Cost effectiveness of hurricane mitigation measures for residential buildings

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ABSTRACT

This paper addresses methods for evaluating the economic feasibility of mitigated residential buildings in Florida. The cost effectiveness of mitigation applied to different types of masonry and timber homes is determined by applying different sets of mitigations. The authors analyzed the cost effectiveness of various combinations of mitigation measures for different types of residential structure of different age and quality. Different sets of mitigation measures were investigated that combined improved roofing materials, improved roof to wall connections, and opening protection. This mitigation measures were applied to typical timber box and masonry residential structures of different age and quality of construction, from weak pre-1970 to stronger post 2002 construction. In each case, a detailed cost analysis of the unmitigated and mitigated building was performed and the relative cost effectiveness of mitigation was assessed, through comparisons of the results of portfolio analyses with and without mitigation. This paper presents the results of the mitigation cost effectiveness study, including component vulnerabilities from Monte Carlo simulation, overall building vulnerabilities, cost analysis, and analysis of the effectiveness of different sets of mitigation measures for different regions of Florida. The results are color mapped by zip codes for the whole State.

INTRODUCTION

The 2004, 2005, and more recently the 2008 hurricane seasons resulted in insured losses in excess of several billions. The devastation brought by the hurricanes that frequently impact Florida demonstrates the need for a comprehensive integrated risk management strategy specially adapted to the needs of the people and buildings of Florida. Affordable solutions to mitigate the terrible destruction brought on by hurricanes like Andrew, Charley, Ivan, or Katrina are available and can only be evaluated with a holistic approach that includes the meteorology, engineering, and economic aspect of the problem. In particular, given the limited resources available, it is critical to identify what are the more cost effective solutions to increase the safety of the existing and new building stock and to avoid repeating past errors when rebuilding in disaster areas. Catastrophe models can play a crucial role in this identification process. In particular, the Florida Public Hurricane Loss Model (FPHLM) passed successfully a rigorous certification program from the State of Florida. This computer model combines the latest state of the art in meteorology, wind engineering, and actuarial science to predict the expected annual insured losses in Florida for residential single family homes. The authors applied the expertise acquired in the development of this model together with the lessons learned in the field from past hurricane seasons and used the FPHLM in a state of the art comprehensive study of mitigation cost effectiveness in the State of Florida. The mitigation studies were carried on by a team of engineers at the Florida Institute of Technology and the University of Florida in collaboration with the International Hurricane Research Center at Florida International University. The work included engineering-based cost benefit evaluation of various mitigation measures. This paper describes the steps in the development of the vulnerabilities for the different mitigated model for low rise buildings, and the subsequent cost effectiveness study. Results are presented and discussed.

BRIEF DESCRIPTION OF THE FPHLM

The Florida Public Hurricane Loss Model (FPHLM) is a risk-assessment system that can analyze portfolio files of any insurance company to compute the expected annual losses, or actual scenario losses, of the insured policies, for single family residential houses. The output from this analysis can then be used for the validation of other models, rate making, and other tasks. In particular, the FPHLPM can be used to analyze the effectiveness of mitigation measures.

The model consists of 3 distinct parts that are integrated into a computer platform: the meteorology module, the engineering module, and the actuarial module. For more information on the FPHLM see [1].

In particular, the FPHLM models the losses for the most common types of single family homes in Florida, which are masonry homes or timber box like structures, both with timber truss roofs. Each type of structure is itself represented in the FPHLM with differing strengths as a weak, a medium, and a strong model based on different age and quality of construction, from weak pre-1970 to stronger post 2002 construction. The weak variant corresponds of course to older structures while the strong one corresponds to the newest building built according to the latest building codes [2]. The models that were considered in this study are listed in Table 1.

Table 1: Non-mitigated / basic models – Weak, medium, and strong

Model	Garage Door	Sheathing	Roof-Wall connection	Roof shape	shutters
Weak	30 psf	6d nails	Toe nails	gable	none
Medium	30 psf	8d nails	clips	gable	none
Strong	52 psf	8d nails	straps	gable hip	none

The numbers in the garage door column indicate the wind pressure the door is rated for.

The engineering module of the FPHLM uses the information from the meteorology module to predict the damage to the different types of buildings, based on their vulnerability matrices. These matrices are derived by an independent stand alone vulnerability model. The vulnerability model uses a Monte Carlo simulation based on a component approach to determine the external vulnerability of buildings at various wind speeds. The simulation relates estimated probabilistic strength capacities of building components to a series of deterministic 3 sec peak gust wind speeds through a detailed wind and structural engineering analysis that includes effects of wind-borne missiles [3]. The simulated components include openings (doors, windows), roof cover, roof sheathing, walls, and roof to wall connections. The result is a prediction of the physical damage that occurs to these components of an average house over a prescribed range of wind speeds. The internal, utilities, and contents damages to the building are then extrapolated from the external damage. This includes damage due to water penetration (through broken windows and lost roof sheathing), damage to interior systems (electrical, plumbing, mechanical) and fixtures (fixed cabinets, carpeting, partitions, doors), and damage to contents. The resulting estimates of total building damage result in the formulation of vulnerability matrices for each building type statistically significant in the Florida building stock. The damage model is complemented with estimates of appurtenant structures damage (pool, deck, unattached garage), and additional living expenses (ALE) [4].

MITIGATION MEASURES

The same engineering approach was used to model the impact of mitigation measures. Mitigation measures are classified in different categories, and combined in different mitigation sets. A mitigation set is a combination of different mitigation measures, applied as a retrofit to an existing home. Table 2 defines different categories of mitigation measures.

Table 2: Summary of Mitigation Categories

A-Roofing	A-1Cover	Strong Shingles	Strong Tiles	Metal Roof
	A-2 Membrane	Extra Underlayment[5]	Joint Tape	Joint Sealing
B-Decking	B-1 Improved Roof Decking Nailing Schedule using Hurriquak nails [6]			
	B-2 Bracing of Gable Ends			
C-Roof to wall Connection	C-1 Clip	C-2 Strap	C-3 Lumber plate	
D-Opening protection	D-1 Shutters	D-2 Laminated Glass	D-3 Impact Glass	D-4 Security Film
E- Wall to sill plate connection	E-1 Wall to sill plate connection for Timber			
	E-2 Reinforcing for Masonry			
F-High Tech	F-1 Roof Retrofit Devices [7]			
	F-2 FRP fabric[8]			
G-Garage door	G1-Replacing by a New One			
	G2-Bracing an Existing Door			

Only the items underlined in Table 2 were investigated in this study. All mitigation measurements follow the Florida Building Code [9] and most recent updates on mitigation rules and techniques [10].Mitigation sets were defined for different types of masonry and timber homes with gable roof or hip roof according to their age and quality (weak, medium and strong as classified in table 1). For more details on mitigation sets and categories for more details see [2]. Only the results for weak gable timber homes will be presented and discussed here for the sake of brevity. Table 3 shows the mitigation sets for weak gable timber homes presented here.

Table 3: Mitigation sets for weak-gable-timber homes

Mitigation Type	Set1a	Set1b	Set2	Set3	Set4
D-1 Shutters	on	on	on	on	on
G-2- Garage door bracing	on	on	on	on	on
A-1-1 Shingle	on	on	on	on	off
A-2-3 Joint Tape*	on	on	on	on	off
B-1, B-2 Decking, Bracing of gable ends	on	on	on	off	off
C-2 Roof to wall Connection (strap)	on	on	off	off	off
E-1 Wall to sill (strap)	on	off	off	off	off

* Underlayment includes an extra layer of self adhesive bitumen. Joint sealing or tapping are considered separately instead of underlayment in different mitigation sets.

Sets 1a and 1b are the "deluxe" sets which include everything and will be the more expensive. The difference between 1a and 1b are the wall to sill straps. Set2 is set 1 minus the retrofit of the roof and wall connections, which is expensive and difficult to achieve with minimum disruption. Set3 is set2 minus the decking retrofit. It involves only reroofing and shuttering the home. Set 4 involves only shuttering and garage door improvement. Set 4 is almost a "do it yourself" mitigation set.

COST ESTIMATION

Several sources for cost estimation were used: the 2008 National Renovation & Insurance Repair Estimator [11] which contains material cost data and retrofitting costs; RSmeans 2008 for Residential Buildings [12]; and, third, RSmeans Square Foot Costs 2008 [13]. Average location factors from different cities in the North, South and Central regions of Florida multiplied the national cost of each component to calculate the cost of component in each region. The total cost of a new home and cost of each mitigated component were calculated. Costs were verified by three different professionals as a final check. Table 4 shows the estimation for one type of home by these three different estimators.

Table 4. Summary of Cost Estimates for Melbourne-Florida for a gable roof timber home

	Estimator 1	Estimator 2	Estimator 3
Calculated Cost per square foot	$69.15	$66.88	$68.61
Cost per square foot from RSmeans (with reinforced concrete foundation wall)	$73.43		

Each estimator had a different approach to the problem, but table 4 indicates that all three estimators were reasonably close to each other, and a little bit lower than the RSmeans price for Average Residential Buildings mainly due to the different kinds of foundation used in Florida.
The replacement cost ratio can be defined as the cost of replacing a damaged component or assembly of a home divided by the cost of constructing a complete new home of the same type.

$$\mathrm{Cost}_{\text{Mitigated Component}} = \mathrm{Cost}_{\text{New Component}} + \mathrm{Cost}_{\text{Removing Old Component}} \quad (1)$$

$$\text{Replacement Cost Ratio} = \mathrm{Cost}_{\text{Mitigated Component}} / \mathrm{Cost}_{\text{New Home}} \quad (2)$$

Figure 1 shows the replacement ratio for individual mitigation across different regions for the weak-timber model. Figure 2 shows the distribution of cost of each component for the south-masonry homes with gable roof.

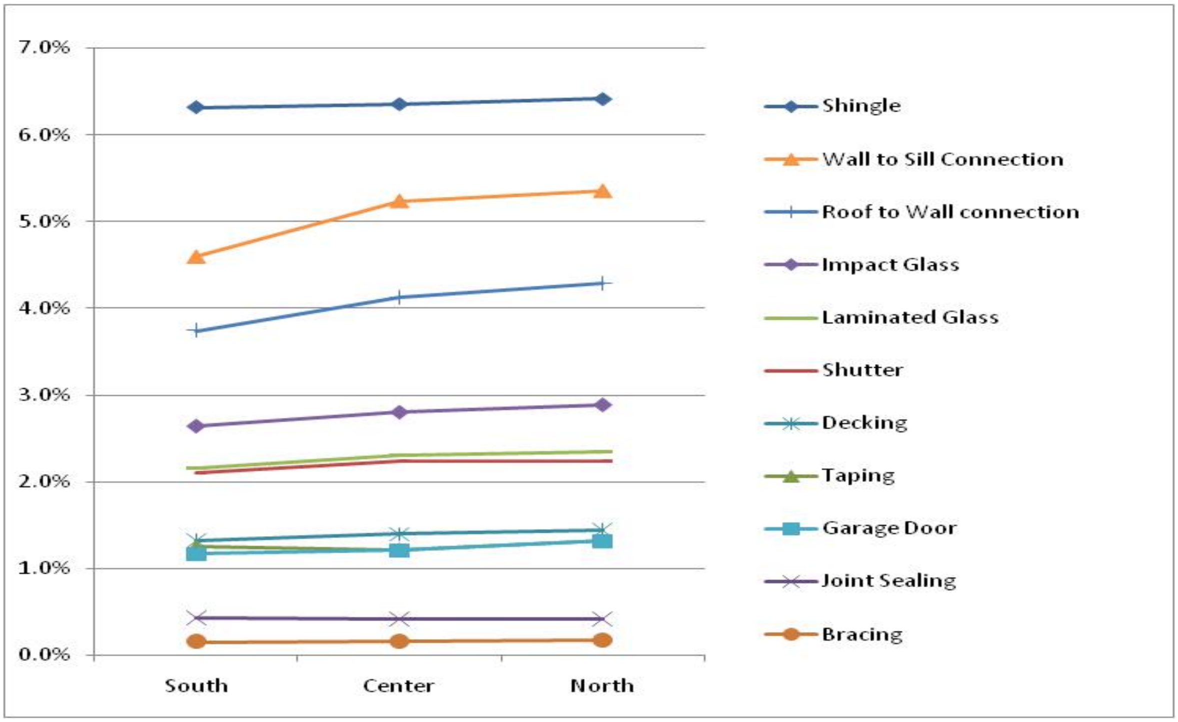

Figure 1: Regional variations of mitigation cost ratios for timber homes (gable roof)

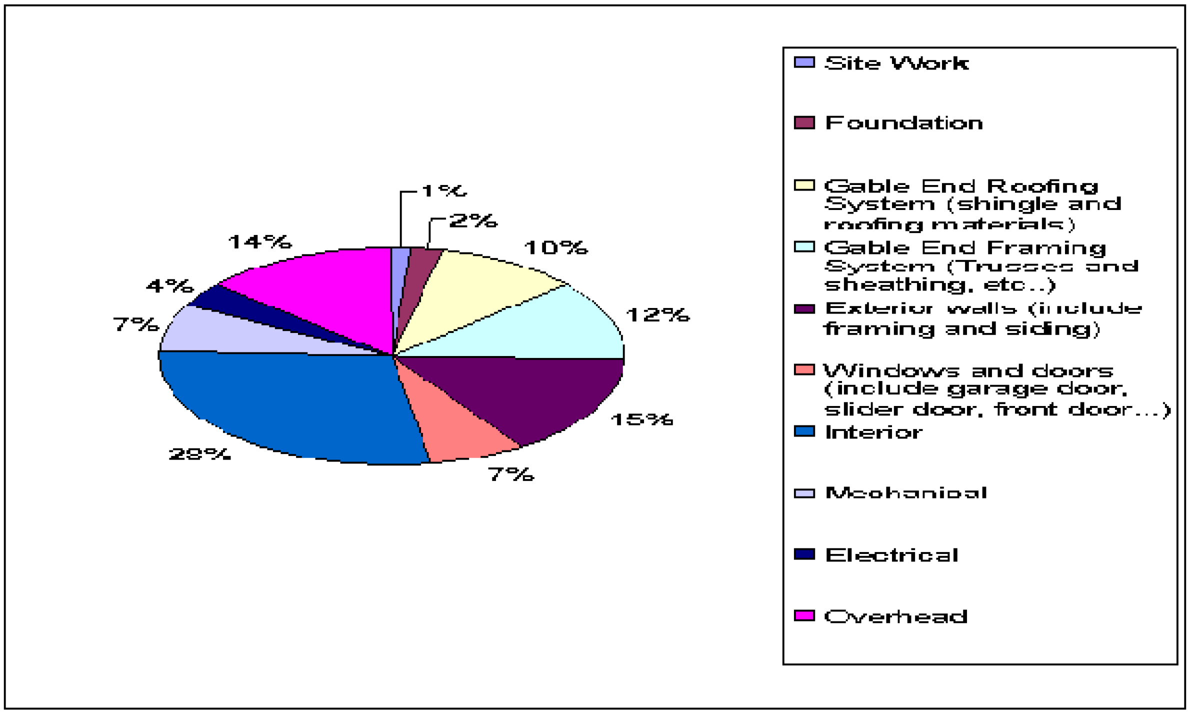

Figure 2: Distribution of cost of each component of a timber home (gable roof) in the South.

VULNERABILITY CURVES

Vulnerability matrices for homes retrofitted with the mitigation sets of Table 2 were computed. In each case, the cost of the mitigation was evaluated according to the percentages shown in Figures 1 and 2. Each column of a vulnerability matrix represents the probability distribution function of damage at a given wind speed interval. The mean value of damage for each column can be plotted versus the wind speed. This function is the vulnerability curve. Figure 3 shows the vulnerability curves for a weak-gable-timber home in South Florida, retrofitted with the different sets of Table 2.

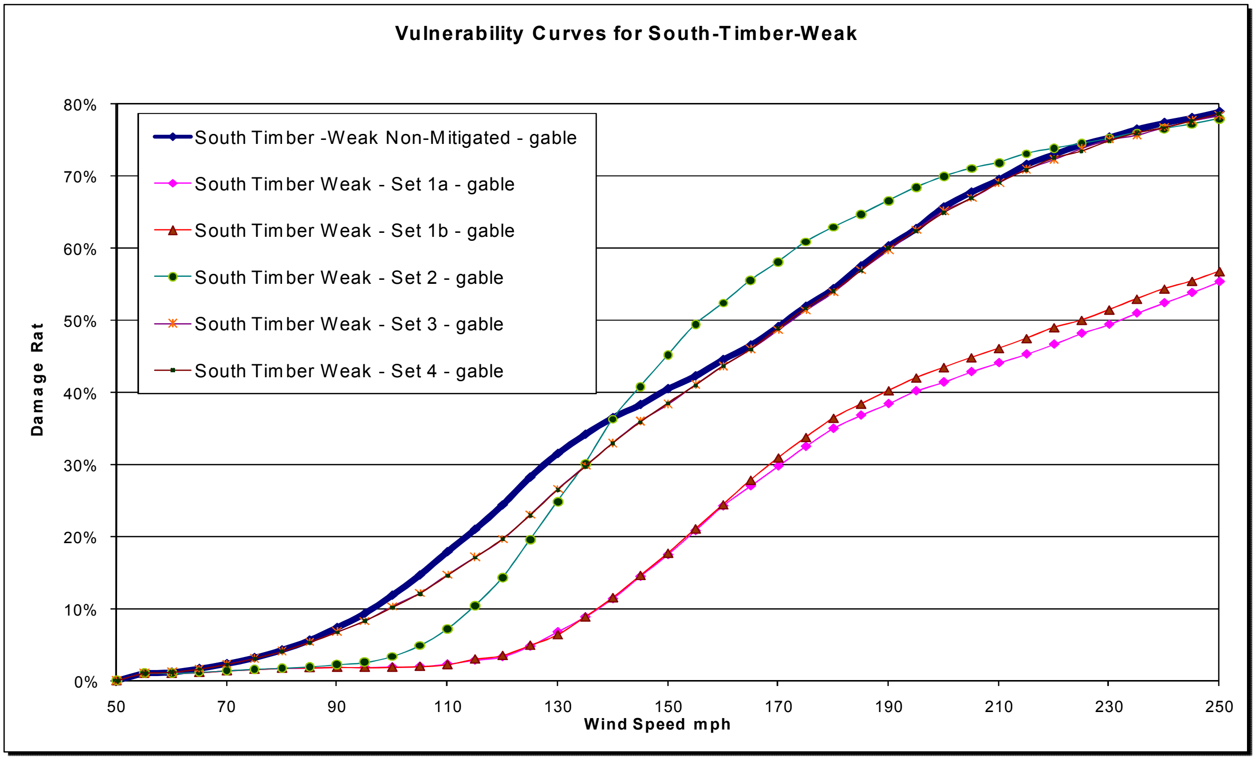

Figure 3: Vulnerability Curves for Weak-Timber-South

Figure 3 shows that as expected the "deluxe" mitigation sets 1a and 1b reduce substantially the vulnerability of the weak building. Set2, on the other hand produces mixed results. It is effective for low to moderate wind speeds up to 135 mph. For higher wind speeds, the set2 mitigation is counterproductive. The strengthened roof decking will result in higher forces on the roof to wall unmitigated toe nail connections. The result is an increased vulnerability at wind speeds higher than 135 mph. The vulnerability curves for sets 3 and 4 are basically identical and are superimposed. They do reduce the vulnerability at low to moderate wind speeds.

Figure 4 compares the vulnerabilities of the three unmitigated categories of timber home with gable roof (Weak, Medium, Strong) versus the mitigated weak homes with sets 1 and 2. As expected, the graph shows that weak mitigated homes with set1a and set1b are very similar to a strong home. On the other hand, the weak mitigated home with set # 2, i.e. with no retrofitting of the roof-to-wall connections and wall-to-sill connections, does not show any improvement at wind speed greater than 135 mph for the reason stated above.

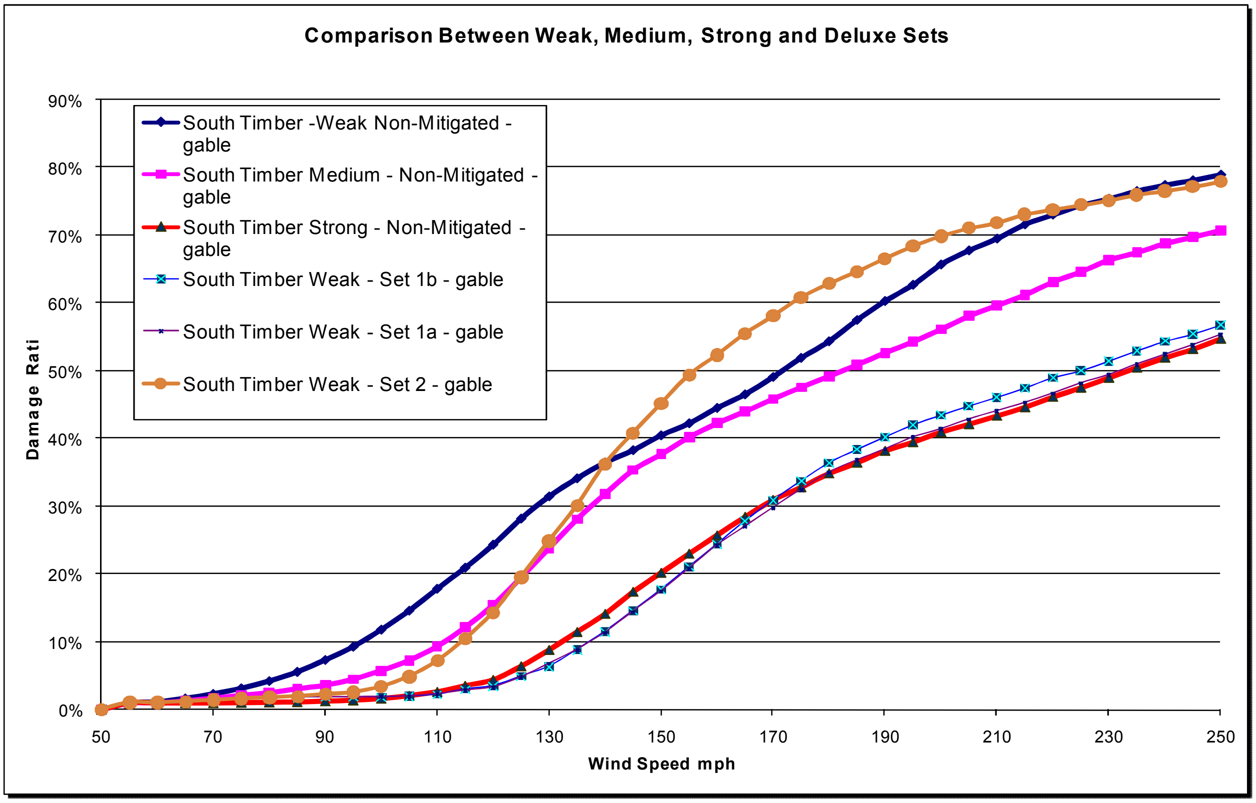

Figure 4: Sets 1 and 2 vulnerabilities compared to strong-medium-weak cases (timber-South).

COST BENEFIT ANALYSIS

The expected annual loss (EAL), defined as the average loss per year over a long period of time (i.e. 50,000 years), is calculated for different mitigated and unmitigated buildings. The EAL of a particular home is expressed as a percentage of the total home's value. Equation 3 shows that the difference between the unmitigated EAL and mitigated EAL defines the benefit of mitigation.

$$\text{Benefit} = \text{EAL}_{\text{Unmitigated Case}} - \text{EAL}_{\text{Mitigated Case}} \qquad (3)$$

The cost of mitigation, including implementation and maintenance, needs to be converted to an annuity. Cost estimation is not an exact science and certain uncertainty is involved in the process, such as the estimate of the interest rate, inflation rate, and other factors like life expectancy. To convert the mitigation implementation and maintenance costs into annual costs, engineering economy principles were employed. The team decided to use a life expectancy of 30 years for all components, with $500 maintenance cost at year 15 for replacing some shutters, etc. The rate of return was defined as the difference between the home equity line (or "2nd mortgage loan rate") and the inflation rate. The home equity line was estimated to be 8 %, based on data from several banks in Florida (e.g., Bank of America and Wachovia). The inflation rate was obtained from the U.S. Department of Labor. The resulting rate of return is 3.88% (8% - 4.22%). Equations 4, 5, 6 and 7 describe the conversion process of current and future costs into an annuity:

$$\text{Present value of maintenance} = \text{Value at year n} * \text{P/F} \qquad (4)$$

$$P/F = 1/((1+i)^n) \tag{5}$$

Where i = Rate of Return
n = year of occurrence

Having transformed all maintenance costs into one single present worth, the cost annuity is calculated by using the following engineering economy formula:

$$\text{Annual Equivalent Cost} = \text{Present value}_{\text{implementation+maintenance}} * A/P \tag{6}$$

$$A/P = (i(1+i)^n)/(((1+i)^n)-1) \tag{7}$$

The benefit over cost ratio of any particular mitigation can then be investigated for any zip code in the state of Florida, in an approach similar to the one adopted by Porter et al. [14], for seismic risk analyses. For the purpose of this analysis, the researchers generated a hypothetical portfolio containing an identical fixed set of modeled homes in each zip code of the state. The distribution of properties in this portfolio consists of the following:

- Masonry Weak Gable Home (constructed in 1970)
- Masonry Medium Gable Home (constructed in 1986)
- Masonry Strong Gable Home (constructed in 1998)
- Masonry Strong Hip Home (constructed after 2000)
- Timber Weak Gable Home (constructed in 1970)
- Timber Medium Gable Home (constructed in 1986)
- Timber Strong Gable Home (constructed in 1998)
- Timber Strong Hip Home (constructed after 2000)

The authors assigned a fixed value for each of the homes in the portfolio. For the purpose of this study, since the researchers at this stage are not concerned with insurance issues, all deductibles were set to $0 (no deductibles), and the insured limit for the building were set to be the same as the home value, with the insured limit for content set at 50% of the home value and the limit for ALE set at 20% of the value of the home [2].

RESULT AND DISCUSSION

Benefit/cost maps for the entire state of Florida, for all zip codes, resulted from this study. 22 maps were generated for different sets of mitigations for different strength categories of masonry and timber homes. These maps were classified into 8 groups based on their structural type and year of construction (year or construction correlates directly to strength category). Figures 3, 4, 5, 6 and 7 show these maps for the weak-timber model.

The maps presented here for weak-timber models, include only cases with braced garage door (mitigation measure G-2) and taped roof sheathing joints (mitigation measure A-2-3) for each set of mitigation (see Tables 2 and 3). Replacing the garage door and using other forms of underlayment would increase the cost of the mitigation.

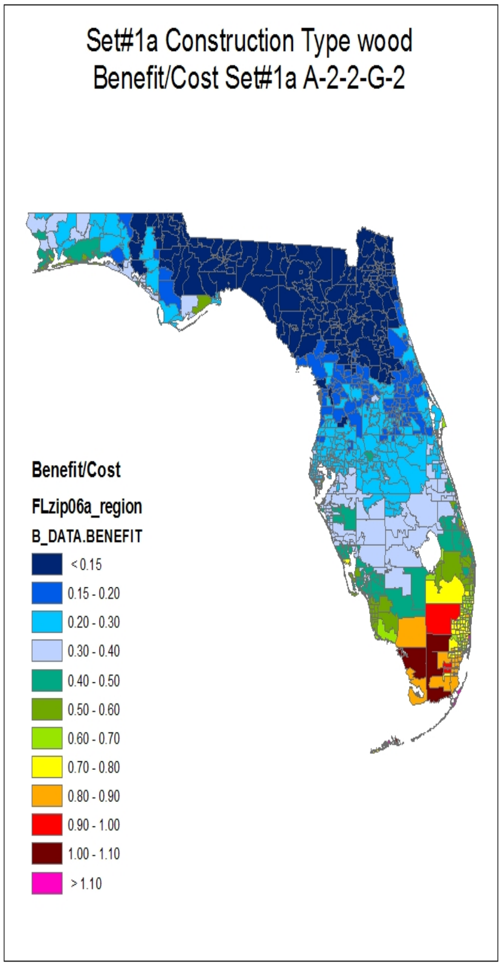

Figure 5: Benefit/Cost Map for Set1a. This set applies to the weak-timber structures and it includes: Shingle, Taping, Roof Decking and Bracing the Gable Ends, Roof-to-Wall Connections, Shutters, Wall-to-Sill Connections, and Bracing the Garage Door. The Keys are shown in pink.

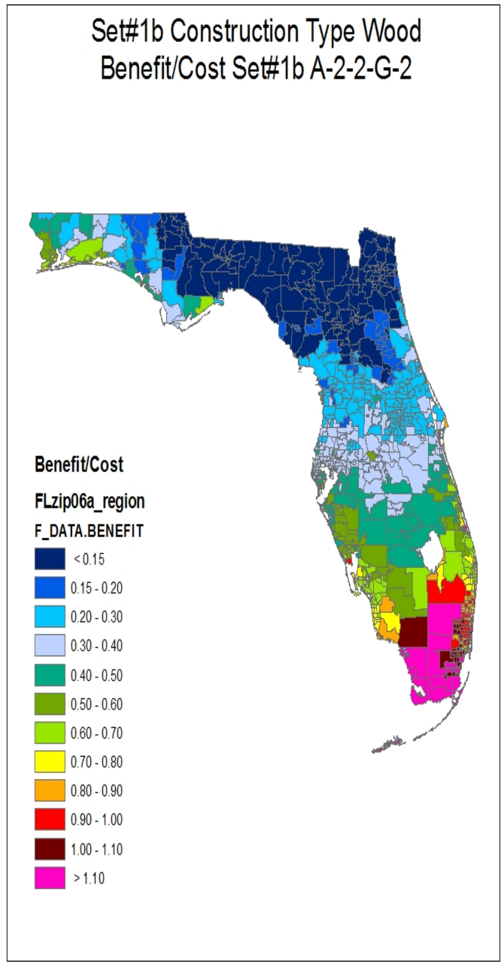

Figure 6: Benefit/Cost Map for Set1b. This set applies to the weak-timber structures and it includes all the measures from set1a except the Wall-to-Sill Connections. The Keys are shown in pink.

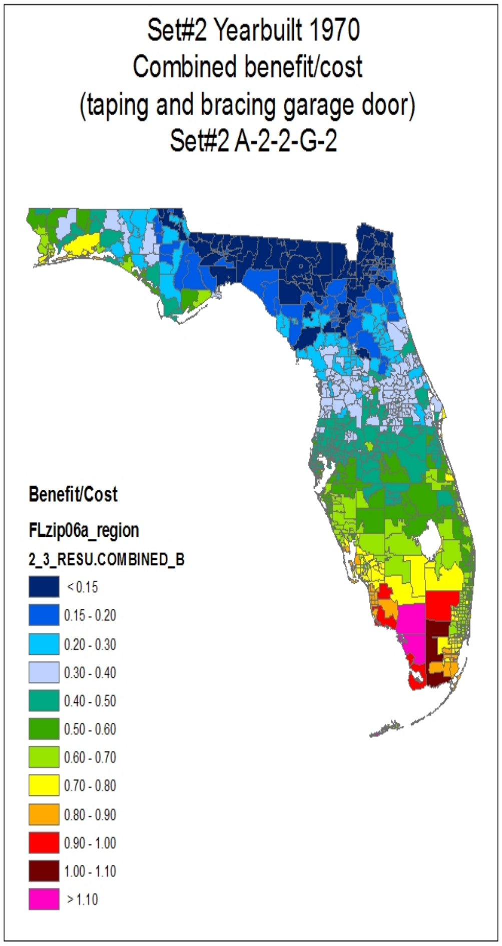

Figure 7: Benefit/Cost Map for Set2. This set applies to the weak-timber structure and includes: Shingle, Taping, Roof Decking and Bracing the Gable Ends, Shutters, and Bracing the Garage Door. The Keys are shown in brown.

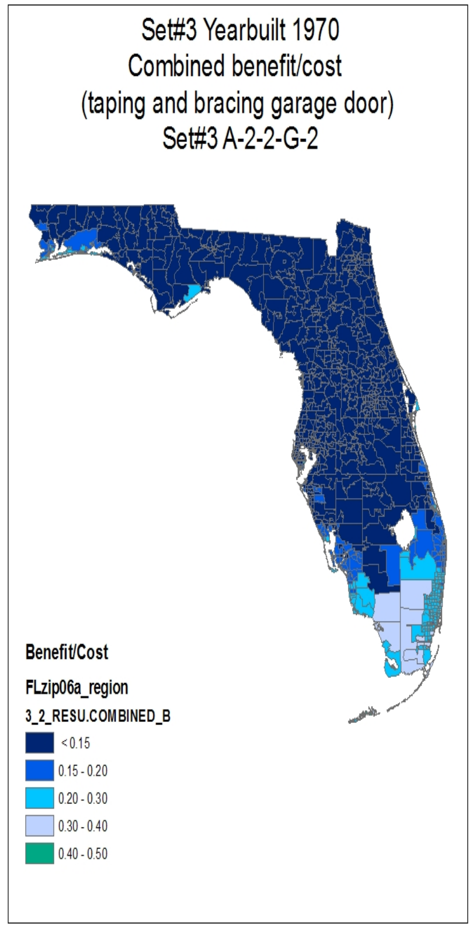

Figure 8: Benefit/Cost Map for Set3. This set applies to the weak-timber structure and includes: Shingle, Taping, Shutters, and Bracing the Garage Door. The Keys are shown in light blue.

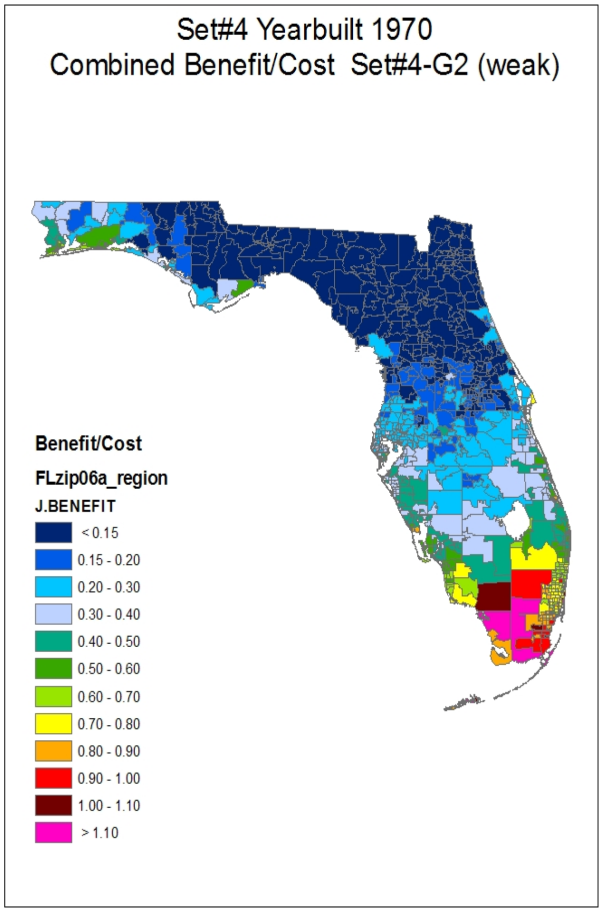

Figure 9: Benefit/Cost Map for Set4. This set applies to the weak-timber structure and includes: Shutters and Bracing the Garage Door. The Keys are shown in red.

The maps in figure 5 and 6 show that Set1b is more cost effective than Set1a in South Florida. None of the two sets appear to be cost effective in the rest of the State.

The maps in figure 6 and 7 also show that Set1b is more cost effective than Set2 in the south for counties like: Miami Dade, Monroe, Collier, and Broward. But Set#2 has a higher B/C than Set1b in the north and central regions, even if still lower than 1.

Set3 (figure 8) has the lowest B/C of all these sets and is never cost effective. The weak nailing sheathing to the trusses and the absence of gable bracing causes the sheathings to be blown away from the roof regardless of any improvement in roof cover. In other words, replacing the roof cover without re-nailing the sheathing and bracing the gable is a waste of resources.

Set4 (figure 9), the “do it yourself” mitigation which includes only shutters and mitigated garage door, has a B/C greater than one in the South. Its B/C is still lower than for Set1b and Set2, but it has a larger geographic area with B/C greater than 1, in the south region. The prevalence of

high wind velocities in the south region would reduce the benefit of Set2 in that region (see Set2 vulnerabilities in Figures 3 and 4). However , in the North and Central regions, where the wind speed are somewhat lower, Set2 exhibit higher B/C's than Set4, although they are never higher than 1 (for more details see [2]).
Table 5 shows the highest B/C for each set shown in the maps.

Table 4: Highest B/C for Timber-Weak-Model

Set	B/C	Zip Code	County
1a (only timber)	1.27	33109	Miami-Dade
1b (only timber)	1.66	33109	Miami-Dade
2	1.66	33001	Keys
3	0.41	33109	Miami-Dade
4	1.31	33109	Miami-Dade
Note: Mitigation is cost effective when B/C is greater than 1. The table indicates that Set1b has the highest B/C among all sets; set3 is never cost effective in any region.			

CONCLUSION

Vulnerability curves are an essential tool to evaluate potential losses due to hurricanes. They also provide a basis to compare the behavior of different mitigated homes subjected to hurricane winds. Different mitigation measures were studied and the cost of these mitigations, including materials and labor, were found to be an important parameter. All mitigation measures can increase the strength of a building and reduce the damage, provided that they are installed correctly and that the combination of mitigation measures is done according to standard practice and take into account the interaction between the different building components. For instance, reroofing a home should include re-nailing the sheathing and bracing the gable ends.
The B/C analysis for different sets indicates that the so-called "deluxe" Sets1a and 1b are the strongest mitigation sets for weak timber homes and reduce the damage more than all other sets, but they are cost effective only in parts of the South. The favorite set would be set 1b without retrofit of the wall to sill plate connection. Set2 is cheaper than sets 1a and 1b and compares favorably with set 1b in term of cost effectiveness. Set3 (reroofing without re-nailing the deck and bracing the gable) is not cost effective and should be avoided. This set is not recommended for any counties in the state of Florida. Set4 is a good alternative in the South. It is the cheapest of all the sets, with a B/C higher than 1 in a large part of the South.
Future studies could look at the effect of so-called "mitigation credits", i.e. reduction in insurance premiums, and possible tax credits. These could be considered as either reductions in costs or increases in benefits, and could substantially modify the distribution of B/C ratios.

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REFERENCES

[1] J.P. Pinelli, C. S. Subramanian, K. Gurley, S. Hamid, Validation of the Florida Public Hurricane Loss Projection Model, Florida Institute of Technology, University of Florida, Florida International University, Proceeding, ESREL 06, Estoril, Portugal, September 18-21

[2] B.B. Torkian, J.P. Pinelli, Cost Effectiveness of Mitigated Homes in Florida, Master's Thesis, Florida Institute of Technology, Melbourne, FL, Department of Civil Engineering, 2008

[3] J.P. Pinelli, E. Simiu, K. Gurley, C.S. Subramanian, L. Zhang, A. Cope, Filliben, Hurricane Damage Prediction Model for Residential Structures, Journal of Structural Engineering, ASCE, Vol. 130, No 11, pp 1685-1691

[4] J.P. Pinelli, C.S. Subramanian, F. Garcia, K. Gurley, A Study of Hurricane Mitigation Cost Effectiveness in Florida, Proceeding ESREL 2007, Stavanger, Norway, June 25-27

[5] D. Sambre, H. Khan, A. Tecle, G. T. Bitsuamalak, Assessing Effectiveness of Roof Secondary Water Barriers, Department of Civil and Environmental Engineering/International Hurricane Research Center, Florida International University, Miami, Florida 2008

[6] E. Sutt, Best of What's New 2006, Popular Science (2006)

[7] G. Breeze, J. Smith, Reduction of wind uplift loads on pitched roofs using retro-fit devices, EACWE4 , The Fourth European and African Conference on Wind Engineering, Prague, 11-15 July, 2005, Paper #303

[8] J.E. Crawford, K.B. Morrill, J.M. Magallanes, Y. Wu, Retrofit of Masonry Walls to Enhance their Blast Resistance, Proceedings, ASCE Structures 2008, Vancouver , CA

[9] Florida Building Commission and International Code Council, Florida Building Code 2007, http://www2.iccsafe.org/states/florida_codes/

[10] W.S. Daskam, D. C. Murray, Changing Laws, Changing Codes, and Changing Coverages

[11] J. Russell, Craftsman Book Company, Carlsbad, National Renovation & Insurance Repair Estimator, CA 2008

[12] RSMeans Residential Cost Data, 27th Annual Edition 2008

[13] RSMeans Square Foot Costs, 29th Annual Edition /Residential/ Commercial/ Industrial/ Institutional 2008

[14] Porter, K. Scawthorn, C. Beck, James, Cost-effectiveness of stronger wood frame buildings, Earthquake Spectra, v 22, n 1, February 2006, p 239 – 266