Performance of Light-frame Structures Subject to Extreme Wind Loads

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Hurricanes and tornadoes are dangerous meteorological phenomena that inflict an incredible level of damage to the built environment and can cause significant loss of human lives. In the United States, the tornadoes of 2011 and Hurricane Katrina in 2005 caused an economic loss of over $25 billion and $90 billion respectively. A substantial percentage of damaged buildings suffered the damage primarily due to lack of proper design for wind resistance. Despite the significant progress made in our ability to model and design buildings for extreme winds, there appears to be little improvement in the quality of construction of light frame structures. After suffering significant losses some states have adopted stricter building codes. This paper provides an overview of the various types of damages suffered by light-frame structures due to extreme wind loads in hurricane and tornado events. It also provides an overview of the economic benefit of mitigation measures.

Keywords: Wind engineering, Wind damage, Building codes, Hurricanes, Wood structures and Wind resistance

Introduction

Hurricanes and tornadoes are the two major meteorological phenomena that inflict severe economic losses in the United States on a regular basis. The U.S. experiences an average of 1200 tornadoes per year and two to three major hurricanes every three years. With the tornado season stretching from March to July and the hurricane season from June to November, the country is essentially endures a severe wind storm season for nine months in a year. In 2011, a total of 1,625 tornadoes occurred in the United States resulting in economic losses exceeding $25 billion and 534 fatalities. In 2005, Hurricane Katrina had a landfall on the Louisiana Gulf coast and caused over $96 billion of damage and 1,833 fatalities. The price tag from wind storms is escalating as more structures are built in vulnerable areas due to population increase. Building codes, lax enforcement of construction standards, prevailing construction practices have contributed to the high level of damage. Despite the significant progress made in our ability to model and design buildings for extreme winds, light-frame residential and low-rise commercial buildings continue to be built in the old ways. These type of structures constitute about 90% of the overall U.S. building stock and this explains the level of losses caused by tornadoes and hurricanes.

Hurricane Katrina was one of the strongest storms (Fig 1 and 2) to impact the coast of the United States during the last 100 years. It struck the Gulf Coast on August 29th, and within 48 hours eighty percent of the City of New Orleans was flooded, with some parts under 20 feet of water. With sustained winds during landfall of 140 mph – classifying it as a category 4 hurricane – and minimum central pressure the third lowest on record at landfall (920 mb), Katrina caused widespread devastation along the central Gulf Coast states of the US. The flooding, coupled with the storm surge, winds and wind driven rain completely destroyed or made uninhabitable over 300,000 homes in the Gulf Coast region. Katrina affected a 93,000 square mile area – equal to that of the United Kingdom – and led to the evacuation of over 1.1 million people and displacement of 770,000 people.

While the flooding and the storm surge inflicted extensive damage to the building stock in the Gulf Coast region, the high winds and wind driven rain caused considerable damage to structures that were outside the flood prone area. Post-storm assessment (1,2,3) of the wood frame residential structures in the coastal areas revealed that failure to construct in accordance with the...
prevailing building codes contributed to a significant portion of the structural damage that was witnessed.

**Damage to Wood Frame Residential Structures**

Residential wood frame structures suffer extensive damage in areas impacted by hurricanes and tornadoes. Even when the wind loads on these structures are at or below the design levels these structures suffer damage due to a one or more of the following: (a) lack of understanding on the part of the builders of load path in buildings and the construction details needed to provide adequate wind resistance to the buildings; (b) absence of design codes that ensure building integrity in extreme winds; and (c) failure to enforce the design codes in construction. The absence of the strict enforcement of the building code is regarded as the primary cause for the wind damage that was witnessed. The wind speeds away from the eye of the hurricane or the tornado are generally below levels required by the building codes and standards. These codes and standards provide a sufficient level of safety if they are adopted and properly enforced. The damage caused to light frame construction near a tornado path is shown in Fig 3 and 4. The impact of storm surge in a

![Fig. 1. Path of Hurricane Katrina.](image1)

![Fig. 2. NOAA's preliminary wind speed contours (in mph).](image2)

![Fig. 3. Complex before a tornado.](image3)

![Fig. 4. Complex after tornado strike.](image4)
hurricane can be observed in Fig 5 and 6. Proper elevated construction can mitigate damage due to wind driven storm surge. In most hurricanes it has been observed that structures located away from the coastline were damaged or destroyed due to serious construction flaws discussed below.

**Improper/Inadequate Roof Sheathing Attachment**

The failure to nail the roof sheathing to the rafters at the code specified spacing led to the breach of the building envelope (Fig 7, 8, 9, & 10) and subsequent damage by the water entering the

![Fig. 5. Before hurricane.](image)

![Fig. 6. After hurricane.](image)

![Fig. 7. Damage caused by loss of roof sheathing.](image)

![Fig. 8. Wind damage to roof](image)

![Fig. 9. Loss of roof sheathing and trusses.](image)

![Fig. 10. Loss of roof sheathing(Courtesy: APA).](image)
structure. The breach of the envelope essentially contributed to the gutting of the structure in many cases. The wood frame construction process requires inspection of critical aspects of the construction that did not appear to have been conducted for the failed structures. Proper fastening of the sheathing would have greatly reduced the wind damage to these structures.

**Inadequate Anchorage of Roof to Wall and Wall to Foundation**

The failure to provide a load path from the roof to the foundation has contributed to a large number of structural failures. The structures were essentially built as gravity load structures but not as wind resistant buildings. The lack of requirement of hurricane clips and straps to ensure that the structure is provided with a load path has been a primary reason for this construction failure. The collapse of the carport and the front porch, and the loss of roof in Fig 11, 12, 13 and 14 are caused by the lack of proper anchorage of the supporting elements to the foundation. It’s not uncommon to find columns in wood frame structures that are not anchored to the concrete foundation.

**Inadequate Nailing and Anchorage of Shear Walls**

A key lateral load-carrying component in wood frame structures is the shear wall. While most of these structures are provided with the corner sheathing panels – to serve as shearwalls – the sheathing is not attached to the studs with the required nail spacing and the shearwalls are not tied down to the foundation to provide the required uplift capacity. This is another case of the
failure of the local codes to require that these structures be built with the needed wind resistance. The adoption of the recommendations in the requirements Wood frame Construction Manual published by AF&PA (5) would have mitigated this damage.

Inadequate Wind Resistance of Roofing Material

The loss of roof shingles and the felt material covering the roof sheathing (Fig 9, 10, 11 & 12) was widespread in the residences that were damaged. The damage or loss of roofing provided paths for water ingress into buildings. Though there was no structural damage due to wind, the loss of shingles and the driving rain contributed to significant interior damage to the structure. It is critical that both the shingle installation and their design be capable of withstanding the design wind loads if significant loss has to be avoided. Improper installation of shingles – inadequate number of fasteners and nailing in wrong locations – was the primary cause for their failure.

Improper Anchorage of Gable End Walls

The loss of the gable end walls often triggered the complete collapse of one side of the wood-frame structures. The gable ends were very vulnerable to loss of sheathing when a breach occurred in the roof. Lack of proper anchorage of the gable end wall to the roof diaphragm led to a loss of the gable ends (Fig 15 and 16). The anchorage details were critical in ensuring the structure had adequate wind resistance.

Absence of Impact Resistant Glazing or Impact Resistant Coverings over Glazings

Even in structures that performed well under the extreme wind loads the damage was extensive due to significant breach of the building envelope cause by the loss of windows, patio doors, etc. Wind-borne debris caused a great deal of damage (Fig 17) to non-impact resistant window nearby and allowed wind driven rain to enter the building. The avoidance of this type of damage requires that the codes mandate the use of impact resistant glazing as have been done in Florida after Hurricane Andrew.

Inadequate Ties to Brick Veneer Walls and Unreinforced Block Walls

The lack of adequate ties for the brick veneer wall has resulted in the collapse of these non-structural elements of wood frame buildings and contributed to easy access of the rainwater to the
wood framing elements. The loss of brick veneer that is common in homes in the Gulf Coast region can contribute to significant damage and loss. The use of unreinforced block walls either as structural load carrying or non-structural exterior walls has resulted in significant damage (Fig 18 and 19) due to the failure to properly anchor and reinforce them as required by model codes. Code enforcement of stricter construction standards is essential to eliminate this type of loss.

**Status of Building Codes in the Gulf Coast Region**

At the time Katrina battered the Gulf Coast area, the states of Louisiana, Mississippi and Alabama had no statewide building code. This was unfortunate since these states needed it as much as the 32 other states that already had statewide model building code. Louisiana had a voluntary code. 

**Louisiana**

Until 2005, the Louisiana Legislature allowed any political subdivision of the state to adopt a building code of their choice. In flood prone areas, the parish and local governments had the authority to enforce the state Uniform Construction Code. The absence of a statewide building code enforcement is essential to eliminate this type of loss.
code modeled after the International Building Code (IBC) and the International Residential Code (IRC) was a major weakness. Lack of this adoption resulted in wood frame buildings being built without the wind resistance necessary in high wind prone regions. A consequence of this approach is the widespread damage to buildings witnessed during Hurricane Katrina.

Mississippi

This state has a patchwork system of no codes in some jurisdictions and minimum codes in others leaving the building stock vulnerable. It was one of the last states in the nation without a uniform building code. The lack of a uniform building code has spelled disaster for the buildings in the coastal parishes during Katrina.

Alabama

The state had a statewide code based on IBC but its jurisdiction was limited to state buildings, school buildings, hotels and movie theaters. The failure to adopt a uniform construction code for homes and business has led to a wide variation in the construction quality of these buildings and significantly increased their vulnerability. Attempts to adopt a statewide code for homes and businesses failed in the Legislature despite a couple of attempts.

As discussed above, these Gulf States, by their failure to adopt uniform building codes essentially poised them to be clobbered by Hurricane Katrina and inflict an enormous economic loss on the nation and the region.

Actions Taken by Impacted States

After experiencing the devastating effects of Katrina there was a push for stricter codes from the insurance and mortgage banking industry, government agencies, builders and the academic/research community. The various state legislatures and governors responded to the urgent need and implemented changes. The following sections discuss the changes that occurred in the three impacted states post-Katrina.

Louisiana

Within four months after Katrina landfall, the state adopted legislation that required the eleven hardest hit parishes to immediately enforce the wind provision of the IBC and IRC for homes and businesses. The design wind speed ranges from 130 mph to 150 mph depending on the location of the property in these parishes. In addition the Louisiana Legislature mandated the use of nationally recognized codes and standards as the state’s Uniform Construction Code. The code includes identified parts of the International Building Code and International Residential Code. The legislation also created the Louisiana State Uniform Construction Code Council to carry out the following functions:

- Review and adopt the state’s Uniform Construction Code;
- Provide training of code officials;
- Provide amendments to the code;
- Establish the requirements and process for certification and continuing education of code enforcement and building officials, and inspectors.

The initial code adopted by the Louisiana State Uniform Construction Code Council became effective on January 1, 2007. The Council enforced only portions of the building code dealing with wind resistance.
Mississippi

In 2006 the state passed legislation requiring adoption of nationally recognized building and residential codes in the five coastal counties. The import of the legislation is the requirement that the counties adopt the 2003 IRC. The legislation also requires that modern wind provisions be applied to new and significantly renovated homes in the coastal and southern counties. Old codes are required to be updated to the state code in 2010. One weakness in the legislation is that areas that were not enforcing codes in the past can continue to not enforce the state codes. This was perhaps done to avoid hardship on rural communities without the resources to enforce the state code. The Mississippi Legislature now allows the gaming portions of the Gulf Coast casinos to be built on land within 800 feet of the high water line and this permits them to be located a significant distance away from the coast.

Alabama

Though the state hasn’t adopted a statewide building code, many coastal jurisdictions have updated to the modern building codes. The continued lack of progress in adopting a statewide building code is unfortunate but attempts continue to be made in the state Legislature to bring about this change.

Key Mitigation Measures

Four key mitigation strategies have been incorporated in the Dade County South Florida Building Code and they have been found to be very effective in enhancing the performance of residential buildings in hurricane events. They are described below:

- Protection of Building Openings
  Since windows and doors are the weak spots in wall envelope, requiring impact resistant windows and doors or debris impact protective coverings (shutters) would prevent most window and door failures. Protecting the wall envelope would help keep the wind and rain out of the building and mitigate damage to the structure and its contents.

- Improved Roof Sheathing Attachment
  Better attachment of the roof sheathing to roof framing by use of appropriate fasteners at closer spacing helps prevent the sheathing from being blown off by the wind. This measure reduces progressive failures and water penetration into the building envelope.

- Improved Roof-Wall Connections
  Installation of metal “hurricane clips” or “hurricane straps” provides a continuous load path from the roof to the foundation and helps prevent catastrophic roof uplift failures.

- Secondary Waterproofing to Roof Joints
  Sealing the joints between the roof sheathing provides a second line of defense against roof leaks when the roof coverings are damaged or destroyed.

Effectiveness of Mitigation Measures

In a study (1) conducted by the Hurricane Center at Louisiana State University to evaluate the effective of the four of the abovementioned mitigation measures in a hypothetical Katrina-West track – that would inflict significantly more damage to residential buildings than the actual Katrina even – reported significant reduction in damage to residential buildings when the mitigation measures were implemented. The results of the investigation are summarized in the below.

In the hypothetical Katrina-West track study, 100 percent implementation of only the “Protection for Building Openings” mitigation measure resulted in the damage figures presented in Table 1. It’s quite clear that even if Katrina had taken a high impact west track the implementation
The performance of light-frame structures subject to extreme wind loads was analyzed in the context of Hurricane Katrina. A key finding was that protection of building openings would have significantly reduced the overall loss by 45 percent as compared to the lower impact east track that Katrina actually took.

The damage figures stemming from a 100% implementation of only the “Improved Roof Sheathing Attachment” mitigation measure are presented in Table 2. Improving the sheathing attachment reduced the damage loss by 20% which is significantly lower than that obtained from protecting the building. It’s pertinent to point out that the implementation of this second measure is considerably lower in cost and offers smaller loss reduction.

Implementation of only the “Improved Roof-Wall Connections” mitigation measure resulted in the damage figures presented in Table 3. This mitigation measure offers the smallest loss reduction benefit and has the least cost for implementation.

Table 1. Hurricane Katrina Mitigation Analysis Results – 100% Implementation of Opening Protection for Residential Buildings

<table>
<thead>
<tr>
<th>Reporting Item</th>
<th>Katrina Estimate Damaged Building Count</th>
<th>Damage Estimate with Opening Protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Damage</td>
<td>153,250</td>
<td>159,304</td>
</tr>
<tr>
<td>Moderate Damage</td>
<td>75,227</td>
<td>69,911</td>
</tr>
<tr>
<td>Severe Damage</td>
<td>24,604</td>
<td>14,234</td>
</tr>
<tr>
<td>Destruction</td>
<td>20,402</td>
<td>4,342</td>
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<tr>
<td>Total Buildings Affected</td>
<td>273,483</td>
<td>247,791</td>
</tr>
<tr>
<td>Building and Content Loss (Billions)</td>
<td>$10.0</td>
<td>$5.5</td>
</tr>
<tr>
<td>Percentage Reduction from Katrina Estimate</td>
<td>-</td>
<td>45%</td>
</tr>
</tbody>
</table>

Table 2. Hurricane Katrina Mitigation Analysis Results – 100% Implementation of Improved Sheathing Attachment for Residential Buildings

<table>
<thead>
<tr>
<th>Reporting Item</th>
<th>Katrina Estimate Damaged Building Count</th>
<th>Damage Estimate with Roof Sheathing Attachment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Damage</td>
<td>153,250</td>
<td>109,787</td>
</tr>
<tr>
<td>Moderate Damage</td>
<td>75,227</td>
<td>44,429</td>
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<tr>
<td>Severe Damage</td>
<td>24,604</td>
<td>17,778</td>
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<tr>
<td>Destruction</td>
<td>20,402</td>
<td>18,474</td>
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<tr>
<td>Total Buildings Affected</td>
<td>273,483</td>
<td>190,468</td>
</tr>
<tr>
<td>Building and Content Loss (Billions)</td>
<td>$10.0</td>
<td>$8.0</td>
</tr>
<tr>
<td>Percentage Reduction from Katrina Estimate</td>
<td>-</td>
<td>20%</td>
</tr>
</tbody>
</table>

Table 3. Hurricane Katrina Mitigation Analysis Results – 100% Implementation of Improved Roof-Wall Connections for Residential Buildings

<table>
<thead>
<tr>
<th>Reporting Item</th>
<th>Katrina Estimate Damaged Building Count</th>
<th>Damage Estimate with Improved Roof-Wall Connections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Damage</td>
<td>153,250</td>
<td>153,250</td>
</tr>
<tr>
<td>Moderate Damage</td>
<td>75,227</td>
<td>78,252</td>
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<tr>
<td>Severe Damage</td>
<td>24,604</td>
<td>27,718</td>
</tr>
<tr>
<td>Destruction</td>
<td>20,402</td>
<td>13,029</td>
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<tr>
<td>Total Buildings Affected</td>
<td>273,483</td>
<td>273,485</td>
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<tr>
<td>Building and Content Loss (Billions)</td>
<td>$10.0</td>
<td>$8.9</td>
</tr>
<tr>
<td>Percentage Reduction from Katrina Estimate</td>
<td>-</td>
<td>11%</td>
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</table>
It was found that the implementation of the fourth mitigation measure “Secondary Waterproofing to Roof Joints” offered a reduction in loss that was the same as that obtained from the third mitigation measure.

When all the four mitigation measures discussed earlier were implemented, then the damage figures were very encouraging and are presented in Table 4 above.

It’s evident that the implementation of all the four measures contributes to a very significant reduction in loss. This clearly demonstrates the economic benefit from enforcing better construction standards in the hurricane prone Gulf Coast area.

**Issues and Challenges**

The actions taken by the various states will have a significant impact on the quality of construction and the wind resistance of residential buildings built along the Gulf Coast. However, the three Gulf Coast states discussed in the earlier sections face numerous issues / challenges listed below:

- Ensuring there are enough engineers to work with the thousands of homebuilders on mandatory residential code changes.
- Ineffectiveness of even the best codes and standards in the absence of strict enforcement.
- Need for compliance mechanisms.
- Critical need for licensing roofing contractors.
- Field inspection programs to monitor roofs under construction.
- Continuing education of roofing contractors.

Without an aggressive effort to address the above listed issues the Gulf States will find it difficult to mitigate building damage in future hurricanes. The three Gulf States discussed in this paper get 50 percent of all the flood insurance payouts in the country though they have only four percent of the nation’s population. While there appears to be no limit on stupidity in the flood insurance plan, the same appears to be true, until recently, in the area of building construction codes in the Gulf Coast region. Not enforcing strict building code standards is not tenable since the nation cannot continue to bear the enormous cost of providing relief to those impacted by the hurricanes – that are occurring with increasing intensity and frequency – primarily because of an avoidable destruction to residential buildings.

**Conclusions**

- The absence of statewide building codes – in some states – modeled after the International Building Code and International Residential Code has had a disastrous consequence on residential buildings.

<table>
<thead>
<tr>
<th>Reporting Item</th>
<th>Katrina Estimate Damaged Building Count</th>
<th>Damage Estimate with All Four Mitigation Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Damage</td>
<td>153,250</td>
<td>113,938</td>
</tr>
<tr>
<td>Moderate Damage</td>
<td>75,227</td>
<td>29,959</td>
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<td>Severe Damage</td>
<td>24,604</td>
<td>3,451</td>
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<td>Destruction</td>
<td>20,402</td>
<td>1,985</td>
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<tr>
<td>Total Buildings Affected</td>
<td>273,483</td>
<td>149,334</td>
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<tr>
<td>Building and Content Loss (Billions)</td>
<td>$10.0</td>
<td>$2.1</td>
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<tr>
<td>Percentage Reduction from Katrina Estimate</td>
<td>-</td>
<td>79%</td>
</tr>
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</table>
After Katrina the various impacted states in the Gulf Coast area responded to the need for stricter building codes and put into place building construction standards that improve the wind resistance of buildings. However some of the states have yet to implement statewide building standards even nearly 6 years after Katrina.

While significant damage to residential buildings was caused by flooding and storm surge in hurricane events there were a large number of buildings that were damaged/destroyed due to the lack of wind resistance in design and poor construction standards.

The various causes for the building damage included: (i) inadequate roof sheathing attachment; (ii) inadequate roof to wall and wall to foundation connections; (iii) inadequate nailing and anchorage of shearwalls; (iv) inadequate wind resistance of roofing material; (v) improper anchorage of gable end walls; (vi) absence of impact resistance glazing or covering over glazing; and (vii) inadequate ties to brick/block veneer walls. All these damages were avoidable with proper building codes and standards.

The four key damage mitigation measures discussed in the paper offer a significant reduction – nearly 80% – in loss to buildings and contents. Implementation of these sensible mitigation measures must be made mandatory in the Gulf Coast region.

The key to hurricane damage reduction is the enforcement of the building codes and standards. There is serious concern about the ability of the states to enforce the codes that they have adopted. The best codes and standards are not useful in the absence of enforcement.

Strategies need to be developed to impart better continuing education to both builders and roofing contractors, and to license roofing contractors.

There is an urgent research need to develop the next generation building envelope construction systems that are very effective in preventing water ingress into buildings.

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