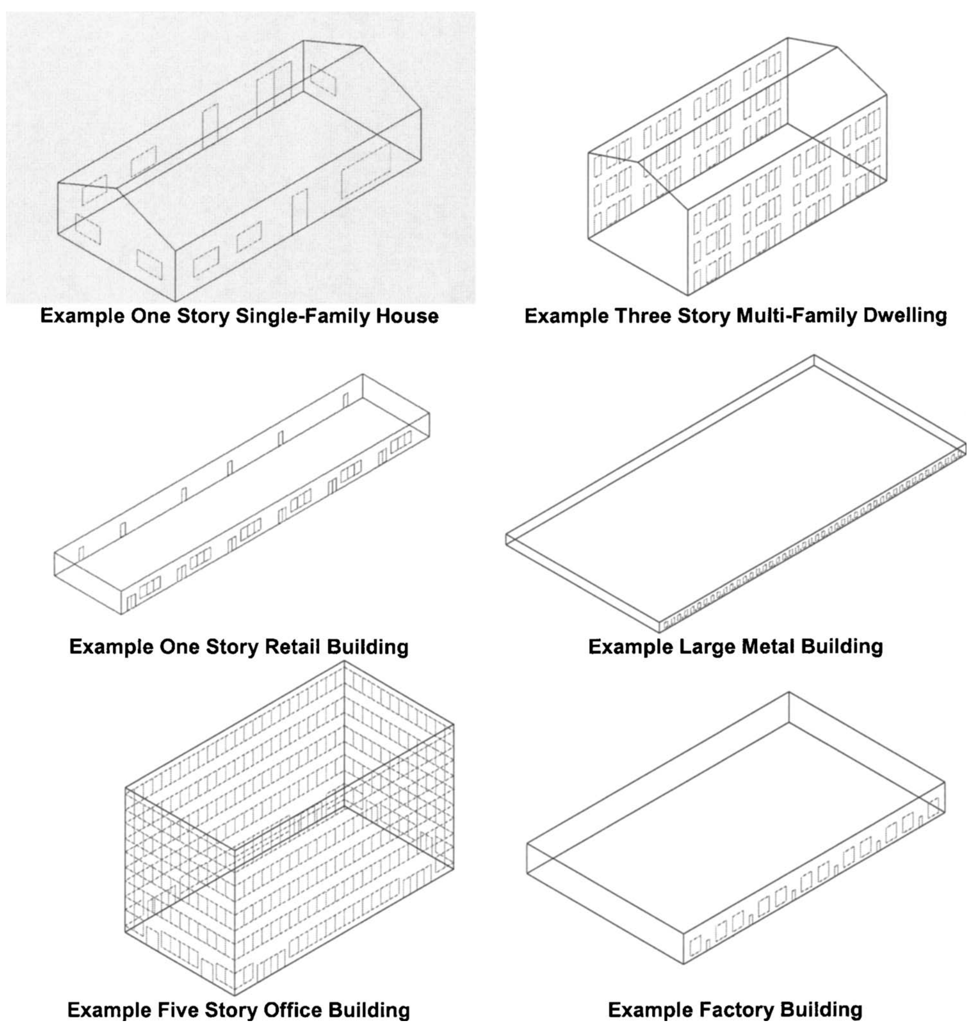

Fig. 2. Example model building geometries

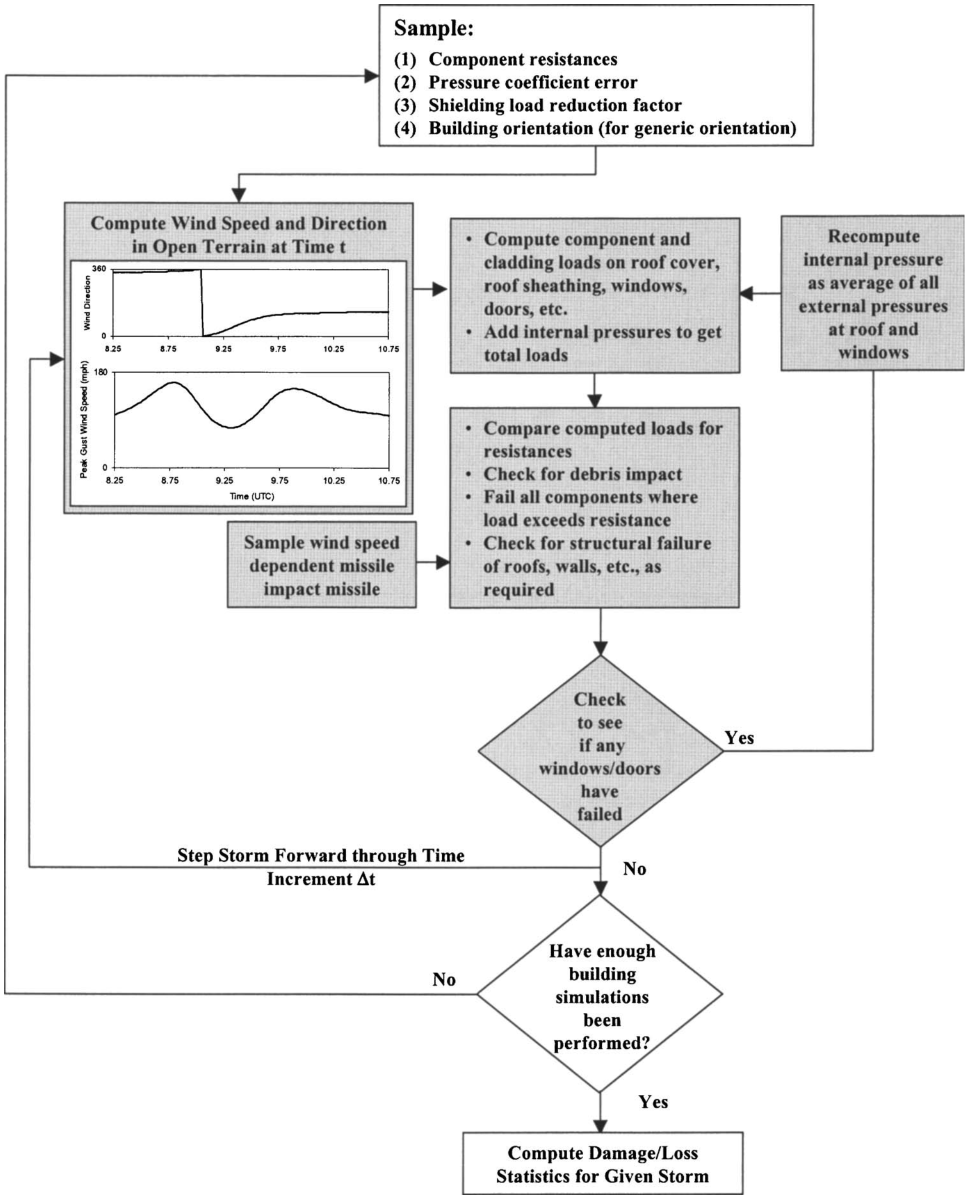

Fig. 3. HAZUS hurricane damage estimation methodology

wall fails, the change in the internal pressure is computed and then the loads acting on the components that have not failed are recomputed with the effect of the internal pressure taken into account. Failure of additional components is computed during the same time step in which the initial breach occurred. The peak value of the internal pressure is assigned a value equal to that of the external pressure at the location where an envelope breach occurred. If more than one window fails, the internal pressure takes on a value near the average of the peak external pressures at those locations. The damage (and loss) modeling approach is shown schematically in Fig. 3.

All resistances and modeling error statistics associated with the wind loads are sampled before the model storm is passed by the building. To obtain damage statistics for a given storm, the component resistances and loading error statistics are resampled and the damage simulation is repeated for the same storm. Table 1 presents an example of the resistance distribution parameters used for a model single-family house. Thirty damage simulations are performed for each simulated hurricane, and each hurricane is drawn from a 20,000-year simulation created using the hurricane model described in Vickery et al. (2000a,b). The simulated storms used to generate damage as a function of the peak gust wind speed have combinations of central pressure, forward speed, and radius to maximum winds that are consistent with historical observations. For example, the higher wind speed simulations are generally associated with the smaller but more intense storms and require the storm to pass closer to the model building, resulting in high winds lasting for a relatively short period of time. At the end of each complete simulation, thousands of data files containing the information on building damage, estimates of rain penetration, and the peak wind speed in the hurricane that caused the damage are retained and used in the damage state and loss analyses described later.

Damage State Definitions

Following an approach similar to that used by Vann and McDonald (1978) for defining damage states to manufactured

Table 1. Component Resistance Values Used to Model Residential Buildings

Component	Distribution	Distribution parameters
Sheathing panel (6d with 6/12 nail pattern)	Lognormal	Mean=54.6 psf, COV=0.11
Sheathing panel (8d with 6/12 nail pattern)	Lognormal	Mean=103.0 psf, COV=0.11
Sheathing panel (8d with 6/6 nail pattern)	Lognormal	Mean=181.9 psf, COV=20.6
Annealed glass impact	Deterministic	50 lb-ft
Tempered glass impact	Deterministic	100 lb-ft
Window/SG door pressure	Normal	Mean=40 psf, COV=0.2
Window glass (all windows on 1 story)	Weibull	C=54.9 psf, k=4.7
Window glass (2 large windows on 2 story)	Weibull	C=38.7 psf, k=4.8
SG door glass	Weibull	C=101.5 psf, k=4.5
Interior garage door pressure	Normal	Mean=30 psf, COV=0.2
Entry door pressure	Normal	Mean=50 psf, COV=0.2
Double garage door pressure (weak)	Normal	Mean=10 psf, COV=0.2
Double garage door pressure (strong)	Normal	Mean=20 psf, COV=0.2
Strap uplift resistance	Normal	Mean=1200 lb, COV=0.3
Toe-nail uplift resistance	Normal	Mean=415 lb, COV=0.25

Note: COV=coefficient of variation.

houses, damage state descriptions have been developed for all building types defined in HAZUS. Table 2 presents an example of the damage state definitions used for single-family residential buildings. The damage states are governed by the performance of the building envelope and are divided into five states, varying between 0 (no damage) and 4 (destruction). In Table 2, a building is considered to be in the higher damage state if *any* of the shaded damage indicators in the corresponding row occur. For example, for a building to be considered to have sustained minor damage, the building must not have sustained structural failure, or roof deck (sheathing) failure, more than one fenestration (window, door, garage door) failure, or more than 2% of the roof cover is missing. Similar damage state definitions have been developed for all building types in the HAZUS HM. Fig. 4 presents example damage state curves for a single-family house, situated in suburban terrain, with the probability of the building experiencing a given damage state plotted versus the peak gust wind speed in open terrain.

Estimates of the mean number of buildings expected to experience a given damage state for each census tract in a study region are given in HAZUS when the user generates a deterministic, user-defined storm. For probabilistic analyses, damage state infor-

Table 2. Damage States for Residential Construction Classes

Damage state	Qualitative damage description	Roof cover failure	Window door failures	Roof deck	Missile impacts on walls	Roof structure failure	Wall structure failure
0	**No damage or very minor damage** Little or no visible damage from the outside. No broken windows, or failed roof deck. Minimal loss of roof over, with no or very limited water penetration.	≤2%	No	No	No	No	No
1	**Minor damage** Maximum of one broken window, door, or garage door. Moderate roof cover loss that can be covered to prevent additional water entering the building. Marks or dents on walls requiring painting or patching for repair.	>2% and ≤15%	One window, door, or garage door failure	No	<5 impacts	No	No
2	**Moderate damage** Major roof cover damage, moderate window breakage. Minor roof sheathing failure. Some resulting damage to interior of building from water.	>15% and ≤50%	> one and ≤ the larger of 20% and 3	1 to 3 panels	Typically 5 to 10 impacts	No	No
3	**Severe damage** Major window damage or roof sheathing loss. Major roof cover loss. Extensive damage to interior from water.	>50%	> the larger of 20% and 3 and ≤50%	>3 and ≤25%	Typically 10 to 20 impacts	No	No
4	**Destruction** Complete roof failure and/or failure of wall frame. Loss of more than 50% of roof sheathing.	Typically >50%	>50%	>25%	Typically >20 impacts	Yes	Yes

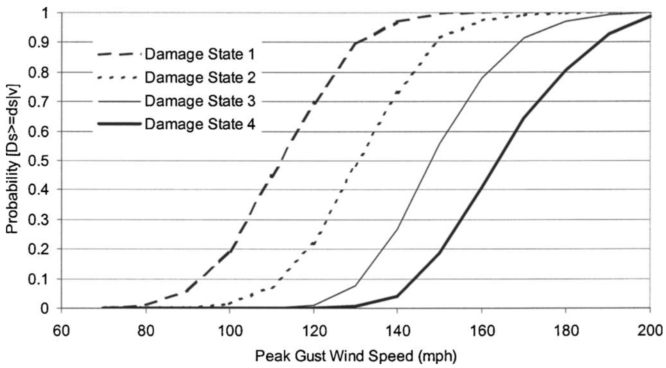

Fig. 4. Example building damage state versus peak gust wind speed function

mation is produced for sample storms characteristic of several selected return periods, where the return periods are computed based on the total economic loss for the study region.

Damage Model Validation

In order to validate the model's ability to predict damage to buildings, comparisons of simulated and observed damage states were performed. The damage comparisons in this example include roof cover damage, roof sheathing damage, and damage to windows. Roof cover and roof sheathing damage states are simulated and compared to roof damage observed following Hurricanes Andrew (1992), Erin (1995), and Fran (1996), however, due to space limitations only some example Hurricane Andrew comparisons are given here. In the case of window damage in residential buildings, the information collected by Housing and Urban Development (HUD), as described in Crandell et al. (1993), provides the only source of an unbiased statistical data set quantifying window damage associated with a hurricane.

In all of the comparisons, the observed damage states are compared to those obtained by modeling the wind loads experienced by the houses using the wind loading and damage models described earlier. To obtain estimates of the wind speeds at the sites of the observed damage, a full reproduction of the wind speed and direction time history at the site are obtained using the hurricane wind field model described in the companion paper (Vickery et al. 2003).

Hurricane Andrew (1992)

The most comprehensive existing report on the performance of residential buildings during Hurricane Andrew is given in Crandell et al. (1993). In the HUD study, the survey team randomly selected 466 houses located in nine separate clusters within the high damage areas and then quantified the damage to each house. In the roof damage validation study performed here, the HUD roof damage data was expanded using aerial photographs corresponding to four of the locations used in the HUD damage survey. The aerial photographs were at a scale of 1 in. = 100 ft, providing enough resolution so that the damage to the roof cover and roof sheathing could be readily estimated. Fig. 5 shows example comparisons of the modeled and observed damage to roof sheathing, roof cover, and windows of residential buildings taken from the HUD damage survey. In the case of window damage, the HUD damage states, 0, 1, 2, and 3, correspond to no windows broken, less than 1/3 of the windows broken, between 1/3 and 2/3 broken, and more than 2/3 broken. Considering the uncertainties in the resistance characteristics of the actual and model buildings, the comparison between the observed and modeled damage is very good. The figures also demonstrate that in both the model and the observed roof damage (sheathing and roof cover), the hip roof buildings perform much better than the gable roof buildings. In the case of the window performance, both the modeled and observed breakage data indicate that the two-story buildings experience far more window damage than the one-story houses.

Economic Loss Modeling

The HM produces estimates of economic loss associated with damage to buildings. The losses estimated include the losses associated with the building, contents, and/or inventory losses, and costs associated with the loss of use of the building. In addition to the computation of economic losses, the model also estimates the quantity of debris produced as a result of damage to buildings. Two categories of debris are modeled: (1) brick, wood, other; and (2) reinforced concrete and steel members.

Building Losses

The cost of each model building used in HAZUS has been estimated using the methodology given in RS Means. The total cost of all the major components of the building have been estimated, including the cost of roof cover, roof frame, windows, structural framing, interior walls, foundation, electrical, HVAC, etc. Given the building damage, the cost of rebuilding a structure is computed using a combination of explicit and implicit loss functions. The explicit cost functions are used to estimate the replacement cost of the components of the exterior of the building that are damaged using the damage model, including: roof cover, roof sheathing, windows, roof frame, walls, and roof structure. Information on replacement thresholds (e.g., the minimum amount of damaged roof cover required for a total roof cover replacement to be performed) has been obtained through the examination of insurance company claim files for residential, commercial, and industrial buildings. The implicit cost functions are used to estimate the cost of repairing the interior of the building, since the damage model produces estimates of damage to the exterior of the building only. These empirical functions define the implicit losses and have been developed using a combination of engineering judgment and insurance company loss data. The implicit functions relate the cost of the interior damage to the physical damage to the exterior of the building, coupled with estimates of the amount of water that has entered the building following envelope breaches associated with failures of the windows and doors.

Contents and Inventory Losses

The contents loss model has been developed using an approach similar to that used for estimating the losses to the interior of the building and is also an implicit model. The model was developed using a combination of engineering judgment and insurance loss data, and is largely a function of the amount of water that enters the building.

Loss of Use

The fact that the damage and loss models estimate the amount of physical damage to the interior and exterior of the building allows for the development of a model to estimate the time required to

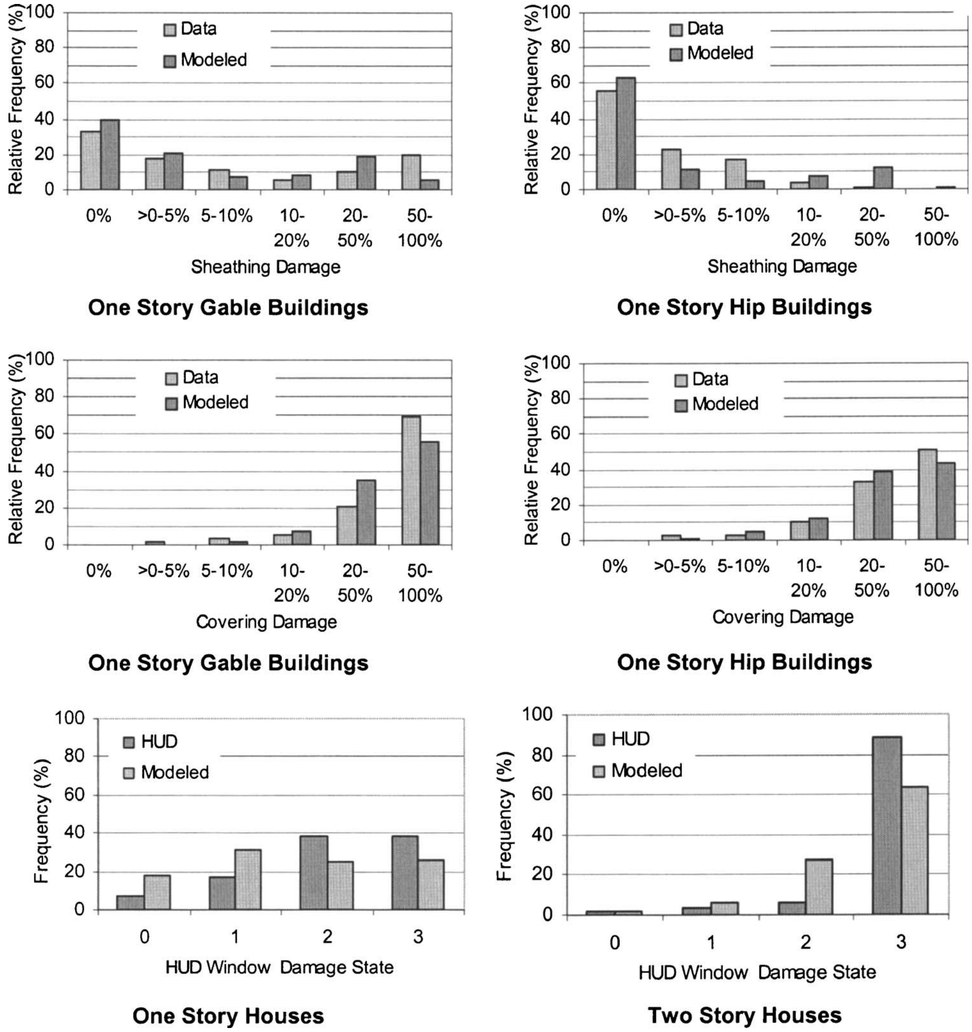

Fig. 5. Example comparisons of modeled and observed building damage (Hurricane Andrew)

reconstruct a damaged building. Using the modeled information on the amount of time a building is not able to be used, coupled with estimates of the rental income, daily production output, etc., estimates of the financial losses associated with the loss of use of the building are made using the methodology developed for the HAZUS Earthquake Model.

Example Fast Running Loss Function

Fig. 6 shows an example of a fast running loss function, defined as the loss to the building and contents divided by the total value of the building and contents, plotted versus the peak gust wind speed in open terrain. The peak gust wind speed is the maximum open terrain wind speed experienced by the structure during a given hurricane simulation. In this example, the building is a one-story, single-family, gable roof house located in a suburban terrain defined with a z_0 value of 0.35 m. Loss functions are given for the mean loss, the median (50% value), and for various percentiles. The curves given in Fig. 6 show the wide variation in losses that can be expected for a given building that experiences a particular maximum peak gust wind speed during a given hurricane. The range in the modeled losses is produced by the variation in the modeled resistance parameters, building orientation, sampled wind load reduction parameters, and storm duration. Note that only the mean loss functions are used in the HAZUS

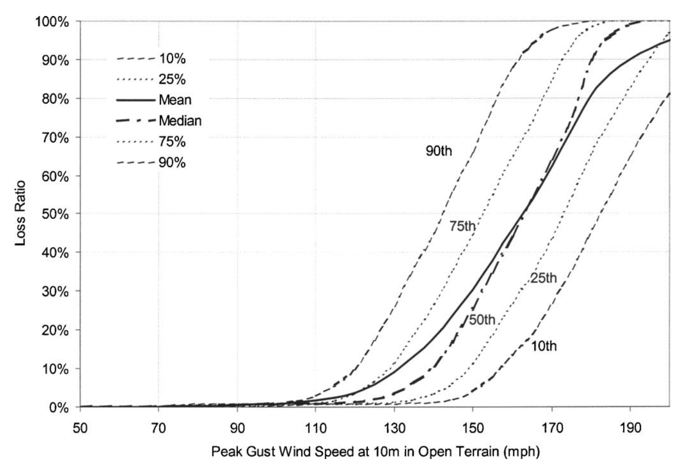

Fig. 6. Example loss function (building and content loss divided by building and content value) showing the mean loss and losses associated with various percentiles

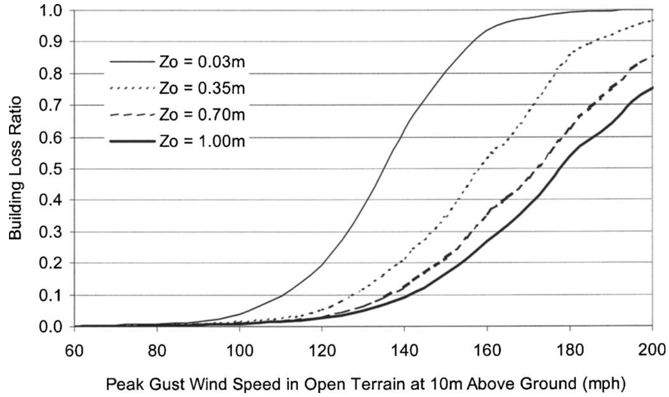

Fig. 7. Example loss curves for one story single-family house (gable roof, 8d roof sheathing nails, strapped roof-wall connections)

HM. Therefore caution must be exercised when interpreting damage and loss estimates for individual buildings, such as essential facilities or user-defined facilities.

Fig. 7 shows example loss curves for a single-family residential building situated in terrains with a roughness length, z_0, varying between 0.03 m (open terrain) and 1.0 m (treed terrain). The example building used to develop Fig. 7 is a single-family gable roof building with strapped roof-wall connections and the roof sheathing nailed to the trusses with 8d nails using a 6/12 nail pattern. The importance of the terrain is readily seen in Fig. 7 through the shift in the loss curves toward higher wind speeds as the terrain gets rougher. The loss curves given in Fig. 7 are examples of the fast running loss curves noted in Fig. 1. These fast running curves have been precomputed for five values of the terrain roughness, z_0 (0.03, 0.15, 0.35, 0.70, and 1.0 m) and are stored in a database for use in the HM.

HAZUS Loss Model Validation Studies

Loss model validation studies have been performed using the wind field model, terrain modeling methodology, and the load, damage, and loss models. The end-to-end loss validation studies have been performed using zip code averaged loss data for Hurricane Andrew in Dade County, for Hurricanes Erin and Opal in the Florida Panhandle, and for Hurricane Hugo in South Carolina. The loss data have been obtained from insurance companies and are only applicable to single-family residential construction. Because the loss data have been obtained from insurance company data, all validation analyses were performed using zip codes instead of census tracts.

Hurricane Andrew Loss Validation Study

The loss data used for the Hurricanes Andrew and Hugo comparisons are described in Bhinderwala (1995) and represent the total repair and replacement losses associated with the building and the

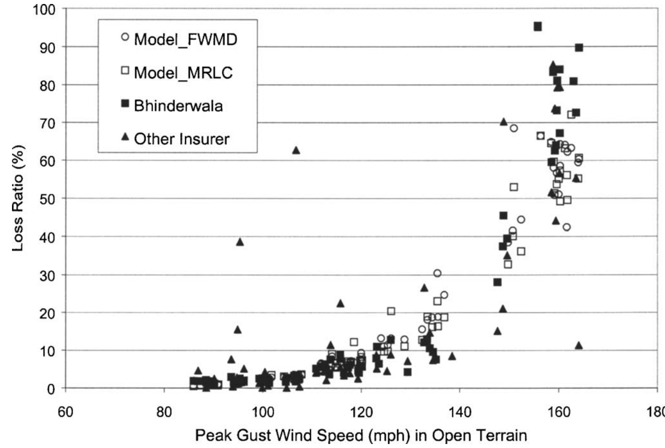

Fig. 8. Comparison of modeled and observed (insurance data) loss ratios versus modeled peak gust wind speed in open terrain (Hurricane Andrew)

contents. Loss data provided by another insurer for Hurricane Andrew were also applicable to building and content losses. For the Hurricane Andrew Dade County simulation, the characteristics used to model the buildings are described in Table 3. The average surface roughness at the zip code level was estimated using both Florida Water Management District (FWMD) Land Use and Land Cover (LULC) data and Multi-Resolution Land Characteristics (MRLC) Consortium LULC data, with results for both terrain databases shown. The hurricane simulation was performed with the wind speeds and directions computed at the geographic centroid of each zip code. The model houses were randomly oriented within each zip code. The loss ratios (total loss divided by the total coverage limits) are plotted in Fig. 8 as a function of the maximum modeled peak gust wind speed (open terrain) computed at each zip code centroid. The results indicate that the methodology implemented in the HAZUS HM, when applied to residential buildings, works well.

The total losses (building plus contents) summed over entire Dade County were estimated assuming that both the number of policies and value of these policies in each zip code were the same. In each case, a contribution to the estimated total loss was computed only if the insurer had policies in the given zip code. The aggregate losses are given in Table 4. Note that the actual and modeled totals given in Table 4 differ between cases because the number of zip codes having policies is different for the different insurers.

Hurricane Hugo Loss Validation Study

For the Hurricane Hugo loss validation study, the characteristics of the modeled buildings are described in Table 5. The average surface roughness at each zip code was estimated using MRLC data. The model houses were assumed to be randomly oriented

Table 3. Characteristics of Buildings Used in Hurricane Andrew Loss Validation Study

		Roof shape (%)		Roof cover (%)		Roof deck nails (%)		Garage (%)		Roof wall connection (%)	
Number of stories	%	Hip	Gable	Tile	Shingle	6d	8d	Yes	No	Strap	Nail
One	80	25	75	50	50	40	60	63	37	100	0
Two	20	25	75	50	50	40	60	50	50	100	0

Table 4. Comparison of Modeled and Observed Dade County Aggregate Losses from Hurricane Andrew

Case	Actual loss ratio (%)	Modeled loss ratio (%) (FWMD)	Modeled loss ratio (%) (MRLC)
Bhinderwala	19.1	16.9	17.5
Other insurer	15.7	13.9	14.1

within a zip code. The insured value of the contents is taken as 70% of the insured building value. Comparisons of the predicted and observed loss ratios are plotted versus the modeled peak gust wind speed at the centroid of the zip code in Fig. 9, which shows a reasonably good agreement between modeled and actual losses. The total loss (building plus contents) summed over the entire state of South Carolina was estimated assuming that both the number of policies and value of these policies in each zip code were the same, with the results shown in Table 6.

Loss Validation from All Storms

Fig. 10 shows comparisons of modeled and observed losses for all cases examined (Hurricanes Andrew, Hugo, Erin, and Opal). The comparisons given in Fig. 10 overall show good agreement, but suggest that the damage and loss models may underestimate the small losses that occur at lower wind speeds (less than about 100 mph). This underestimation of losses at lower wind speeds is not unexpected since the damage and ensuing losses produced by tree blowdown are not currently modeled, nor are some other causes of small losses, such as minor losses of some types of exterior wall coverings, leaking fenestrations, and damage to soffits, chimneys, vents, etc. (Tree blowdown modeling has been initiated and will be included in the HM) Furthermore, in the case of Hurricane Hugo, losses experienced by homeowners to appurtenant structures (fences, driveways, sheds, decks, etc.) were lumped into payments made for losses to the structure and could not be separated.

In summary, the loss validation studies have shown that the damage and loss models reproduce observed losses reasonably well. Until the damage associated with tree blowdown is introduced to the model, no attempt will be made to add an empirically based low wind speed model to account for small losses not modeled in the HAZUS HM. With this in mind, the HM will probably tend to underestimate losses caused by small, low intensity storms. This underestimate in losses will play an insignificant role in estimating local or regional average annual losses, since these losses are driven by storms having a Saffir-Simpson scale of three or higher (Landsea 1993).

Mitigation

Since the methodology used to develop the HAZUS HM has been developed using an engineering-based load-resistance-damage-loss modeling approach, it is ideally suited for assessing the reduction in losses associated with mitigation. In the HAZUS HM, mitigation is limited to single-family residential buildings. The mitigation options supported in the HAZUS HM are one or more of the following: installation of window protection (shutters), upgrading the roof sheathing-to-truss nailing connection to meet the 1994 SFBC Dade County provisions, increased roof shingle wind resistance, application of secondary water resistance (SWR), and installation of roof-to-wall straps (considered a mitigation option if the existing buildings have toe-nailed roof-wall connections).

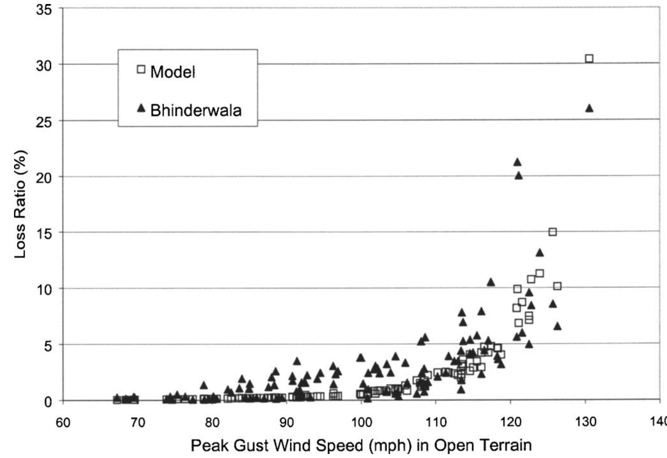

Fig. 9. Comparison of modeled and observed (insurance data) loss ratios versus modeled peak gust wind speed in open terrain (Hurricane Hugo)

In modeling shutters, the approach taken is that if a shutter is impacted by debris having an energy greater than 350 ft-lb, the shutter-window system is considered to have failed, allowing the full effects of both internal pressure and rain to enter the house. This assumption is probably conservative, since impacted shutters will often remain in place and experience only a relatively small perforation, limiting the amount of water that can enter the building.

Secondary water resistance (SWR) is modeled as self-adhesive bituminous strips that are applied over the joints between plywood/oriented strand board (OSB) sheets on a plywood/OSB roof deck. The SWR prevents water from entering the building through the gaps between the plywood/OSB after the roof cover has failed. The SWR is modeled as being 85% effective (i.e., the amount of internal damage associated with cover loss is reduced by 85% if SWR is applied).

Fig. 11 shows example loss curves for an unmitigated and a mitigated single story gable house, located on typical suburban terrain, defined with a z_0 value of 0.35 m. The as constructed house has the same construction characteristics as the house used in the development of the loss curves given in Fig. 7. The miti-

Table 5. Characteristics of Buildings Used in Hurricane Hugo Loss Validation Study

Number of stories	%	Roof shape (%)		Roof cover (%)		Roof deck nails (%)		Garage (%)		Roof wall connection (%)	
		Hip	Gable	Tile	Shingle	6d	8d	Yes	No	Strap	Nail
One	70	25	75	0	100	30	70	71	29	10	90
Two	30	25	75	0	100	30	70	50	50	10	90

Table 6. Comparison of Modeled and Observed Aggregate Losses from Hurricane Hugo

Actual loss ratio (%)	Modeled loss ratio (%)
2.96	3.64

gation techniques applied to the house include window protection (shutters), upgraded roof cover, the roof sheathing renailed with a 6/6 pattern, and the application of SWR. As seen in Fig. 11, the expected losses for the mitigated building significantly decrease over the full wind speed range examined, but with the percentage in the reduction in losses changing with wind speed.

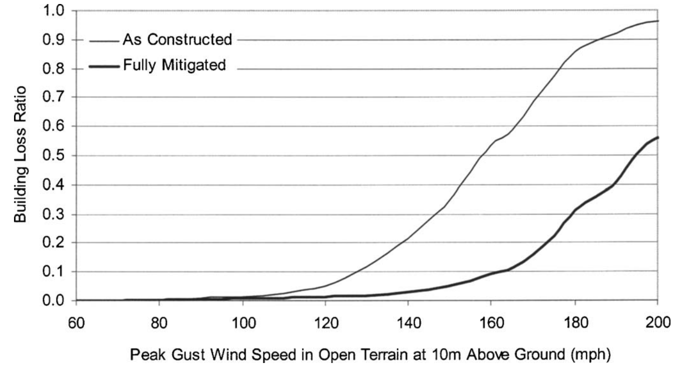

Fig. 11. Fast running loss curves for unmitigated versus fully mitigated single-family house

Implementation in HAZUS Hurricane Model

For the prediction of losses with HAZUS, the model is run in either a probabilistic mode or a deterministic mode, with all losses estimated using the terrain-dependent fast running loss functions described earlier, combined with the open terrain peak gust wind speeds computed at the centroid of each census tract. In the probabilistic mode of operation, the peak gust wind speeds are obtained from the 100,000-year hurricane simulation described in the companion paper (Vickery et al. 2003). The losses, L_i, associated with any given simulated storm, i, are computed as

$$L_i = \sum_{j=1}^{N} \sum_{k=1}^{M} C_{jk} l_k(z_{0j}, \upsilon_{ij}) \quad (1)$$

where N=number of census tracts in the region being studied; M=number of different building types being considered; C_{jk}=total replacement cost, or value, of all buildings of type k in census tract j; $l_k(z_{0j}, \upsilon_{ij})$=loss ratio (from the fast running loss functions) for building type k; z_{0j}=value of the surface roughness in census tract j; and υ_{ij}=peak gust open terrain wind speed produced by storm i in census tract j. The value of the loss ratio for the given values of z_{0j} and υ_{ij} is obtained by interpolating between velocities and the terrains for which the fast running loss curves have been precomputed. The interpolation within terrain is performed in logarithmic space. The computation of the storm-by-storm losses is performed for every storm in the 100,000-year storm set that produces a peak gust wind speed of at least 50 mph anywhere within the region being studied.

Upon completion of all the loss estimates, the loss data are rank ordered and used to define the loss probability distribution, $P(l>L)$, conditional on a storm producing a peak gust wind speed of at least 50 mph in the study region. The probability that the loss, L, is exceeded during time period t is

$$P_t(l > L) = 1 - \sum_{x=0}^{\infty} P(l < V|x) p_t(x) \quad (2)$$

where $P(l<L|x)$=probability that individual storm loss, l, is less than L given that x storms occur, and $p_t(x)$=probability of x storms occurring during time period t. From Eq. (2), with $p_t(x)$ defined as Poisson and defining t as 1 year, the annual probability of exceeding a given loss from a single event is

$$P_a(l > L) = 1 - \exp[-\upsilon P(l > L)] \quad (3)$$

where υ represents the average annual number of storms producing a peak gust wind speed of at least 50 mph anywhere in the study region. The average annual loss in the study region is simply the mean value (averaged over the 100,000 years) of the per storm losses.

In the deterministic mode of operation the user supplies HAZUS with information on a scenario hurricane (central pressure, wind speed, track, radius to maximum winds, and translation speed) and the model produces estimates of the financial losses,

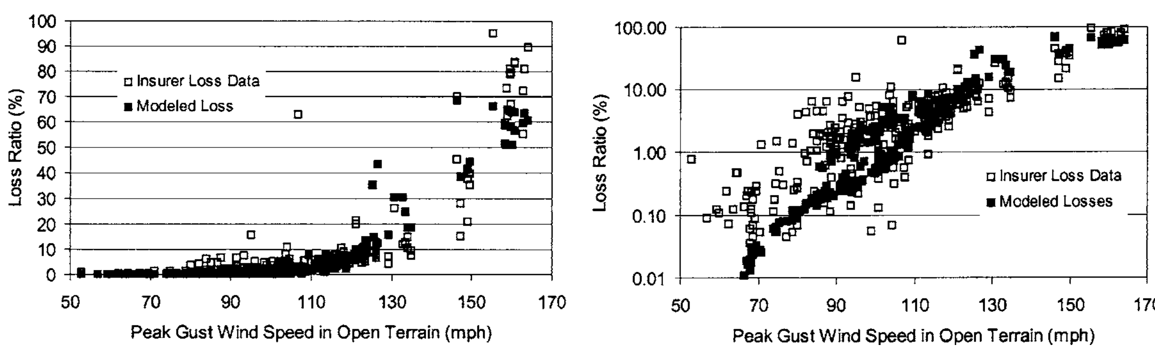

Fig. 10. Comparison of modeled and observed (insurance data) loss ratios versus modeled peak gust wind speed in open terrain (Hurricanes Hugo, Andrew, Erin, and Opal). Left plot losses presented using a linear scale, right plot losses presented on a logarithmic scale.

number of buildings experiencing a given damage state, number of displaced households, etc. The deterministic mode of operation can be used in cases where a hurricane is forecast to make land fall within a study region, or a user wants to examine what would happen if their community were to be impacted by a storm of a given Saffir–Simpson Scale category.

Summary

An overview of the damage and loss modeling components of the HAZUS Hurricane Model has been presented. The damage approach used in the model is an engineering-based load and resistance model. The damage model has been validated, wherever possible, through comparisons of modeled damage to observations from poststorm damage studies. The loss model estimates the costs associated with repairing the damaged building, replacing damaged contents, and estimating the costs associated with the inability to occupy and use the damaged building. The costs associated with repairing the building are estimated using a combination of an explicit cost estimation model and an empirical model developed using insurance data. The combined damage-loss modeling methodology has been validated through comparisons of modeled and actual insurance losses associated with four landfalling hurricanes.

The engineering-based load and resistance damage model, coupled with the loss given damage model, allowing users to quantify the cost effectiveness of various mitigation techniques in different geographic locations.

References

Bhinderwala, S. (1995). "Insurance loss analysis of single-family dwellings damaged in Hurricane Andrew." M.S. thesis, Clemson Univ., Clemson, S.C.

Crandell, J. H., et al. (1993). *Assessment of damage to single-family homes caused by Hurricanes Andrew and Iniki*, Contract HC-5911, NAHB Research Center, Upper Marlboro, Md., for U.S. Dept. of Housing and Urban Development Office of Policy Development and Research.

Landsea, C. W. (1993). "A climatology of intense (or major) Atlantic hurricanes." *Monthly Weather Rev.*, 121(3), 1703–1713.

Vann, W., and McDonald, J. (1978). *An engineering analysis: Mobile homes in windstorms*, Institute for Disaster Research, Texas Tech Univ., Lubbuck, Tex.

Vickery, P. J., Lin, J. X., Skerlj, P. F., Twisdale, L. A., and Huang, K. (2003). "HAZUS-MH hurricane model methodology. I: Hurricane hazard, terrain and wind load modeling." *Nat. Hazards Rev.*, 7(2), 82–93.

Vickery, P. J., Skerlj, P. F., Steckley, A. C., and Twisdale, L. A. (2000a). "Hurricane wind field model for use in hurricane simulations." *J. Struct. Eng.*, 126(10), 1203–1221.

Vickery, P. J., Skerlj, P. F., and Twisdale, L. A. (2000b). "Simulation of hurricane risk in the U.S. using empirical track model." *J. Struct. Eng.*, 126(10), 1222–1237.