Hurricane Risks and Economic Viability of Strengthened Construction

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Abstract: This paper describes a procedure for evaluating the effect of changes to existing residential structural vulnerability on hurricane-induced building damage and expected insurance losses. Two scenario-based models are proposed for modeling changes in the vulnerability of the existing building stock due to improvements in building envelope performance, for both existing and new residential construction. The influence of changes in structural vulnerability over time on expected insurance losses can then be obtained. The cost of retrofit or additional cost to upgrade new construction can be included in the hurricane damage risk-cost-benefit analysis to assess the economic viability of this and other scenarios. ‘‘Zones of economic viability’’ are developed that illustrate in a graphical manner whether retrofitting of existing residential construction is cost-effective. For example, in some cases retrofit costs of up to 40% of initial building costs may be economically viable. The risk analysis also enables the time to economic viability to be calculated.

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Introduction

Economic losses from wind and hail amount to 90% of losses from all natural hazards (Stubbs and Perry 1996), and these losses are by no means insignificant. Damages in the United States averaged $1.6 billion annually for the period 1950–1989 and more than $6 billion annually for the period 1989–1995 (mainly due to Hurricanes Andrew and Hugo) (Pielke and Pielke 1997). The potential for even larger losses exists given that the population and property at risk are increasing dramatically; for instance, in Florida the total coastal insured property values increased from $566 billion in 1988 to $872 billion in 1993 (a 55% increase).

Until recently, total insurance losses from natural disasters were $2–4 billion annually and reinsurance was able to spread this risk across the insurance industry worldwide. However, insurance losses since 1989 have been significantly higher, leading to greater difficulty in obtaining reinsurance. This has resulted in reinsurers ‘‘demanding a much higher level of accountability in terms of assessment of risk from insurance companies before providing reinsurance’’ (Walker 1995). The risk of death and injury from hurricanes is very low (Sparks et al. 1994), so the main criteria for minimizing insurance (and housing owner) losses are economic (i.e., reducing damage to the building and its contents) rather than life-safety. This is not the case with other natural hazards, such as seismic and flood hazards.

It is therefore increasingly important to estimate probable maximum losses (i.e., expected insurance losses) and the effect that changes to existing structural vulnerability have on building damage and expected insurance (and societal) losses. This has led to some preliminary insurance or economic risk analysis (Englehardt et al. 1993; Stubbs and Perry 1993) that considered in a simplified manner the effect of proposed changes to building codes. However, a more realistic and robust long-term GIS-based hurricane hazard risk analysis has been developed (Huang et al. 2001) in which event-based simulation is used to model the stochastic and spatial characteristics of hurricane-induced wind speeds and associated insurance losses over a 50-year exposure period for any zip code. A key aspect of previous work has been the need for accurate structural vulnerability models; namely, models representing the effect of wind speed on the proportion of insurance claims and damages.

Existing structural vulnerability models provide a ‘‘point-in-time,’’ or a snapshot, of housing as it was during the time period when they were developed. Naturally, over time this ‘‘point-in-time’’ structural vulnerability will vary because of changes in housing types or styles; new materials; age profiles (rate of new housing construction); code specifications, compliance, and enforcement; changes in exposure categories (e.g., effect of increased urbanization); and so on. Of interest in the present study is how changes to structural vulnerability over time will affect short-term and long-term insurance risks. For example, it has been widely suggested that 25–40% of insurance losses from Hurricane Andrew (total insured loss of $17 billion) would not have occurred if the properties had been built to the requirements of the then-existing building code (Roth 1997).

This paper proposes two scenario-based models of changes in the structural vulnerability of residential construction due to improvements in building envelope performance, for both existing and new construction. The hurricane damage risk-cost-benefit analysis model developed herein assesses the influence of the changes in structural vulnerability over time on expected insur-

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ance losses. One scenario, for example, is retrofitting existing houses immediately after they experience hurricane damage. The cost of retrofit or additional cost of upgrading new construction can be included in the hurricane damage risk-cost-benefit analysis in order to assess the economic viability of this and other scenarios. The model can also aid decision makers by determining at what point in time a particular retrofit strategy will be economically viable; namely, the time when the sum of additional cost of retrofit and reduced damage costs fall below the expected damage costs of existing vulnerability (i.e., ''do nothing'' scenario). Clearly, such work has great potential for more rigorous and rational economic analyses of retrofitting and strengthening proposals for increased hurricane resistance that may be used to estimate insurance premium underwriting costs, develop disaster mitigation or postdisaster strategies, or form public policy.

Prediction of Expected Losses

Expected losses to be calculated herein are based on the hurricane hazard risk analysis framework developed by Huang et al. (2001). This study used event-based simulation to generate hurricanes. The simulation procedure for this stochastic process is summarized as follows:

1. Hurricane arrival time is generated from a Poisson arrival model.
2. Gradient wind field is generated.
3. Gradient-to-surface conversion factor is used to determine surface wind speed.
4. Hurricane is moved to next location and the wind field is regenerated taking into account spatial changes such as decay. A similar process also calculates wind speeds in nearby zip codes.
5. After the hurricane has degraded to a point where wind speeds are no longer significant, the simulation randomly generates the next hurricane event.

The exposure period is 50 years. A structural vulnerability model that related claims and damages to surface wind speed allows the claim and damage ratios at each zip code (centroid) to be determined for each hurricane event, summed for each hurricane event, and then divided by 50 at the end of each 50-year period to obtain expected annual claim and damages ratios for all zip codes in North Carolina, South Carolina, and Florida. The Monte-Carlo simulation analysis considered 1,000 simulated 50-year exposure periods.

This is a particularly realistic long-term hurricane hazard analysis model since spatial parameters considered in this model include annual occurrence rate, approach angle, central pressure difference, radius of maximum wind speed, translational constant, decay constant, and gust factor. Note that no account is taken of losses caused by extratropical cyclones and thunderstorms, which may be significant (from a percentage standpoint) for inland regions in which these events contribute more to the extreme wind climate (Huang et al. 1999).

Existing Hurricane Structural Vulnerability Models

A limited number of structural vulnerability models have been developed for hurricane or tropical cyclone damage (Leicester et al. 1979; Leicester 1981; Sparks et al. 1994; Holmes 1996; Mitsuta et al. 1996; Stubbs and Perry 1996; Unanwa and McDonald 2000). Leicester et al. (1979) and Leicester (1981) developed vulnerability curves for various housing types based on damage surveys of cyclone damage in Australia. Sparks et al. (1994) used insurance claims records to determine relationships between damage ratio and gradient wind speed, for different building components. Holmes (1996) proposed a vulnerability curve for an ideal, fully engineered structure on the assumption that the vulnerability curve could be derived from the cumulative distribution of strength of any element. A relationship between wind speed and house losses from Typhoon Mireille was then proposed by Mitsuta et al. (1996). The structural vulnerability model proposed by Stubbs and Perry (1996) was based on an analysis of the performance of different building components and their corresponding relative importance. The damage ratio for the entire structure is thus weighted in proportion to the expert-supplied constants representing the relative importance of the contribution of the consequence of each damage mode. A somewhat similar approach has been developed by Unanwa and McDonald (2000), although their model is more versatile and capable of predicting wind damage for a large number of different house types and building performance parameters.

One of the most comprehensive (based on large data sets) structural vulnerability models to date has been developed by Huang et al. (2001) using claim and loss information from Hurricanes Hugo and Andrew obtained from a very large insurer. The data from Hurricane Hugo covered 81,161 policies from 118 zip codes with insured values totalling $10.4 billion. The total number of claims was 44,448 in South Carolina amounting to damages of $247.7 million (2.4% of total insured value). Following Hurricane Andrew, information was collected from 71 zip codes in Florida covering 72,796 policies with insured values totalling $12.4 billion. The total number of claims was 59,523 and the total claim amount reached $2.6 billion (21.3% of the total insured value).

Two measures of structural vulnerability were used: claim ratio and damage ratio. The claim ratio is defined as the total number of claims in a zip code divided by the total number of insurance policies in that zip code. The damage ratio is defined as the amount paid out by the insurer (in damages) divided by the total insured value (including contents).

Both the temporal and spatial characteristics of gust winds are highly variable; this can lead to significant uncertainty in the predicted gust wind speeds. The mean wind speed is a more representative measure of wind conditions over a large spatial area, and we have greater confidence in our ability to estimate mean wind speeds than gust wind speeds. Furthermore, the severity of wind damage (over a large area) is more a function of the mean wind speed than a potentially isolated gust, which would not be correlated over a large area. Hence, the reference wind was assumed to be the effective mean surface wind speed, averaged over 10 min, which would be measured at a height of 10 m at a hypothetical exposed location, located at the geographical centroid of the zip code area taking into account, in broad terms, the local exposure. Surface wind speeds at the centroid of each zip code for Hurricanes Andrew and Hugo were obtained from a hurricane wind field model, and the vulnerability models were then developed by relating the effective mean surface wind speed to the claim ratio and damage ratio in each zip code. A statistical analysis weighted the data from zip codes having similar effective mean wind speeds according to the total number of policies in each zip code (i.e., claims ratios and damage ratios were weighted averages). The relationships between the weighted claim ratio (F_C) and weighted damage ratio (F_D) with effective mean wind speed are

$$F_C(v) = 100 * \exp\{-\exp[-0.239(v - 21.21)]\} \tag{1}$$

and

$$F_D(v) = \exp(0.252v - 5.823) \quad v \leqslant 41 \text{ m/s}$$
$$F_D(v) = 100 \qquad v > 41 \text{ m/s} \tag{2}$$

where v = effective mean surface wind speed (m/s).

Note that the damage and claim ratios are normalized and so are not influenced by changes in housing numbers, but rather by changes in the mix of housing for a particular zip code. It is assumed herein that changes in structural vulnerability will not influence the number of insurance claims but rather the value of such claims (i.e., damage ratio). Thus, the term "structural vulnerability" subsequently refers to the effect of effective mean wind speed on the damage ratio of residential construction.

Proposed Structural Vulnerability Models

It has been observed that housing damage is closely related to the performance of the roof and wall building envelope (e.g., Sparks et al. 1994). This suggests that structural vulnerability may be broadly categorised as

1. Minor damage to building envelope—lost shingles, broken windows, damage to doors, damage to external facilities.
2. Loss of building envelope—rain entering building as a result of substantial damage to building envelope (loss of weather protection), significant structural damage.

Changes in code and standard specifications, housing design, etc., are likely to affect the structural vulnerability of these two damage types differently. For this reason, the structural vulnerability model developed by Huang et al. (2001) is modified to better illustrate the transition between these damage categories. Based on the characteristics of the structural vulnerability model and on past experience, the transition between minor and major damage occurs at a damage ratio of 20%. The damage data from Hurricanes Andrew and Hugo show that the relationship of minor damage to wind speed is nonlinear. However, at higher wind speeds the trend appears nearly linear. Consequently, the structural vulnerability model to be used in the present study is expressed as

$$F_D(v) = \exp(0.252v - 5.823) \quad v \leqslant 35 \text{ m/s}$$
$$F_D(v) = 20 + 11.43(v - 35) \quad 35 \text{ m/s} < v < 42 \text{ m/s} \tag{3}$$
$$F_D(v) = 100 \qquad v \geqslant 42 \text{ m/s}$$

This proposed structural vulnerability model is shown in Fig. 1. In this case, the "transition point" is 20% damage ratio at a mean surface wind speed (v) of 35 m/s.

The literature contains a large amount of experimental data showing the increase in the strength/capacity for a wide range of potential retrofit and strengthening procedures. For instance, Sutt et al. (1996) have shown that screw fasteners have a mean withdrawal capacity four times larger than nails. Unfortunately, such data provides little indication of how existing and proposed retrofit procedures quantitatively affect structural vulnerability. The general belief—from experimental testing, damage surveys, and anecdotal evidence—is that many retrofit procedures, if properly designed and installed, will significantly reduce structural vulnerability. There is clearly a need to quantify these improvements. This will require additional research focusing on the interaction of probabilistic wind field and structural response modeling to predict reductions in structural vulnerability and hence increases in structural reliability.

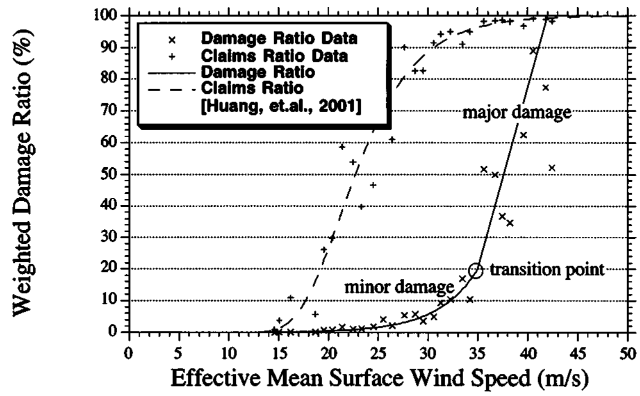

Fig. 1. Claims ratio and proposed model of existing structural vulnerability

There is clearly a need for a more comprehensive suite of structural vulnerability models that are conditional on type of construction, quality of construction, age, code specifications, etc. These factors are also interrelated. Unfortunately such models do not exist, so the present paper will propose two scenario-based structural vulnerability models. These are described in the following sections.

Reduced Vulnerability to Minor Damage

If it is assumed that improvements to building construction will mostly affect the vulnerability to minor damage, then Eq. (3) can be modified such that the conditional structural vulnerability (F_{DR}) may be expressed as

$$F_{\mathrm{DR}}(v) = \frac{(100-\phi)}{100}\exp(0.252v - 5.823) \quad v \leqslant 35 \text{ m/s}$$
$$F_{\mathrm{DR}}(v) = \frac{(100-\phi)}{100} 20 + 11.43(v - 35) < 100 \quad v > 35 \text{ m/s} \tag{4}$$

where ϕ = reduction in existing (1989–1992) structural vulnerability. In other words, the transition point is reduced by $20 \times (100\text{-}\phi)\%$. For example, Fig. 2 shows the effect of $\phi = 40\%$ and $\phi = 80\%$ reductions in existing structural vulnerability.

Reduced Vulnerability Due to Design to ASCE 7-98

If all materials, section sizes, connections, fixings, and external facilities in a building (particularly the building envelope) are

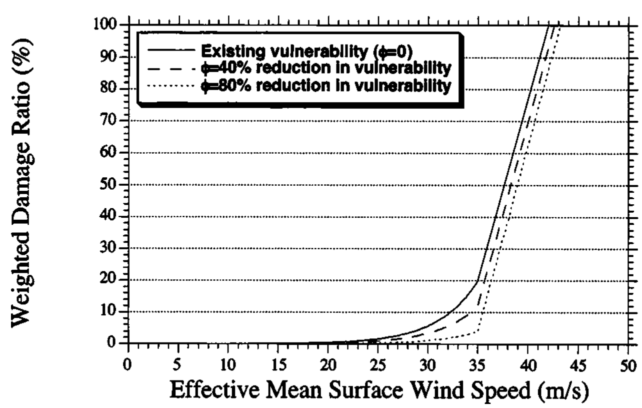

Fig. 2. Effect of reduced vulnerability to minor damage

''fully engineered,'' then structural vulnerability for most houses will be reduced considerably since most existing houses are non-engineered. The term ''fully engineered'' would typically imply that the building would be designed to withstand design wind forces, for example, as specified by the ASCE Standard ''Minimum Design Loads for Buildings and Other Structures'' (ASCE 7-98). It might be noted that following Cyclone Tracy in 1974, building regulations in Australia were revised and now require domestic housing in cyclone-prone areas to be structurally engineered to the same performance criteria of other ''fully engineered'' buildings (Walker 1980). The effect of a fully engineered building envelope on structural vulnerability and associated predicted insurer costs due to retrofit and upgrading of new construction are described elsewhere (Stewart et al. 2000).

Future Residential Construction Scenario Models

There are many possible scenarios for changes to structural vulnerability over time of new and existing residential construction. However, for the present study three scenarios associated with (1) ''do nothing'' (existing vulnerability), (2) strengthening (retrofit), and (3) changes to population mix of new (strengthened) construction are considered. The latter two scenarios can be expected, over the passage of time, to lead to significant reductions in the vulnerability of communities to hurricanes.

Since costs of upgrading and damage costs are likely to occur at different times, it would be rational to discount future costs to present values, e.g., present value is equal to $C/(1+r)^t$, where C is the future cost at time t and r is the discount rate. Note, however, that future costs are given in terms of the insured value of a house (structure and contents) whose replacement value is likely to increase in value beyond the rate of inflation. Although discounting can readily be incorporated into the risk-cost-benefit analyses to follow, discounting of costs will open up many possibilities regarding parameter selection, and so for convenience are omitted from the analyses described herein.

For both scenarios it is assumed that the wind speed characteristics are constant across an entire zip code and that the structural vulnerability of an individual house in its initial (undamaged) condition is time-invariant and deterministic. Thus, a low wind speed event will only cause damage to the same subset of houses previously damaged by a higher intensity wind event.

Retrofit during Repair to Hurricane Damage

If a house is damaged by a hurricane then this is a convenient time to retrofit (strengthen, upgrade) the house, since a builder is already on-site conducting repairs. It is quite likely that the additional cost of retrofitting will only be incrementally greater than the cost of simply restoring the house to its initial (undamaged) condition. However, the cost of retrofitting residential structures is often a deterrent to homeowners. Hence, some form of financial assistance or incentives from insurance firms or government agencies is generally needed to encourage retrofitting (Cook et al. 1993). This scenario therefore assumes that insurance fully covers the cost of retrofitting, and the hurricane damage risk-cost-benefit analysis to follow will help assess if such an investment strategy will prove to be economically viable to the insurer.

The analysis assumes that retrofitting is conducted once, and only after the first hurricane-induced incidence of damage. For the first hurricane-induced damage the damage ratio is thus:

$$F_{D_1}(v)=F_D(v)+F_c(v)\,\frac{C_{\mathrm{ST}}}{1.5\times 100} \tag{5}$$

where $F_C(v)$ and $F_D(v)$ = damage and claim ratios (%) given by Eqs. (1) and (3); C_{ST} = cost of retrofitting a single structure expressed as a percentage of the value of the structure; and i = hurricane event. Huang et al. (2001) assumed that the insured value of a house is 150% of the value of the structure. The damage ratio for subsequent events will then be influenced by the proportion of retrofitted housing, and this proportion in turn is affected by the peak mean wind speed experienced by the site up to this time. For subsequent hurricane-induced events, the damage ratio for hurricane event i is

$$F_{D_i}(v)=F_{\mathrm{DR}}(v) \quad F_c(v)\leqslant F_{c_{\max}} \tag{6}$$

if the hurricane event is of lesser intensity than all previous hurricanes (i.e., reduced damage loss for houses previously retrofitted and no additional houses retrofitted), or

$$F_{D_i}(v)=\frac{(F_c(v)-F_{c_{\max}})}{F_c(v)}F_D(v)+\frac{F_{c_{\max}}}{F_c(v)}F_{\mathrm{DR}}(v) + (F_c(v)-F_{c_{\max}})\,\frac{C_{\mathrm{ST}}}{1.5\times 100} \quad F_c(v)>F_{c_{\max}} \tag{7}$$

if the hurricane event is of greater intensity (i.e., reduced damage loss for houses previously retrofitted, additional houses damaged and retrofitted). The reduced vulnerability due to retrofitting is represented by F_{DR}, which may be expressed by Eq. (4). In this case $F_{c_{\max}}$ represents the percentage of houses retrofitted immediately prior to the next hurricane event and is calculated as the maximum claims ratio experienced up to hurricane event i. This gives

$$F_{c_{\max}}=\max_{j=1,i-1}(F_{c_j}) \tag{8}$$

where F_{cj} = claims ratio for hurricane event j.

Rate of Growth of New (Strengthened) Construction

Another possible scenario considers the effect of the rate of growth of new housing assuming that such new housing is constructed with reduced structural vulnerability. For a hurricane event i occurring at time t, the damage ratio conditional on t-years of x% annual growth of new housing is

$$F_{D_i}(v)=\frac{100-(xt)}{100}F_D(v)+\frac{xt}{100}F_{\mathrm{DR}}(v) \tag{9}$$

where xt represents the percentage of new housing at time t (this product cannot exceed 100%). Clearly, xt may also be seen to represent the rate of growth of retrofitted houses or other strategies that result in houses of reduced vulnerability. For example, Cook et al. (1993), Sutt et al. (1996), and others suggest that stripping of old roof coverings, improved attachments of the sheathing followed by installation of wind resistant roof covering, and using hurricane straps to secure rafters and trusses to walls should become a regular part of reroofing. If reroofing occurs every 20 years then x would be equal to 5% per year to ensure 100% retrofitted houses within 20 years. The additional cost of new housing is assumed to be borne by the homeowner, not the insurer.

Hurricane Damage Risk-Cost-Benefit Analysis and Results

Huang et al. (2001) estimated annual expected damage ratios for all zip codes in North Carolina, South Carolina, and Florida for

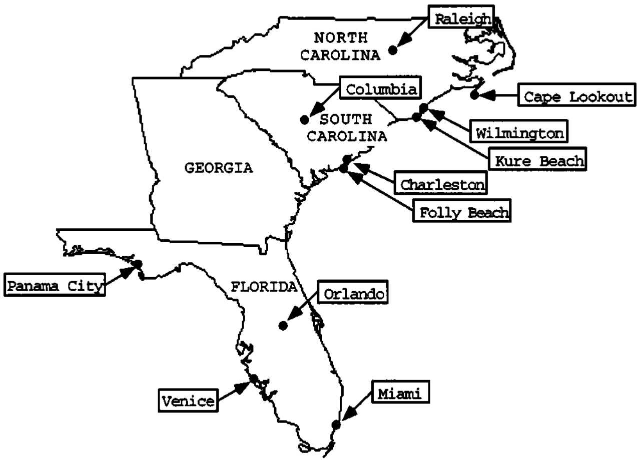

Fig. 3. Map of Southeastern U.S.

existing structural vulnerability given by Eqs. (1) and (2). The present study will consider a smaller number of sites—namely,

- North Carolina: Cape Lookout, Kure Beach, Raleigh, Wilmington
- South Carolina: Charleston, Columbia, Folly Beach
- Florida: Miami, Orlando, Panama City, Venice

These sites contain both coastal and interior (several hundred km) geographic locations with exposure to hurricanes originating from both the Atlantic and Gulf coasts (Fig. 3). Furthermore, the effect of short distances from the coast is illustrated by considering coastal and inland (several km from the coast) locations at Miami and Venice, in Florida. The Monte-Carlo simulation method is similar to that described previously in the paper except that structural vulnerabilities are modified, as discussed with Eqs. (5)–(9). Expected annual damage ratios are annualized for a 50-year exposure period.

A number of studies have found that the additional cost to new housing for increased hurricane resistance is in the range of 1–10% (e.g., Stewart et al. 2000). There is very little data on the costs of retrofitting a house for increased hurricane resistance. However, Leicester (1981) has observed that ''estimated'' additional costs for houses in Australia range from 15% to 50% for retrofit of existing houses. While there can be expected to be a relatively wide range of additional costs due to the large choice of strengthening procedures available for housing construction, work is evidently needed to more precisely estimate these costs.

Unless noted otherwise, all expected losses assumed herein are those borne by the insurer. If more costing data were available it would be possible to consider other scenarios or costs and benefits of other interested parties in a multiattribute decision analysis. See Stewart et al. (2000) for more details and results of the hurricane damage risk-cost-benefit analysis.

Existing Structural Vulnerability

The expected annual damage ratios based on the existing structural vulnerability (i.e., ''do nothing'') are shown in Table 1 for all sites. Naturally, these results are nearly identical to those reported by Huang et al. (2001). It is observed that the expected annual damage ratio may be as low as 0.08% for sites far inland (Columbia, Raleigh) and as high as 2% for exposed coastal sites (Folly Beach). An expected annual damage ratio of 2% implies that houses will experience losses totaling 100% of the insured value, on average, every 50 years. However, the expected annual damage ratio decreases significantly for sites only 2–4 km inland. Table 1 also shows that major damage (Fig. 1) can constitute a large proportion of expected losses, but a relatively small proportion of claims.

Retrofit during Repair to Hurricane Damage

The expected annual damage ratios (excluding costs of retrofit) for this scenario are shown in Table 2, for retrofitting with structural vulnerability reduced by 40% and 80%. In all cases at least 50% of houses will be retrofitted over the 50-year exposure period. The proportion of houses retrofitted represents the proportion of houses that experienced hurricane-induced damage, and thus repairs and retrofitting. As such, the expected annual damage ratio decreases dramatically for the retrofit scenarios considered herein. In some cases this reduction is up to 65% for an 80% reduction in vulnerability to minor damage.

Table 1. Annual Expected Damage Ratios and Categorization of Damage for Existing Structural Vulnerability

		Proportion of Costs		Proportion of Occurrences	
Site	Existing vulnerability (%)	Minor damage (%)	Major damage (%)	Minor damage (%)	Major damage (%)
North Carolina:					
Cape Lookout	1.642	32.2	67.8	89.2	10.8
Kure Beach	1.337	32.1	67.9	88.9	11.1
Raleigh	0.080	100.0	0.0	100.0	0.0
Wilmington	0.163	80.1	19.9	99.5	0.5
South Carolina:					
Charleston City	0.541	65.8	34.2	97.9	2.1
Columbia	0.080	100.0	0.0	100.0	0.0
Folly Beach	2.088	28.1	71.9	88.7	11.3
Florida:					
Miami: Coast	1.012	61.1	38.9	96.9	3.1
2–4 km Inland	0.530	88.8	11.2	99.6	0.4
Orlando	0.508	88.0	12.0	99.5	0.5
Panama City	0.366	87.4	12.6	99.6	0.4
Venice: Coast	1.624	53.0	47.0	96.1	3.9
2–4 km Inland	0.479	89.4	10.6	99.5	0.5

Table 2. Annual Expected Damage Ratios for Existing Structural Vulnerability and Retrofit during Repair to Hurricane Damage (Excluding Cost of Retrofit)

Site	Existing vulnerability (%)	Reduced Vulnerability to Minor Damage		Houses retrofitted (%)
		$\phi=40\%$	$\phi=80\%$	
North Carolina				
Cape Lookout	1.642	1.363	1.085	95.6
Kure Beach	1.337	1.123	0.909	94.2
Raleigh	0.080	0.058	0.035	50.9
Wilmington	0.163	0.129	0.095	70.6
South Carolina				
Charleston City	0.541	0.409	0.276	88.0
Columbia	0.080	0.058	0.035	50.9
Folly Beach	2.088	1.754	1.420	96.6
Florida				
Miami: Coast	1.012	0.746	0.480	93.6
2–4 km Inland	0.530	0.362	0.194	88.2
Orlando	0.508	0.352	0.196	88.1
Panama City	0.366	0.257	0.149	83.4
Venice: Coast	1.624	1.219	0.814	95.6
2–4 km Inland	0.479	0.330	0.182	88.0

Zone of Economic Viability

The cost-effectiveness of the retrofit scenarios considered herein can be evaluated by comparing the insurer costs (damage ratio for a particular reduction in structural vulnerability + retrofit cost C_{ST}) with the ''do nothing'' scenario. There are a large number of combinations of reductions in structural vulnerability and retrofit costs. Hence, an ''envelope'' of these combinations producing expected annual insurer costs lower than the ''do nothing'' expected annual damage ratio is developed—this is referred to herein as the ''zone of economic viability.''

Fig. 4 shows the zones of economic viability for Columbia (interior) and Folly Beach (coastal). Each combination of retrofit cost and reduction in structural vulnerability (ϕ) determines the percentage change in annual insurer costs. If the change in annual insurance costs is negative then this scenario is economically viable. The zone of economic viability is much smaller for Columbia because of its reduced exposure to hurricanes; however, Fig. 4(a) shows that retrofitting is still cost-effective if a 60% reduction in vulnerability can be achieved for a retrofit cost not exceeding 5% of the initial building cost. For Folly Beach, retrofitting is cost-effective even if retrofit costs for the same reduction in vulnerability ($\phi=60\%$) reach 40%. Clearly, the zones of economic viability (particularly for coastal or exposed regions) show that for the scenarios considered herein, retrofit costs may be cost-effective even if they achieve only modest reductions in structural vulnerability.

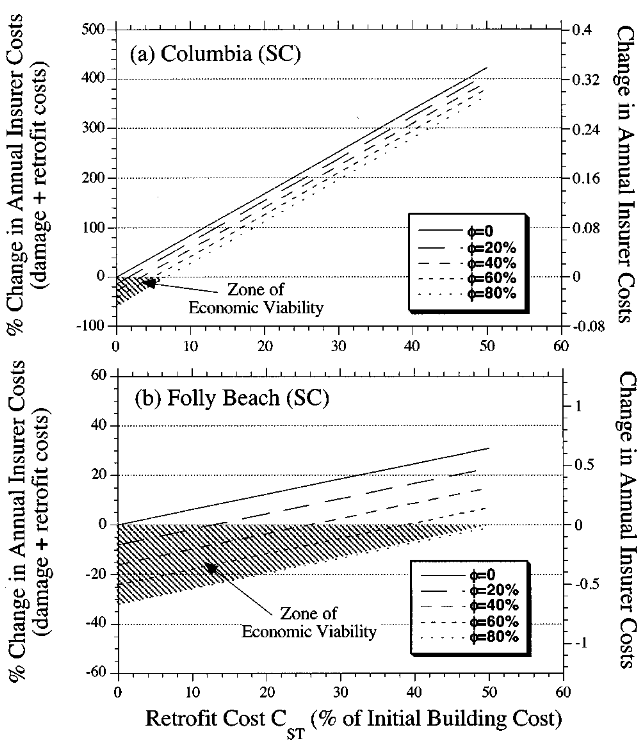

Fig. 4. Zone of economic viability for retrofit during repair to hurricane damage (reduced vulnerability to minor damage), for (a) Columbia and (b) Folly Beach

Time to Economic Viability

The preceding analyses have considered costs annualized over a 50-year exposure period. However, it may also be useful for de-

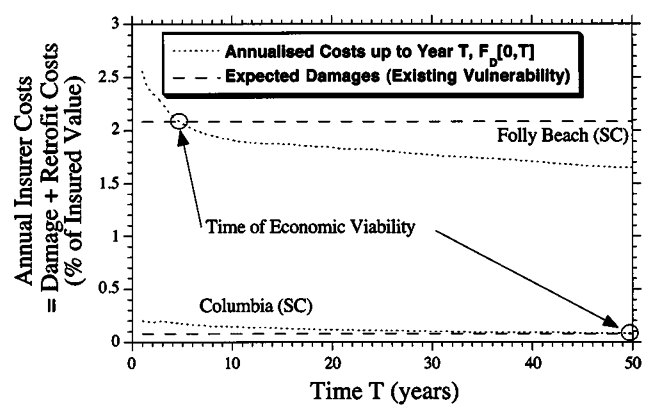

Fig. 5. Time to economic viability for $\phi=60\%$ and retrofit costs of 5%

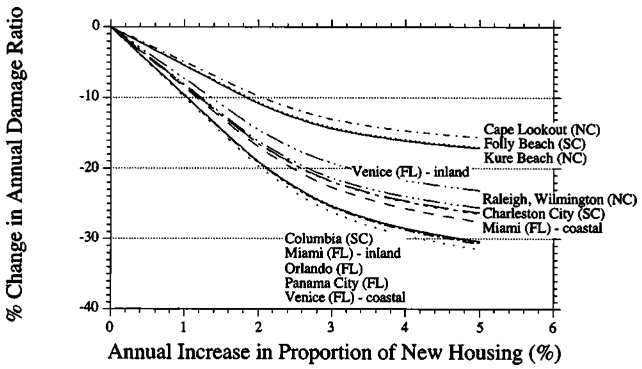

Fig. 6. Percentage change in expected annual damage ratio for $\phi = 40\%$ reduction in structural vulnerability

cision makers to monitor changes in insurer costs (damage + retrofit costs) over time, as this will give an indication as to when a particular retrofit strategy will be economically viable. This is achieved by considering a time-variant measure of expected costs, namely, insurer costs (damage + retrofit costs) for all years up to year T annualized over this time period, $F_D[0,T]$ expressed as

$$F_D[0,T] = \sum_{t=1}^{T} \frac{F_D(t)}{T} \tag{10}$$

where $F_D(t)$ = insurer costs for year T. It should be noted that for the "do nothing" strategy, $F_D[0,T]$ is the same for all values of T since structural vulnerability is time-invariant and there are no additional retrofit costs. For example, annualized costs up to year T are shown in Fig. 5, for retrofit during repair to hurricane damage ($\phi = 60\%$, $C_{ST} = 5\%$) for sites in Columbia and Folly Beach. The intercept of the cumulative costs for all years up to year T annualized over this time period and the "do nothing" expected damages shows the time needed for this particular retrofit strategy to be economically viable. In this case, this particular retrofit strategy becomes economically viable after 4 years and 50 years for Folly Beach and Columbia, respectively.

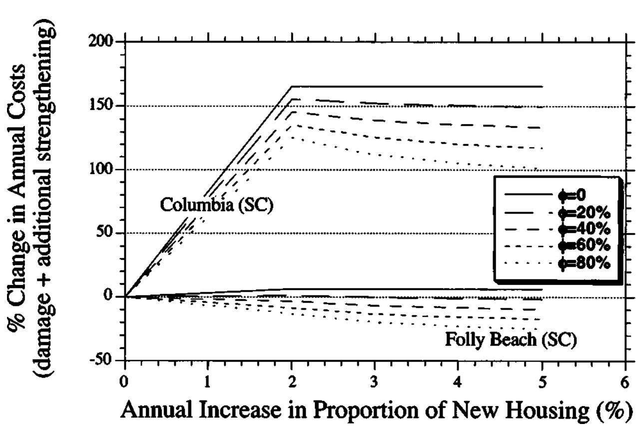

Fig. 7. Percentage change in expected annual costs for retrofit causing reduction to minor damage (ϕ) and additional cost of construction (C_{ST}) of 10%

Rate of Growth of New (Strengthened) Construction

Any increase in the proportion of new construction (designed and constructed to reduced vulnerability) will reduce expected annual damage ratios. This is evident from Fig. 6, which shows the reduction in expected annual damage ratios for a $\phi = 40\%$ reduction in vulnerability, for all sites. Even a 1% annual increase in the proportion of new housing can reduce expected annual damage ratios by at least 6%.

It is possible to determine the cost-effectiveness of a range of possible strengthening requirements for new design and construction. This might include combinations of rate of new construction, reduction in vulnerability, and additional cost of strengthening. Fig. 7 shows the changes in total costs for one such combination of parameters. In this case, strengthening causes a reduction to minor damage (ϕ) and the additional cost of upgrading new construction is taken as 10%. This additional cost of construction is probably conservative since it was shown earlier that additional cost to new housing for increased hurricane resistance is generally in the range of 1–10%. It is assumed that insurers will pay for hurricane damage and the homeowner will pay for the additional cost of construction; hence, these costs are essentially societal costs or losses. In this particular case it appears that strengthening of new houses is cost-effective for exposed regions such as Folly Beach, but not for a less exposed region such as Columbia. To be sure, similar analyses could be conducted for an almost infinite number of scenarios. These are beyond the scope of the present paper.

Further Work

There is clearly much opportunity for further work. This may include developing structural vulnerability models for different housing types or construction techniques (and materials), age profiles, code specifications, compliance and enforcement, changes in exposure categories (e.g., effect of increased urbanization), and so on. The development of such models will require a substantial research effort that may include collection and analysis of insurance claim (loss) data, field or test data (or more subjective data obtained from "experts"), structural system modeling to assess effect of component strengthening on the structure and building envelope, and probabilistic wind field and structural response modeling to predict changes in reliability. There is also a need for the quantification of the additional costs for increased hurricane resistance.

Finally, more rigorous economic decision analyses may be developed that consider the effect of insurance premiums, deductibles, insurer incentives, discount rates, life safety, hurricane mitigation and response costs, and other costs and benefits (direct and indirect) of hurricane mitigation strategies related to the building owner, insurer, reinsurance company, government agency, or society in general. This will require a more detailed multiattribute decision analysis. Whether such analyses are conducted will depend on data and support from the insurance industry.

Conclusions

A GIS-based hurricane simulation model was used to statistically characterize the extreme wind climate (considering hurricane events) at selected sites in the Southeastern United States. This information was then used in a risk-cost-benefit analysis to model the stochastic and spatial characteristics of hurricane-induced wind damage (specifically, insured losses to residential structures) over a 50-year exposure period. The paper developed two scenario-based models for changes in vulnerability of the existing building stock due to improvements in building envelope performance, for both existing and new residential construction. Scenarios considered included retrofitting existing houses immediately after they experience hurricane damage and ensuring new construction is built with reduced vulnerability. The cost of retrofit or additional cost of upgrading new construction was then included in the hurricane damage risk-cost-benefit analysis in order to assess the economic viability of these scenarios. ‘‘Zones of economic viability’’ determined the potential for cost-effective retrofitting of existing residential construction. For example, in some cases retrofit costs of up to 40% of initial building costs may be economically viable. The risk analysis also enabled the time to economic viability to be calculated. It was found, for instance, that some retrofit scenarios may become economically viable to insurers within only a few years.

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Notation

C_{ST} = cost of retrofitting;
F_C = claims ratio;
$F_{c_{\max}}$ = percentage of houses retrofitted immediately prior to next hurricane event;
F_D = damage ratio;
$F_D[0,T]$ = cumulative insurer costs for all years up to year T then annualized over this time period;
F_{DR} = structural vulnerability conditional on reduced vulnerability;
i = hurricane event;
T,t = time (years);
x = growth of new housing;
v = mean surface wind speed (m/s); and
ϕ = reduction in existing structural vulnerability.

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