

Performance of Wood-Frame Structures during Hurricane Katrina

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Abstract: The costliest natural disaster in U.S. history was Hurricane Katrina, which made landfall on August 29, 2005 at 7:10 a.m. EDT (6:10 CDT, local time) in Plaquemines Parish, La. Tragically, Katrina caused widespread damage and loss of life but also provided an opportunity to collect data on wood-frame construction which will be useful for design engineers and building code officials in order to design safer and stronger buildings in the future. The objective of this study was to gather and process perishable wind damage data on residential wood-frame structures in nonflooded regions of Mississippi that can be used by the research and design code development community to improve the performance of wood-frame structures to strong wind loading. This study consisted of 3 days of data acquisition of wind damage to wood-frame structures along the U.S. Gulf Coast and was funded by the National Science Foundation. A total of 27 case studies, ranging from entire subdivisions to individual wood-frame structures, were examined in detail. This paper presents both general and specific observations during data reconnaissance. It was generally found that most residential wood-frame construction in the regions inspected are built using conventional construction practices, when engineered or prescriptive construction should be used. The paper is divided into (1) structural; (2) nonstructural; and (3) general observations.

DOI: 10.1061/(ASCE)0887-3828(2007)21:2(108)

CE Database subject headings: Framed structures; Wood structures; Hurricanes; Damage; Gulf of Mexico.

Introduction

The data reconnaissance consisted of 3 days of data acquisition of wind damaged wood-frame structures along the U.S. Mississippi Gulf Coast. A total of 27 case studies, shown in Table 1, ranging from entire subdivisions to individual wood-frame structures were examined in detail by the team. Significant wind damage was observed for many additional wood-frame structures that are not specifically discussed because the failure mechanisms were not believed to be different than those presented herein. Figure 1 shows a satellite image of Hurricane Katrina when it was a Category 5 hurricane in the Gulf of Mexico. However, by the time it made landfall in Louisiana it had been downgraded to a Category

3 storm. Figure 2 presents two geographical information system maps with Hurricane Katrina's NOAA-estimated wind speeds, major roadways, city locations, and the location of each structure examined. The top panel shows the wood-frame damage study area and the bottom panel shows the case study locations in more details with associated ground level wind speeds. More information is available on the project web page at: <http://www.engr.colostate.edu/~jwv/hurricane-Katrina-woodframe> including multiple photographs and detailed descriptions for each case study.

Background on Hurricane Damage in the United States

Billions of dollars are spent annually in the United States to repair damage related to wind, which underscores the importance of learning from disasters such as Hurricane Katrina through data reconnaissance. Although the majority of the devastation and loss of life during and after Hurricane Katrina was due to surge and flooding, these mechanisms are ultimately caused by wind (and pressure) driving an increase in the ocean level. Hurricane Katrina was by far the most costly hurricane (and disaster) in U.S. history. Published records of hurricanes striking the contiguous United States are from 1851 through 2004 (Blake et al. 2005; Jarrell et al. 2001). The data for the 2005 hurricane season was compiled by the writers and added to the data developed by Blake et al. (2005).

Fig. 3 presents a map of the United States showing both the total number of hurricanes per state and the percentage of storms in each category in the form of a pie chart. In summary, there are 19 states that have had one or more hurricanes cross state boundaries over the last 155 years. It should be noted that hurricanes typically travel through several states and always weaken as they

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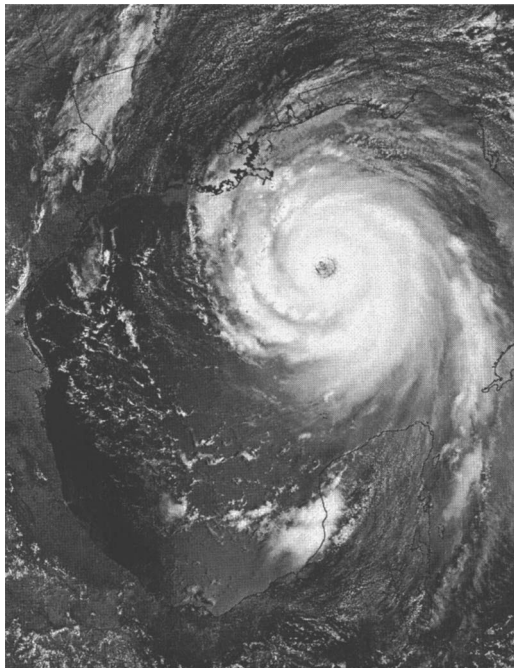
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Note. Discussion open until September 1, 2007. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on January 30, 2006; approved on June 20, 2006. This paper is part of the *Journal of Performance of Constructed Facilities*, Vol. 21, No. 2, April 1, 2007. ©ASCE, ISSN 0887-3828/2007/2-108-116/\$25.00.

Table 1. Case Studies Investigated during the Course of This Study

Structure identification number	Structure name/note	Latitude	Longitude	Date examined	Time examined (CDT—local time)
1	HWY 49 porch collapse	30.822	89.137	September 23, 2005	12:58 p.m.
2	CMU building lost second roof	30.782	89.138	September 23, 2005	1:40 p.m.
3	Porch collapse	30.708	89.134	September 23, 2005	1:51 p.m.
4	Convenience store collapse	30.498	89.106	September 23, 2005	2:30 p.m.
5	Flooded apartment complex	30.399	89.043	September 23, 2005	3:42 p.m.
6	Yellow garage—door blown in	30.445	89.090	September 23, 2005	5:38 p.m.
7	Two-car garage—center support blew in	30.444	89.088	September 23, 2005	6:07 p.m.
8	Panel loss newer neighborhood	30.446	89.084	September 23, 2005	6:40 p.m.
9	Corner roof uplift	30.446	89.084	September 24, 2005	8:47 a.m.
10	Front porch post shift	30.446	89.084	September 24, 2005	8:59 a.m.
11	Gable vent blown in	30.456	89.082	September 24, 2005	9:10 a.m.
12	Newer subdivision—garage door blown in	30.457	89.073	September 24, 2005	9:33 a.m.
13	Windsong neighborhood	30.465	89.068	September 24, 2005	10:03 a.m.
14	Newer subdivision—south of Windsong	30.461	89.073	September 24, 2005	10:22 a.m.
15	Diamond Head—condo roof loss	30.385	89.363	September 24, 2005	11:48 a.m.
16	Newer subdivision—storm surge in places	30.451	89.024	September 24, 2005	1:53 p.m.
17	Brighton Place—new subdivision	30.416	89.031	September 24, 2005	2:30 p.m.
18	Plantation—three-story apartment complex	30.405	89.004	September 24, 2005	3:00 p.m.
19	Thomasville Apartments—brick veneer loss	30.401	89.002	September 24, 2005	3:04 p.m.
20	CMU commercial structure—complete wall failure	30.401	88.979	September 24, 2005	3:48 p.m.
21	New construction south of Back Bay of Biloxi	30.413	88.970	September 24, 2005	4:29 p.m.
22	Tire Kingdom	30.458	88.893	September 25, 2005	8:10 a.m.
23	Cypress Points	30.450	89.137	September 25, 2005	9:12 a.m.
24	Crystal Lake	30.451	89.138	September 25, 2005	9:55 a.m.
25	Lake Village Estates	30.468	89.164	September 25, 2005	10:30 a.m.
26	Two-story ranch	30.460	89.316	September 25, 2005	11:16 a.m.
27	Small detached garage	30.450	89.321	September 25, 2005	11:20 a.m.

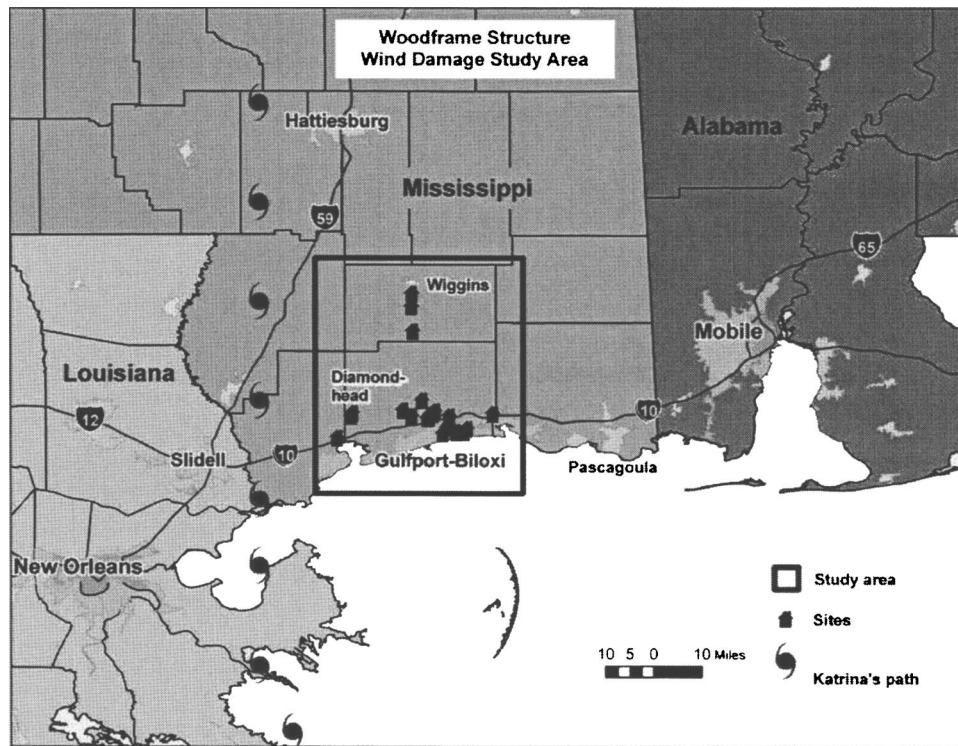
**Fig. 1.** Satellite image of Hurricane Katrina when it was still a Category 5 storm in the Gulf of Mexico (NASA n.d.)

move inland. Therefore, the data presented in Fig. 3 are the number and severity of hurricane occurrences per state and not the total number of individual hurricanes. In fact, there are 415 entries in Fig. 3, but only 273 hurricanes have made landfall over the past 155 years including the 2005 hurricane season.

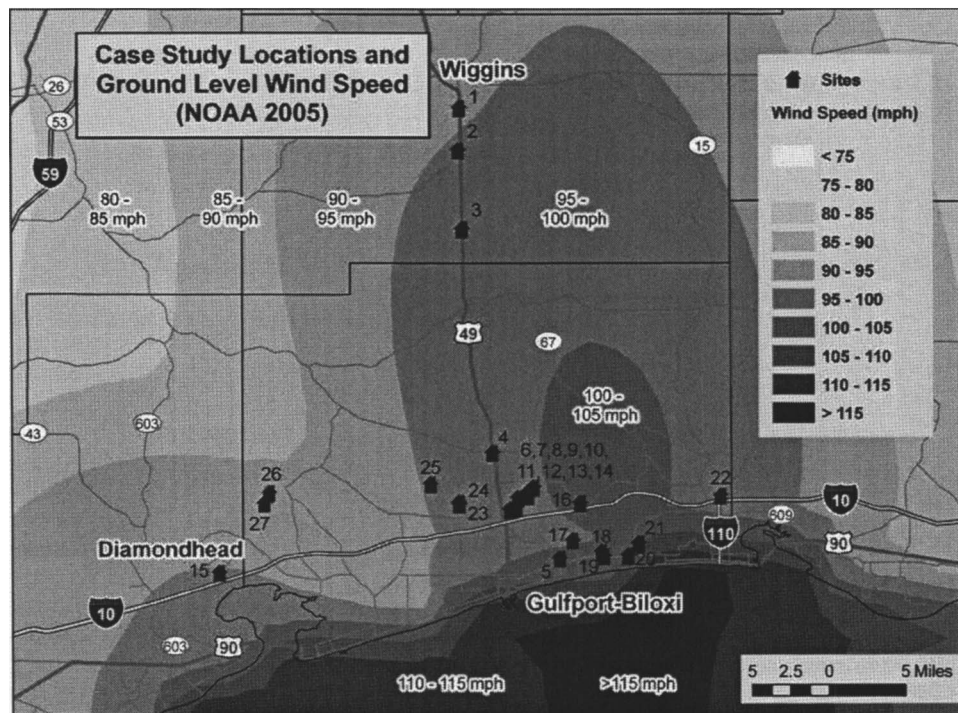
Only Florida, Louisiana, and Mississippi have experienced at least one Category 5 storm over this time period. Florida has experienced the most hurricanes during this period at 113 hurricanes giving that state an annualized occurrence rate of approximately 0.73. Texas and Louisiana have experienced the second and third most occurrences at 59 and 49, respectively. The state of Mississippi has experienced only 15 hurricanes (not including rainfall and tropical storm winds from nearby hurricanes) over the last 155 years resulting in an annualized occurrence rate of less than 0.1. Interestingly, 6 out of every 10 storms that have entered Mississippi are Category 3 or higher. This higher occurrence percentage of strong storms is, by far, the highest for all states in the United States.

Construction Methods

Prior to discussing observations made on damaged wood-frame structures along the Mississippi Gulf Coast, the reader is asked to consider three types of construction methods prevalent in the



(a)



(b)

Fig. 2. Locator map and estimated ground level wind speeds produced by Hurricane Katrina along with locations of structures investigated in this study (data adapted from NOAA 2005)

wood-frame industry, particularly residential construction. The following descriptions of variation in construction type are suggested by the writers.

Conventional Construction

Conventional construction includes the majority of residential construction and in general consists of following a document such

as the International Residential Code. For example, in the conventional construction method, wall bracing materials can range from fiberboard panels, to wood structural panels, or even gypsum wall board (APA 2005). In general, these braced wall panels occur at each end of each wall line and are spaced approximately 7.6 m (25 ft) on-center. The International Residential Code (IRC 2003) outlines certain exceptions and limitations, and in “higher

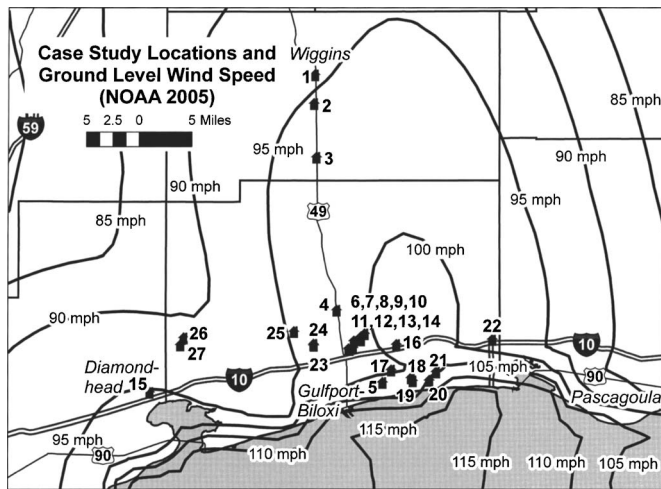


Fig. 3. Number of hurricanes, the states they affected, and their category (1851–2005)

risk” situations requires that braced wall panels be spaced closer than 7.6 m (25 ft). Braced wall panels used in conventional construction practices do not usually have hold downs.

Engineered Construction

For engineered construction, the structures are specifically designed by a design professional to meet jurisdictional requirements. An example of engineered construction is the specification of using hold downs for shearwalls at either end of each full-height wall segment (this is known as the segmented approach) or at the end of the wall lines (this is known as the perforated shear-wall approach). In general, these shear walls are sheathed with wood structural panels, i.e., plywood and/or oriented strand board (OSB). It has been the writers’ observation that few residential structures outside of the West Coast seismic regions and perhaps high wind regions in parts of Florida are engineered.

Prescriptive Construction

This type of construction is essentially the same as engineered construction, but rather than beginning at the basic mechanics/material strength level, tabulated values (e.g., from the *Wood Frame Construction Manual*) are typically used. Bolt spacing, tie down spacing, and nailing schedule, etc., are all based on tabulated values.

It should be noted that the previous descriptions of construc-



Fig. 4. Porch overhang collapse due to lack of anchorage for support column/post



Fig. 5. Carport collapsed and structure breeched

tion practices are used within the wood-frame industry and are provided as general terminology for the unfamiliar reader and are not clear-cut definitions without exceptions.

Observations during Reconnaissance Trip

Structural Observations

Observation No. 1—Lack of Uplift Load Path

In the design of structures for wind loading (see ASCE 2005, for a detailed explanation) it is necessary to provide a continuous load path from the roof down to the foundation. In a noticeable number of structures examined, this continuous load path was not present. Fig. 4 shows a photograph of Case Study 7, which was a single-family dwelling with brick veneer whose wood support columns under the porch overhang were not anchored to the concrete. Presumably, the overhang had been built to resist gravity loads and was able to resist moderate winds due to its self (dead) weight. However, with the wind gusts associated with Hurricane Katrina the porch uplifted, the column was blown out, and then the overhang collapsed due to lack of support. Fig. 4 also shows the results of not anchoring the sill plate to the foundation. The wall pier between the two single car garage doors was not anchored, and as a result the bottom pushed inward in excess of 0.3 m (12 in.), nearly causing collapse of that portion of the structure.

In many cases the porch roof diaphragm is framed back into the roof system, thus failure of the porch overhang resulted in a significant breach of the structural envelope and subsequent water



Fig. 6. Wood to concrete connection at base of porch overhang support post



Fig. 7. Loss of CMU wall that was not properly connected to the structure

damage from numerous inches of wind-driven rain resulted. It also allowed the attic areas to become internally pressurized, further adding to damage.

The same type of failure was seen in carports, whose support columns/posts were not properly anchored to the concrete. Fig. 5 shows an example of this type of failure for a carport. This type of failure was not seen when wood to concrete hold downs were used at the base of support posts. The correct use of this type of connector is shown pictured in Fig. 6. The aesthetic vinyl wrap was peeled off but the support post, and subsequently the porch overhang and roof, remained intact.

A lack of wind load path was observed in many cases during the site visits. This was observed, specifically in Case Studies 1, 3, 7, 10, 16, 19, and 20. Full details of each of these case studies are available on the project web page at <http://www.engr.colostate.edu/~jvw/hurricane-Katrina-woodframe.htm>.

Fig. 7 shows a photograph of an unreinforced masonry wall (CMU) (Case Study 20) located next to a light commercial wood-frame building. The CMU wall was essentially free standing as it was only connected to the structure by light gauge flashing along the gable roof line. Fig. 8 shows a photograph of a similar situation (Case Study 19) where the brick veneer on a wood-frame apartment building was lost. This may have been the result of a parapet detail which allowed pressurization.

Observation No. 2—Loss of Roof Sheathing at Corners

The perimeters, including corners, of roofs typically experience the highest uplift pressure during wind storms. Loss of roof sheathing was observed at the perimeters and corners in numerous cases. It was also observed that when roof sheathing was lost it was not attached with the current code minimum nail spacing of 160 mm (6 in.) on-center for the perimeter and 320 mm (12 in.)



Fig. 8. Loss of brick veneer due to lack of anchorage



Fig. 9. Roof sheathing damage; a heavier nailing schedule may help protect against this type of damage

on-center in the field. Figs. 9 and 10 (Case Study 9) show typical roof sheathing loss as a result of Hurricane Katrina winds. Using nail spacing that meets the code minimum would have most likely reduced loss of sheathing in the Mississippi Gulf Coast region.

Observation No. 3—Gable End Wall Loss

A common failure that was observed was the loss of sheathing on the gable end walls, as shown in Figs. 10 (Case Study 23) and 11 (Case Study 25). There are two possible causes: The vinyl siding was lost, and the wind caused failure of the foam sheathing, or air entered through attic vents or other means and pressurized the attic dislodging one or more sections of nonstructural sheathing. The latter of these may have resulted in the breach of the building envelope that allowed wind driven rainwater to enter the building causing significant damage. The rainwater saturated the ceiling insulation resulting in the failure of the gypsum/drywall ceiling.



Fig. 10. Loss of nonstructural sheathing at the gable end wall



Fig. 11. Loss of gable end wall, roof shingles and sheathing, and garage door (note the debris bags to the left of the driveway)

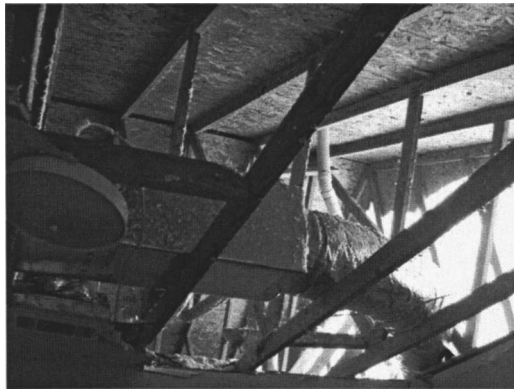


Fig. 12. Second floor bedroom that was very badly damaged due to the loss of nonstructural sheathing on the gable end wall

Fig. 12 shows a photograph from inside a second floor bedroom of the house in Fig. 10. The structures shown in these photographs had been severely damaged by rain water and were in the process of being renovated. According to one homeowner, the repair estimate was equal to the cost of the home when it was built in 1999.

Observation No. 4—Use of Conventional Construction in High Wind Region

Recall the brief description of the three types of construction practices commonly associated with wood-frame construction. It was observed that most or all of the construction in this region is based on conventional construction which does not require any engineering calculations. An example of this is shown in Fig. 13 (Case Study 21) where 1.22 m (4 ft) wide braced panels were placed at the ends of a 7.62 m (25 ft) exterior wall without any hold downs to resist lateral (e.g., wind) forces. It should be noted that ASCE-7 (2005) shows this region having a design wind speed of 130–140 mi/h (209–225 kph). These high winds would result in these areas falling out of the scope of conventional building code provisions such as the International Residential Code, thus the need for engineered construction including possibly the use of hold downs. This results in engineering calculation for the



Fig. 13. Braced-wall panels (prescriptive) at the ends of an exterior wall in a region having a design wind speed of 130–140 mph



Fig. 14. Condominium roof, retrofitted onto the original flat roof, failed after approximately 4 h of wind gusting

width of shear wall (in place of braced panel) along with nailing and anchoring requirements. As an alternative to detailed calculations, these structures could have been built following the *Wood-Frame Construction Manual* (AF&PA/AWC 1995) which is a prescriptive code but is based on engineered loads and load paths. Yet another alternative would be the use of the engineered wood code (NDS (ANSI/AF&PA) 2005) which requires engineering calculations. If the wall in Fig. 13 was designed using engineered code or calculations, the shear walls at the ends of the wall may have been more than four feet long with stricter nailing requirements and hold-downs at the ends of the shear walls. It appears that inspectors and builders seem to be familiar with conventional construction in this region but there were multiple cases where homes should not fall under this provision.

Observation No. 5—Details Were Key

It was observed that seemingly small details that were not addressed, such as a lack of nails in hurricane clips, resulted in failure. Fig. 14 (Case Study 15) shows the remains of a condominium roof that lifted off after 4 hours of wind gusting (according to an eyewitness). Fig. 15 shows a close-up of a hurricane tie that did not have the recommended number of nails. Another example of inadequate load transfer was also observed in the same condominium community. An entire roof, truss system, and top plate lifted off a structure. In that case, the truss uplift forces were transferred adequately to the top plate, but the top plate had no mechanism to transfer the load to the wall assembly, since the top plate was not anchored properly. The result was complete loss of the roof system.

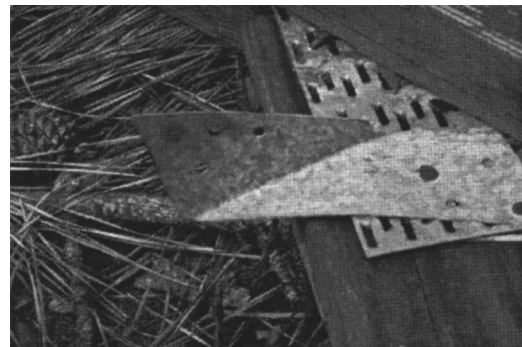


Fig. 15. Hurricane clip connecting a roof truss and wall (note that the proper number of nails was not used)

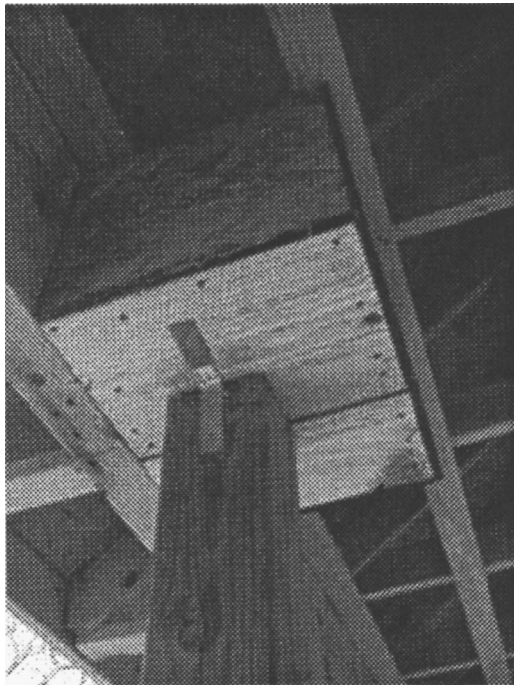


Fig. 16. Misuse of uplift strap

Further, in Fig. 16 (Case Study 17) is a strap that has been field modified in the shape of an “L.” It is not clear what the design requirements are for this particular connection, but such modification renders the strap ineffective for uplift resistance. Connections such as this strap should always be installed in accordance with the manufacturer’s recommendations to ensure that it performs as expected.

Nonstructural Observations

Observation No. 6—Roof Shingles

In the majority of case studies investigated there was some amount of roof shingle loss, which is consistent with other observers (Kirby and Scislo 2005). Many of these buildings were covered with temporary tarps four weeks after Katrina when these observations were made. Based on investigation as well as discussions with homeowners, architectural roof shingles tended to perform better than normal roof shingles. It should be noted that



Fig. 17. Loss of roof shingles on an older home; this was quite common for regular roofing shingles



Fig. 18. The result of vinyl siding and nonstructural sheathing loss left just a shell for many of the homes in this subdivision

only newer residential structures had the option to use these high wind shingles. Fig. 17 (no case study number) shows the loss of roof covering for a typical wood-frame residential structure in the area. Loss of shingles was common to both older and newer structures in all areas studied even though these areas did not experience winds in excess of 100 mi/h (161 km/h). It should be noted that in recent years the design wind speed has been increased and therefore many of the structures investigated were not built to present code (Kirby and Scislo 2005).

Observation No. 7—Connection of Vinyl Siding

Vinyl siding assists in maintaining the integrity of the building envelope. Manufacturer recommendations state that vinyl siding be connected to the wood framing members with a penetration of at least 3/4 in. (19 mm). In one subdivision (Case Study 23), it was observed that the vinyl siding was connected directly to a foam board substrate and/or OSB and did not have the recommended fastener penetration. This resulted in a loss of vinyl siding followed by the failure of the foam board substrate followed by significant water damage to the buildings. Fig. 18 (Case Study 23) is a view of one street in a subdivision with significant vinyl siding loss and rainwater damage. A neighboring subdivision did not have this level of damage (Case Study 24), but it is not known if proper penetration and stapling of the vinyl siding was present in that subdivision, since the siding was still intact.

Observation No. 8—Vulnerability of Soffits and Trim Pieces

Damage to trim pieces and soffits was routinely observed. Winds in the region studied (see Fig. 2) were significantly below



Fig. 19. Damage to the top right trim piece on the roof just left of the garage; this was the only damage to this one-story house with a hip roof



Fig. 20. Attic vent allowed attic to pressurize and roof sheathing to fail

ASCE-7 (2005) design wind speeds, thus the amount of observed trim damage could potentially be considered excessive. Fig. 19 shows damage to the trim of a gable roof just to the left of the garage on a home that fared quite well. Many two-story homes just across the street did not perform as well with significant nonstructural and some structural damage, as shown earlier in Figs. 11–13 and 19. In this particular subdivision, one-story houses performed much better than two-story houses, possibly due to localized wind effects.

Observation No. 9—Attic Vents

Attic vents were a common entrance for wind flow resulting in pressurization of the attic and failure of the roof sheathing and interior ceiling drywall. Fig. 20 (Case Study 11) shows a damaged attic vent and roof sheathing in a 1970s one-story home. Attics that were vented using perimeter ventilation near the soffit typically performed better than structures with attic vents located on the gable. This trend was common for both older and newer wood-frame residential construction.

General Observations

Observation No. 10—Structural Age Played a Factor

Although there were many older residential wood-frame houses that performed well, the general trend was that newer homes tended to sustain less structural and nonstructural damage. Fig. 21 (Case Study 12) shows a picture of new homes, very recently constructed, in the foreground and older circa 1970s homes in the



Fig. 21. Newer home with very little structural or nonstructural damage in the foreground; older neighborhood in the back ground with most structures having significant damage



Fig. 22. Example of a hip roof, which performed very well during the hurricane winds

background. The difference in the sustained damage levels was notably higher in the older structures. It may be inferred from this that design code changes, following Hurricane Andrew in 1992, were likely successful.

Observation No. 10—Roof Types

Hip roofs performed significantly better than gable roofs. Fig. 22 is an example of a hip roof that performed significantly better than gable roofs during the hurricane. This was the trend throughout the study area, shown in Fig. 2, and for both one- and two-story houses.

Conclusions and Recommendations

The following conclusions were reached by the investigating team as a result of field observations and subsequent literature investigation. More details can be found in the case studies section of the project web site at <http://www.engr.colostate.edu/~jwv/hurricane-Katrina-woodframe.htm>, as each case was not presented here in detail in the interest of brevity.

1. Wood-frame residential and light commercial structures that followed design codes and guidelines performed well during Hurricane Katrina wind loading. Thus, there is circumstantial evidence to suggest that design code revisions following Hurricane Andrew in 1992 have been successful.
2. Builders and inspectors in the Mississippi Gulf Coast region appear to be familiar with conventional construction provisions. However, these provisions were used erroneously in a high wind region in some cases, as evidenced by very recent and in progress construction.
3. A closer/heavier nailing schedule for roof sheathing may be helpful in reducing the amount of roof sheathing loss due to uplift, particularly at the edges and corners, and result in significantly less water intrusion. In many cases the current code minimum spacing was not being met.
4. Support columns/posts should be anchored to both the roof and foundation, particularly in high wind regions such as the Gulf Coast.
5. Architectural shingles tended to remain intact more often than regular roof shingles.
6. Careful attention must be paid to all details, particularly the (correct) use of all straps and ties, to ensure a continuous load path from the roof to the foundation. This includes proper anchor bolt positioning and use.

7. Seemingly insignificant details such as the connection of vinyl siding resulted in substantial financial loss due to water intrusion, once a breach of the building envelope occurred. Although these are nonstructural issues they present important cost concerns for wood-frame structures during hurricanes.

Acknowledgments

This study was sponsored by the National Science Foundation through the Hurricane Katrina Quick Response Damage SGER Fund, Grant No. CMS-0553058 under the program direction of Dr. Richard Fragazy, Civil and Mechanical Systems. The project was entitled "Collection of Perishable Data on Woodframe Residential Structures in the Wake of Hurricane Katrina." That support is gratefully acknowledged.

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