Constructing Scale Model Roof-to-Wall Connections In Residential Construction for Dissemination of Hurricane Mitigation Techniques

Submitted to:

South Carolina Sea Grant Consortium
287 Meeting Street
Charleston, SC 29401

SC Sea Grant Project Number: V337S

Prepared by:

Report No. WLTF 02-07

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31 May 2007

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ABSTRACT

Home owners have limited knowledge of wind-induced loads on low-rise residential buildings. The lack of homeowner attention to develop reliable post construction roof-to-wall connections may, by default contribute in part to disproportionately high damage occurring to residential construction.

This investigation was conducted to construct scale model of the framing of a residential building to display past and current roof-to-wall connection details used in residential construction. The purpose is to use the models as dissemination tools that can be used to show the proper retrofit techniques for mitigation of hurricane damage. The main deliverables are four one-eighth scale wood models highlighting aspects of single-family residential construction. The models show the development over time of the structural retrofits that are designed to mitigate hurricane wind damage. This report provides a summary of the literature reviewed in preparing the dissemination models, including a summary of the damage caused by excessive wind and proper retrofit methods for hurricane mitigation and it was funded in part by a seed/developmental grant awarded from the South Carolina Sea Grants Consortium.

The author wishes to acknowledge the contributions of several civil engineering students who participated in this research including, graduate students Clayton Greene and Stephen Furr who initiated the model construction and directed the research work of the undergraduate student assistants. The models were constructed by Mr. Greene assisted by Mr. Kenneth Hill and Mr. Andrew Halliday, civil engineering undergraduate students. Mr. Peter L. Datin, civil engineering graduate student prepared the accompanying posters mounted with each demonstration model. The author wishes to also acknowledge the help of Mr. Chas Fant, Civil engineering undergraduate senior, in formatting the final manuscript.

1. INTRODUCTION:

As was witnessed in 2005, hurricanes continue to have a destructive effect on residential construction. Despite the moderate wind speeds in Hurricanes Katrina and Rita, the housing stock in coastal Mississippi and Louisiana suffered significant damage as documented by the Institute for Business and Home Safety post-storm survey. The average annual loss due to windstorm damage in the East and Gulf Coast states exceeded about $5 billion in 1998 (Pielke Jr et al. 2003) and this figure increased to about $6.3 billion in 2005.

Damage from high winds disproportionately affects low-rise residential buildings located along vulnerable coastal areas of the Carolinas, Florida and Gulf States. The failure of residential buildings in high winds typically occur in a brittle manner as the components and cladding elements separate and break apart at weak connections. The vulnerable building envelope elements include roof coverings and sheathing, wood framing members, wall cladding and fenestration. While wind engineering research and the building industry continue to develop improved connection systems that resist higher wind loads, the majority of existing building stock in the state remains un-retrofitted and therefore at a higher risk of vulnerability to wind damage. One reason for this is the limited reach of dissemination about the benefits of improved connection designs and materials. There is an urgent need to address the lack of homeowner knowledge about the availability and feasibility of reasonably priced retrofit techniques to improve wind performance of low-rise residential buildings, particularly of buildings in coastal South Carolina.

The deliverables completed under this project include the following:

- Visit the 113 Calhoun Street site to collect the existing wood-framed scaled residential house and transport it to Clemson's Wind load Test Facility.
- Documentation of the roof-to-wall connections used in the model house and using current literature, provide a narrative explaining the purpose and benefits of the designs for typical housing construction.
- Development of several scale model of the main structural connections used in existing residential construction that demonstrate examples current code provisions and advances in structural mitigation of wind damage to houses.

2. RESEARCH

The literature contains publications that provide mitigation techniques in wood framed, low- rise residential construction and this research collected data using four primary sources Cheng (2004), van de Lindt (2005), IBHS (2005), and Simpson Strong-Tie (2006).

Damage to residential construction caused by Hurricane Andrew identified systematic weaknesses in structural systems, especially limited uplift capacity of toe-nailed connections. Since that time, demand has risen for the advancement of structural connections and a revision in building codes. Cheng (2004) conducted studies to determine if the typical toe-nailed connections used to fasten roof structure to walls have adequate wind uplift capacity to meet building design loads. His study compared the performance against ASCE 7-98 (ASCE,1998), the International Building Code (ICC 2000), and the Southern Building Code Congress International, Inc. (SSTD 10-99). Cheng conducted a parametric study of the withdrawal capacity of toe-nailed connections following test procedures ASTM D 1761 (ASTM 2001). His study investigated the withdrawal capacity performance of three lumber types, four fasteners, two lumber sizes, and three nailing methods as described in Table 1 below.

Lumber Species	Fasteners	Lumber Size	Nailing Method
• Southern-Pine-Fir (SPF) • Southern Pine (SP) • Douglas-Fir (DF)	• 3-8d box nails • 2-16d box nails • 2-16d common nails • 2-2.5” screws	• 2” x 4” • 2” x 6”	• Hammer driven nails without pilot hole (HD) • Driving in nails at 30 degrees with pilot hole (PH) • Automatic screwdriver (Gun)

Table 1: Material used in testing

Cheng’s test included approximately 15 samples of each parameter and he obtained the mean withdrawal capacity of the nail systems. All told Cheng tested 300 fasteners and he made the following conclusions:

- Smaller diameter nails (e.g. 8d and box nails) fail at lower loads than larger diameter 16d and common nails.
- The withdrawal capacity of nails installed in 2 in. by 6 in. lumber is essentially the same nail withdrawal capacity as installed in 2 in by 4 in. lumber.
- The nail withdrawal capacity is approximately the same for nails installed in Douglas-fir and southern pine. The primary failure mode in these lumber species was “bent-nail pullout”.
- Southern-pine-fir has the lowest nail withdrawal capacity and the primary failure mode was “straight-nail pullout”.
- Dense lumber has higher nail withdrawal capacities.
- The withdrawal capacity of fastener screws was approximately 140% higher than nail withdrawal capacities of the 16d nails.
- Only the members joined by screws pass both ASCE 7-98 and IBC 2000 requirements for 90 mph wind speeds.

Figure 1 summarizes pertinent findings from Cheng's study:

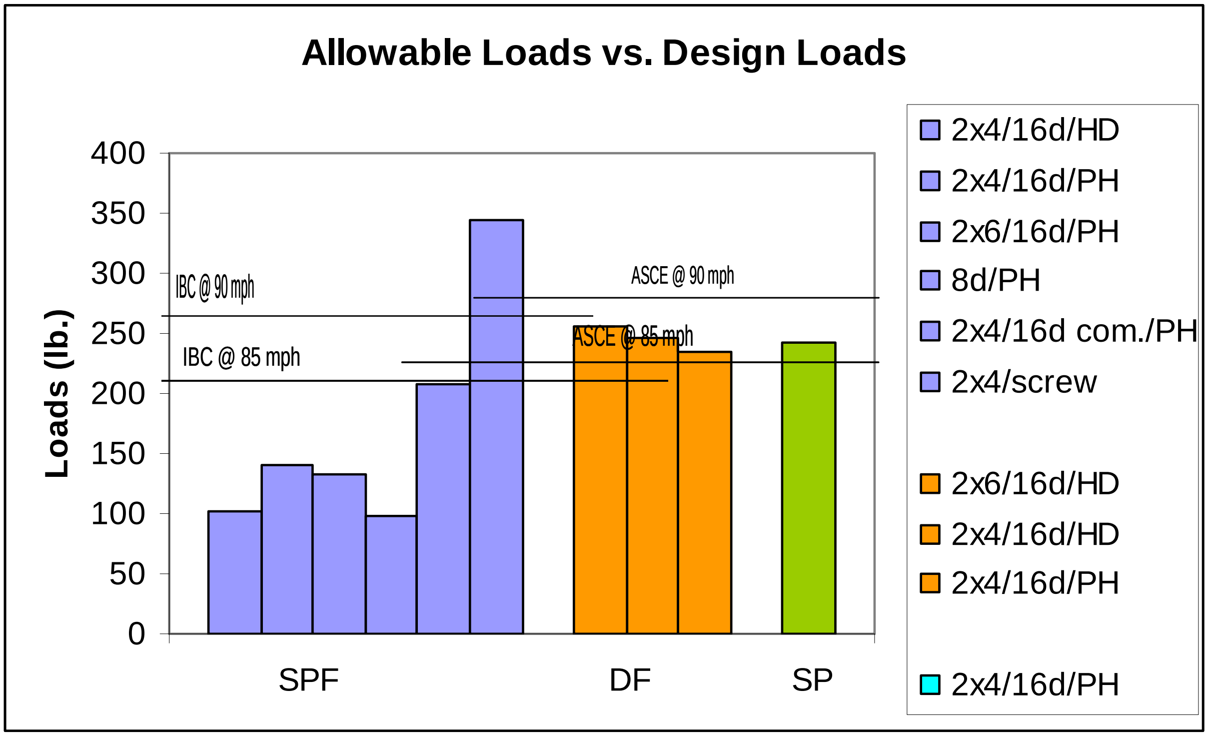

Figure 1: Tested allowable loads versus Allowable design loads

Cheng compared his experimental results with allowable loads and he found that only wood members joined by screws exceed the wind uplift allowable loads specified by ASCE 7-98 and IBC 2000 for an 85 mph design wind event. The results from the study reproduced in Figure 1 show that even though toe-nailed connections are still commonly used in the construction process, they cannot reach the required design uplift strength.

Reed (Reed, et al. 1996) observed that toe-nailed connections do not have the capacity to withstand high wind forces at roof-to-wall connections. As a result hurricane-resistant metal straps have been used in hurricane-prone areas to resist uplift forces. These straps can provide as much as seven times the capacity as toe-nailed connections (Greene, 2006). Steps to improve the quality of construction include retrofitting existing roof structures using metal strap connections. Table 2 displays the connection characteristics of these metal straps provided by Simpson Strong-Tie versus toe-nailed connections.

Connection Category	Connection Type	Quantity Needed	Allowable Uplift Loads		Fasteners
			DF/SP	SPF	
Toe-nailed*	Nailed	3	256	207	16d box for DF 16d common for SPF
Rafter-to-Top plate	H10	1	1,810	780	16-8d to rafters 16-8d to plates
Rafter-to-Stud	HTS20	1	1,450	1,245	12-10d to studs 12-10d to rafters

Table 2: Toe-nailed connection uplift capacity vs. metal strap connection uplift capacity
* Loads established in results provided by Cheng

Cheng's results highlight the structural inadequacy of toe-nailed connections for wind uplift applications. Cheng's study has produced valuable laboratory results that prove that toe-nailed connections are inadequate, especially for South Carolina's coastal counties. ASCE 7-05 recommends a design wind speed of 130 mph for these counties (ASCE, 2005). Clearly, the limited withdrawal capacity is a contribution to the cause of failure of wood-framed residential buildings which have occurred recently during hurricanes and tornadoes. Based on the results, the use of toe-nailed connections should be avoided in areas where design wind speeds exceed 85 mph because the design uplift loads are twice as large as the withdrawal capacity of a toe-nailed connection. More importantly, retrofit methods should be developed to install hurricane-resistant metal strap connectors to ensure adequate strength at the roof-to-wall connection. My recommendation for home owners in the coastal areas is to assess their homes and to retrofit any toe-nailed connections. For public safety and the advancement of the performance of residential construction during wind driven storms, building codes should require metal hurricane-resistant straps for roof-to-wall connections.

van de Lindt et al. conducted a three day field investigation to observe damages to wood framed structures affected by Hurricane Katrina. This NSF- sponsored study collected a total of 27 case studies of both structural and non-structural damage to entire subdivisions and to individual structures. The main findings were as follows:

- <u>Lack of continuous uplift load path</u> due to the use of toe-nailed connections, lack of anchorage for studs/posts, and inadequate roof-to-wall connections.

- <u>Loss of sheathing at roof corners</u> caused by nails not meeting the code minimum nail spacing of 6" on center. The authors note that using nail spacing that meets the prescribed code minimum would have significantly reduced the loss of sheathing in the Gulf Coast region.

- <u>Gable end wall loss</u> due to air entering the attic through attic vents and pressurizing the attic dislodging sections of sheathing. The loss allowed wind driven rain to penetrate and saturate the attic's insulation.

The use of conventional construction in a high wind region was a major observational concern for the researchers. The report commented that conventional construction which does not require engineering calculations produces homes incapable of withstanding the ASCE 7-05 recommended design wind speed of 130-140 mph for the Gulf Coast region. The report recommended that homes in this area should be engineered, incorporating hurricane ties and anchors.

The researchers generally noted the neglect of vital structural details, including several roof failures due to missing nails in the hurricane clips, and inadequately anchored top plates that pullout from the wall. Another case study showed that a garage wall was blown off after the garage became pressurized. The authors noted that this sheathing section failed because the builder cut the sheathing section in the shape of an “L” to fit around a window. This modification severely weakened the sheathing.

<u>Sources of Retrofit Details</u>

In preparation of the demonstration models, the researchers relied on the existing two-story scale model of a single-family residential structure provided to us by the South Carolina Sea Grant Consortium, in addition we acknowledge the following sources for additional information.

- **<u>Simpson Strong-Tie Company, Inc.-</u>** is a connector manufacturer established in 1956 that design, engineer, and produce structural connectors, anchors, and bracing products for new and retrofitting construction and is currently the leading manufacture of structural connectors in the United States and Europe. Connections produced by Simpson Strong-Tie were chosen and modeled to display the development of typical connections from the early 1990s to today. Several typical connections are modeled: roof-to-top plate, roof-to-stud, wall stud-to-wall sill plate (at floor level), sill plate-to-foundation, and stud-to-stud connection (at inter-story height).

- **<u>Institute for Business and Home Safety (IBHS)-</u>** is a nonprofit association whose mission is to ease the social and economic effects of natural disasters by promoting research, innovative construction, and maintenance techniques. Typical installation of soffit details and fortification techniques offered by IBHS were modeled to display ways to prevent water penetration due to excessive winds.

3. WIND UPLIFT FAILURE MODES IN WOOD FRAMED CONSTRUCTION

3.1 Continuous Load Paths

In the design of structures it is vital that a continuous load path is provided from the roof down to the foundation. In ensuring a continuous load path the building's chances for survival are increased significantly due to the redistribution of external pressures of the wind from the frame of the house to the foundation. During a storm, a structure has three distinct failure modes due to excessive wind.

The first possible failure mode is known as uplift, which occurs when air enters a structure through attic vents or soffits and pressurizes the attic, causing an outward force which in turn dislodges sections of sheathing. Particular attention must be paid to avoiding uplift around wall openings in walls because the structural members around these openings must be able to withstand higher loads than other members due to the lack of supporting members in the opening. A continuous load path must be kept for the concentrated loads exerted by the uplift pressures that are placed on the king studs and jack studs. The second possible failure mode is known as overturning. Overturning occurs when a loaded structure rotates off its foundation. Structures may also slide off its foundation, which can occur when wind forces exerts sufficient horizontal to overcome the friction and resistance of the building.

3.2 HURRICANE-RESISTANT CONSTRUCTION TECHNIQUES

3.2.1 **<u>Tie Straps</u>**- Tie straps are used to establish connections between members to resist uplift forces. Ties are used in, for example the floor-to-floor connections forces, acting as tension members between two butting wood members. Ties straps are also use to distribute the in-plane shear forces in the sheathing. The MST tie straps, which were used for the model, are punched to receive 16d common nails and ½ inch diameter bolts spaced 5-1/4 inches on center parallel to the strap. When installing fasteners, care should be taken to prevent wood splitting. A fastener that splits the wood may not take the design load. Wood that shows symptoms of dry wood have the tendency to split more easily and should be evaluated to ascertain it can develop the expected load capacity.

3.2.2 **<u>Twist Straps</u>**- Twist straps are installed to anchor wood trusses or rafters to wood top plates, wood top plates to studs, and other applications requiring uplift anchorage. They can be used to resist uplift from wind or other loading. When installed as truss-to-top plate connections the strap is nailed vertically across the stud and top plate moving diagonally onto and over to the attached truss member. When installed as a truss-to-rafter connection the strap is nailed vertically across the heel of the rafter and moves diagonally onto and over the attached truss member. The 3" bend section eliminates interference at the transition points between steel members. Either 14-10d common nails or 14-10dx1-1/2" nails are used for this installation. The MTS Twist Strap is formed from 16 gage galvanized steel and is 1 ¼ inches wide. The steel used has a minimum yield strength of 28,000 pounds per square inch and a minimum tensile strength of 38,000 pounds per square inch. The straps also have a maximum load capacity of 995 pounds.

3.2.3 **<u>Strong-Tie Rod System (STR)</u>**- A Strong-Tie Rod System is a system of engineered components that are assembled in the field into a system that resists uplift forces at the top plate. The STR system is comprised of 3 components: a foundation anchor, coupler nuts, and a take up washer. These are combined in the field with a minimum of ASTM A36 ½" diameter all thread rod to result in the complete system. The Simpson STU ½ (Take up Washer) ensures that the slack in the threaded rods, due to wood shrinkage and joint compression, is automatically removed so that the system will provide the required uplift resistance without excessive deflection. The STR ½, as used in the model, is installed into the foundation using a cast in place anchor that is provided.

The Simpson Anchor Bolt (SAB) is manufactured form steel meeting ASTM A307 Grade A and is coated with a zinc electroplate finish. The Coupler Nuts have minimum yield strength of 50,000 pounds per square inch and a minimum tensile strength of 60,000 pounds per square inch. The coupler nuts are also coated with an electrodeposited zinc plate finish.

3.2.4 <u>Hurricane Ties</u>- Hurricane ties are anchors designed to connect rafters or joist to wall plates or studs to protect against wind uplift forces. Hurricane ties are superlative for securing a continuous load path from the roof to the building's foundation in the Southeastern region of the United States. These ties are used in connections designed to be able to withstand the three second gust speed category of 120-130 mph found in the coastal region of South Carolina. The H2.5T hurricane ties, which were used in the construction of the model, are formed from No. 18 gage galvanized steel and have a minimum yield strength of 28,000 pounds per square inch and a minimum tensile strength of 38,000 pounds per square inch. The H2.5T is a twisted strap tie used to attach a rafter of stud member to the side of a top plate of bottom sole plate. The lower end is fastened to the wall plate and is long enough to locate the nails into each of the tow top plates. The 3" bend section eliminates interference at the transition points between steel members. The H2.5T's condensed design was developed to accommodate trusses with 2x4 bottom chords. The easy to install, 5 nail pattern is stronger and gets better uplift loads than the popular H2.5 hurricane tie. The H9 hurricane tie was also used in the construction of the model. The H9 hurricane tie is in the form of an inverted U-shaped element. The H9 attaches the heel of a double ply truss of a rafter to a stud member below.

3.2.5 Stud Plate Connectors- Stud plate connectors may be installed to help prevent overturning and uplift. SP connectors, which were used in the construction of the model, are die-formed from No. 20 gage galvanized steel with minimum yield strength of 28,000 pounds per square inch and a minimum tensile strength of 38,000 pounds per square inch. The connectors can either be fastened to a single plate or a double plate. The stud connector is installed vertically covering the base plate and a portion of the stud at its base. The connector is three times as large as the width of the stud allowing for the connector to wrap around the stud for better stability.

3.2.6 **<u>Predeflected Holdowns (PHD)</u>**- Predeflected holdowns may be installed to hold against overturning, uplift, and sliding. The predeflected holdowns may be used to anchor wood members to foundations or as floor-to-floor ties. These installation techniques are very beneficial since both prevent overturning as well as uplift. The predeflected holdowns can also be used as horizontal wall anchors protecting against sliding. When the holdowns are used the stud closest to an opening such as a window or door and is attached to a base plate that is anchored into the foundation using anchor bolts. When the holdowns are used as floor-to-floor ties the holdowns are then connected using as anchor bolt which goes though the floor. The two holdowns are then connected using an anchor bolt which goes through the floor. When the holdowns are installed as horizontal wall anchors the anchors are placed on the inside portion of the stud located at the end of the wall, protecting the wall against high lateral winds. The predeflected holdowns are predeflected during manufacturing eliminating future deflection form material stretch.

5. CONSTRUCTION OF SCALE MODELS-

Clemson University graduate students constructed the models using 1:8 scale basswood components purchased through Midwest Products Company. The models were assembled using Zap-A-Gap super glue, 18 gauge pin nails installed using a Senco pin-nailer. Wood base for each model were constructed using red oak and assembled using

Liquid Nails adhesive. All metal plate connections were built to scale using 30 gage sheet steel roof flashing material except for the PHD-5 hold-down anchor connection which was milled from acrylic and painted. Table 1 shows the material used in the construction process.

Material	Product	Comments
Glue	Elmer's wood glue	. • Elmer's wood glue was too messy • Elmer's wood glue was too weak to hold the model's together.
	Zap-A-Gap super glue	• Zap-A-Gap was the strongest glue available
Nails	Senco Pin Nailer with 18 gauge pin nails	• Pin nails were used to hold the studs to the bases and top plates • The glue alone was not strong enough to effectively hold the models together.
Model wood	Basswood	• Basswood was chosen for its strength over balsawood
Base wood	Red oak	• Red oak was chosen for its appearance.
Base glue	Liquid Nails	• Liquid Nails was chosen to assemble the bases due to its strength and ability. • Nails were not used to keep the appearance of the bases
Connections	Generic roof flashing	• Roof flashing was chosen because of it's texture and flexibility

6. POWERPOINT SLIDES OF POSTERS DISPLAYING MODEL DETAILS

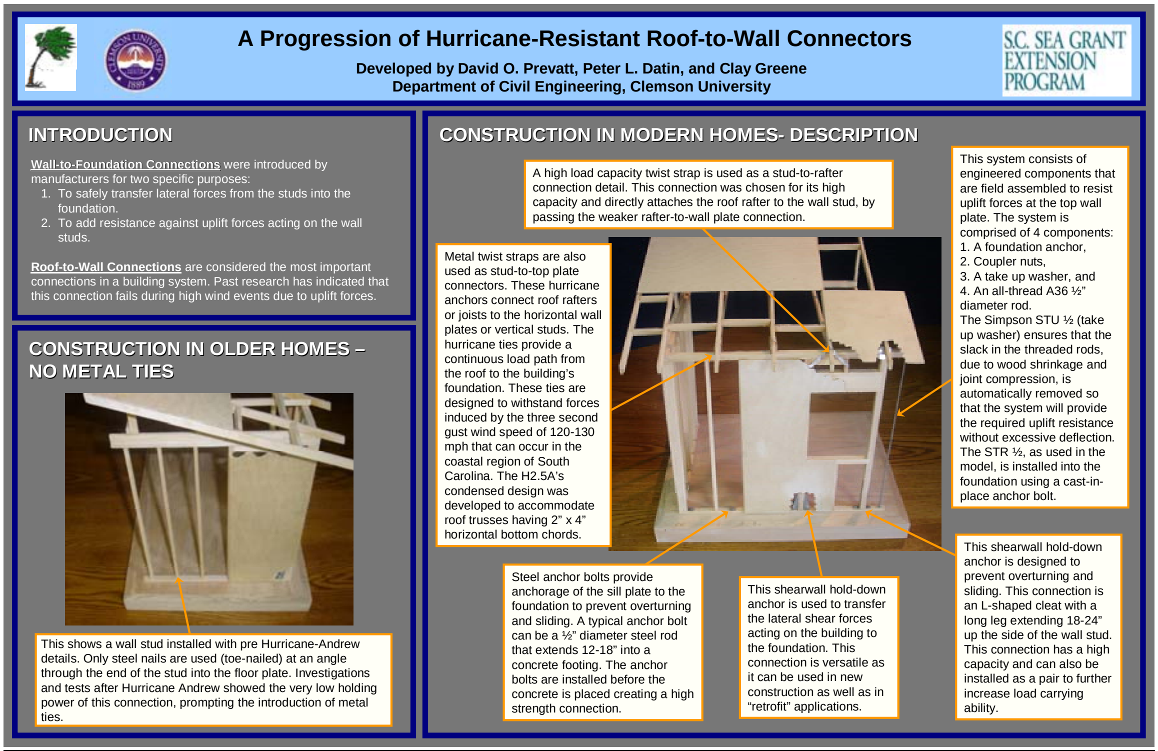

Figure 1: Hurricane Resistant Roof to Wall Connections

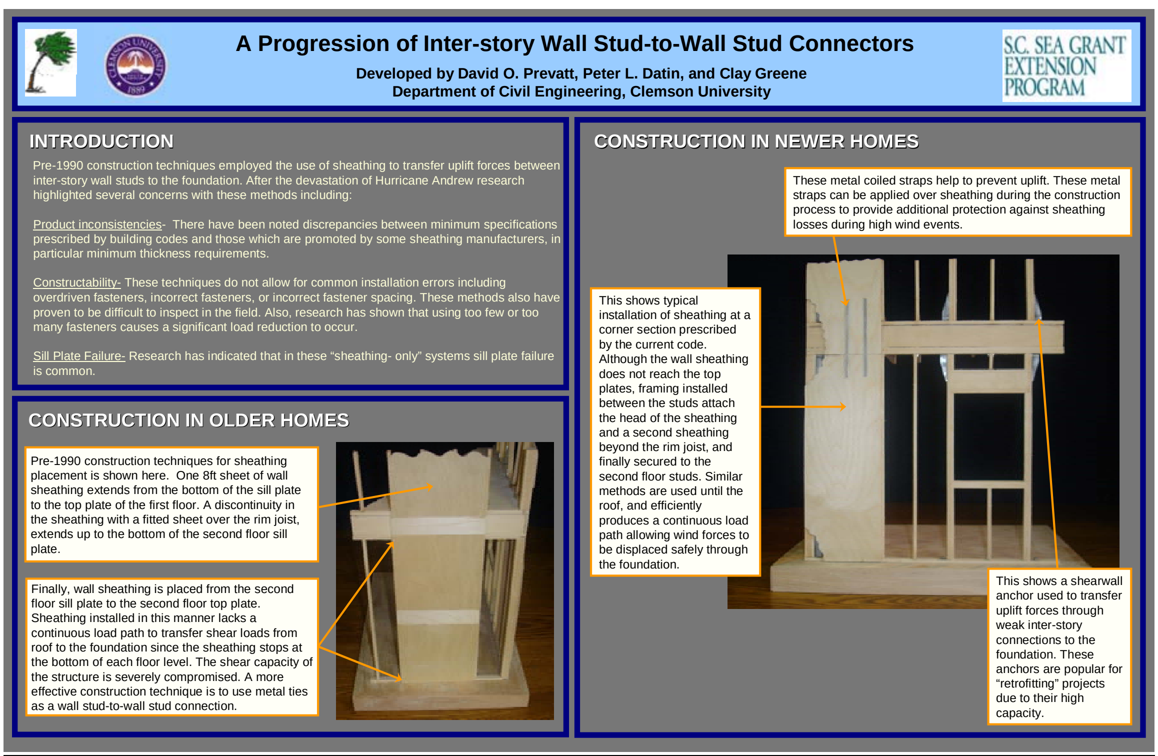

Figure 2: Development of Inter-story Ties in Wood Construction

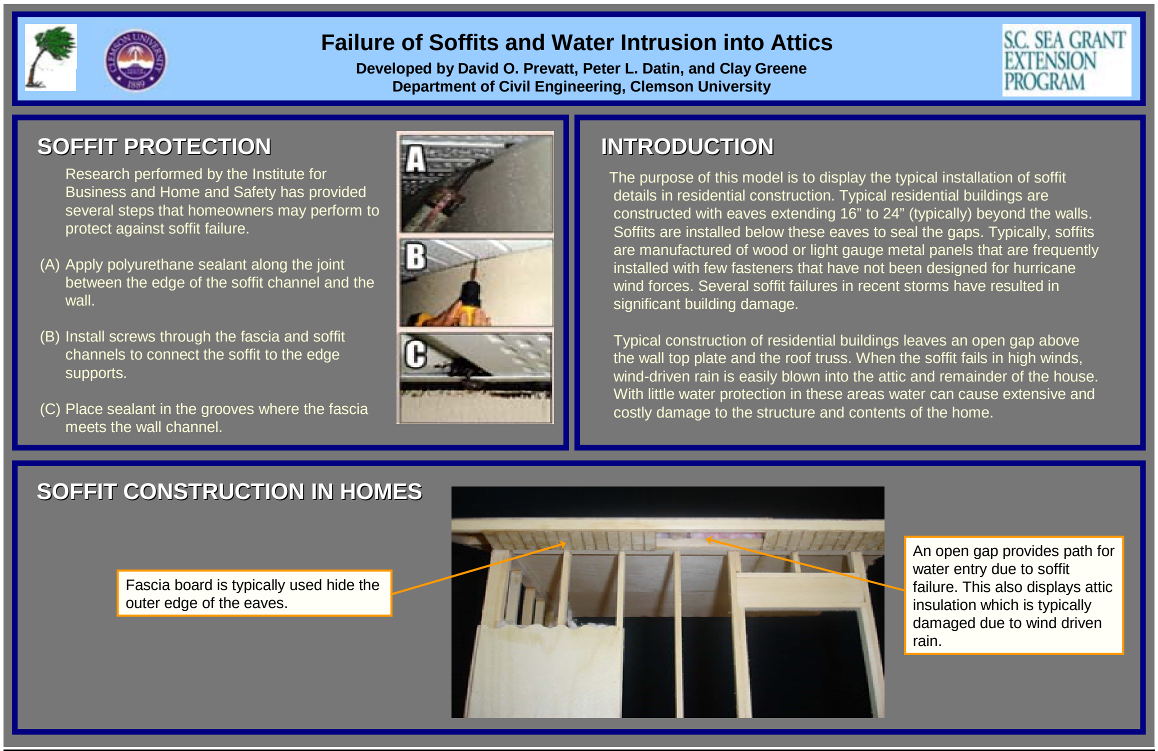

Figure 3: Mechanism for water penetration through failed Soffits

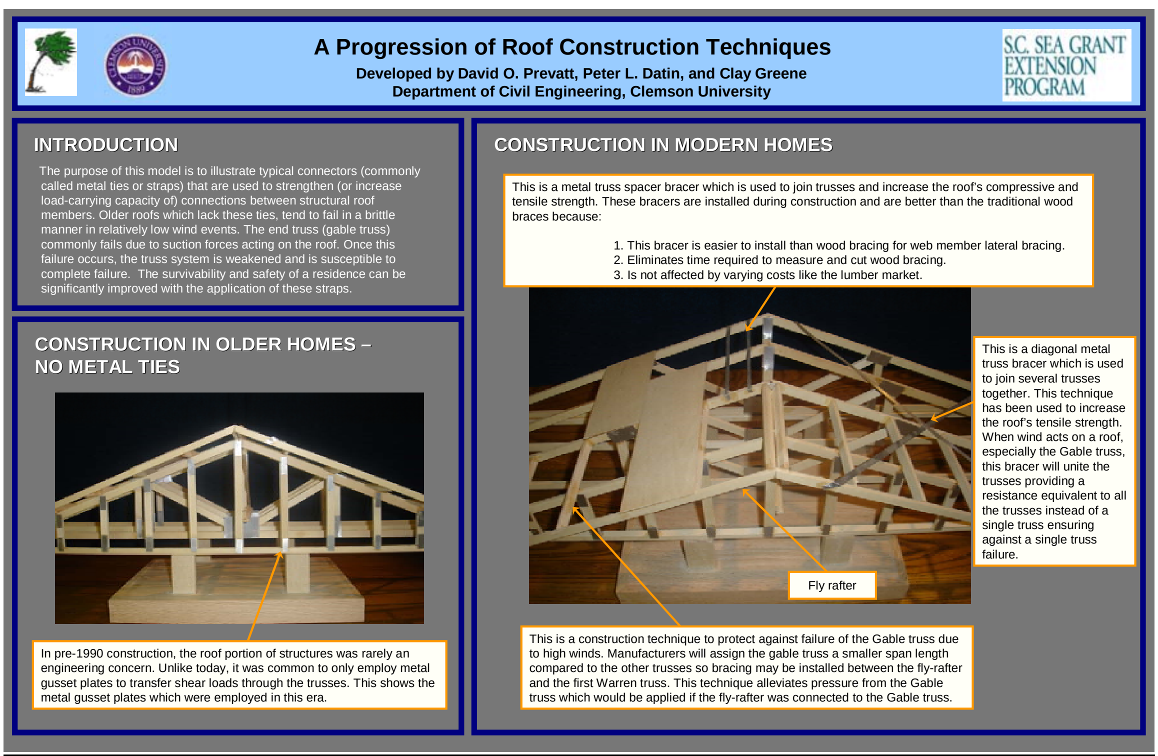

Figure 4: Hurricane Resistant Roof Construction Techniques

References

American Society of Civil Engineers (ASCE). 2000. “Minimum design loads for building and other structures”. ASCE standard 7-98, Reston, Va.

American Society for Testing and Materials (ASTM), 2001. Annual book of ASTM standards, Vol. 04.10, D 1761-88. ASTM, West Conshohocken, PA. pp.277-288.

Cheng, Jim. (2004). “Testing and analysis of the toe-nailed connection in the residential roof-to-wall system.” Forest Products Journal, 54(4), 58-65.

International Code Council, Inc. (ICC) 2000. International building code. Falls Church Va.

Institute for Business and Home Safety (2005). ““S” marks the spot.” Hurricane Protection Series.

Simpson Strong-Tie Company, Inc. www.strong-tie.com

Southern Building Code Congress International, Inc. (SBCCI), 1999. Standard for hurricane resistant residential construction. SSTD 10-99, Birmingham, Al.

Van de Lindt, et al. (2005). “Damage assessment of woodframe residential structures in the wake of Hurricane Katrina.” Colorado State University, Fort Collins, CO.