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Statistical and analytical models for roof components in existing light-framed wood structures

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ABSTRACT

Residential wood-framed construction failures account for the majority of economic losses following hurricanes. A common failure in these constructions during high wind events is loss of roof sheathing, especially in corner areas. Less common perhaps, but usually catastrophic, is the failure of the roof-to-wall connections in these structures. The main objective of the current research project is to evaluate the in-situ capacity of roof-to-wall connections and sheathing to rafter fasteners in light-framed wood constructions. The unique opportunity provided by Clemson University to access four residential structures located within a residential complex enabled the collection of perishable yet statistically significant data on the strengths of existing residential structures. The uplift capacities of 100 roof-to-wall toenail connections and 34 plank sheathing units were evaluated from field and laboratory tests. Realizing the key role of probability distributions in developing fragility estimates and loss prediction models, distribution fits and parameters for these structural components are postulated. One conclusion drawn is that the uplift capacities of two and three nail connections are best described by a lognormal distribution. The initial stiffness and the vertical displacement at peak load of both two nail and three nail connections follow a normal and Weibull distribution respectively. The uplift capacity of plank sheathing follows a lognormal distribution. An analytical model designed to approximate the uplift behavior of toenail connections is developed to facilitate modeling of roof systems. These probabilistic and analytical models developed by this study allow for the performance of detailed reliability based studies on light-framed wood roof structures.

1. Introduction

The tremendous devastation caused by hurricanes mark them as one of the most significant natural hazards affecting the United States. The recent increase in the occurrence of hurricanes [1] and the continuing growth of construction activities along the shorelines has further increased the potential of hurricane damage [2]. The losses suffered by the insurance companies and governments and also the hardships faced by the general public have promoted research initiatives to focus on damage mitigation and loss prediction.

One significant area of research is looking at performance and damage mitigation of low-rise wood structures. Low–rise wood framed structures comprise the majority of residential structures (90%) and have shown appreciable vulnerability to high wind loads. For any structure to perform well, wind forces must be transferred from the roof and walls to the foundations through a complete and continuous vertical load path. Any discontinuity in this load path affects structural performance and subsequently reduces resistance to wind forces. Furthermore, load path discontinuities may result in damage propagation to other structural components and increase the likelihood of complete failure of the structural system.

Two structural components within this vertical load path, which demonstrate substantial vulnerabilities to extreme winds, are the roof sheathing to truss/rafter and roof-to-wall connections. According to the US Census Bureau [3], the vast majority of residential structures (over 80%) in U.S. hurricane-prone regions were built before 1994 — the year building codes were upgraded due to Hurricane Andrew. The failures of pre-1994 structures were most often a result of an insufficient number of nails (nail schedule) in roof-to-wall and sheathing-to-rafter connections, resulting from inadequate or unenforced building codes at the time of construction. While these types of connection are simple to install they were never designed to resist significant uplift loads. As a result, these connections fail at relatively low wind speeds resulting in brittle failure of the structure. Over 90% of the existing

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Fig. 1. Douthit Hills duplex residential structure.

inventory of light wood frame houses utilized these connections. Therefore, much effort has been devoted to understanding the uplift performance of these components, to quantify infrastructure vulnerability [4–6] and to develop mitigation solutions.

Numerous studies have been undertaken to understand the uplift behavior of toe nailed connections [7–9] and to investigate various retrofit strategies using both commercial metal connectors and adhesives [8–11]. Cost comparisons of various rafter tie installations indicated that the additional cost incurred by using metal connectors is negligible compared to the total cost of the structure [9]. This resulted in a noteworthy conclusion stating that toenail connections should not be permitted in hurricane prone regions [7].

Recognizing that the apparent behavior of these connections can be influenced by other elements in the framed structure, Reed et al. [8] also conducted laboratory experiments on systems of connections. Even though the number of connections which could be tested was limited (less than 20), some basic statistical estimators (i.e. mean and variance) of the uplift capacity were obtained along with an estimate of an appropriate probability distribution — Normal [12]. This type of information becomes essential for conducting vulnerability [4,13] and loss estimation [5] studies.

The loss of roof sheathing during a high-wind event exponentially increases building damage as it readily permits water intrusion causing extensive damage to walls and interior contents [14]. Numerous experimental studies on uplift capacities for roof sheathing have been carried out. One such parametric study, estimated the uplift capacity of plywood sheathing for different types and spacing of nail fasteners [15]. Additionally, a functional relationship between individual fastener capacities and sheathing capacities has been proposed [16]. Past studies revealed that a single nail failure often resulted in progressive failure (i.e. complete loss) of entire pieces of roof sheathing and the uplift capacity can be conveniently described using a normal distribution [16,17]. In-service conditions also had a significant influence on the capacity [18].

The estimated probability models for roof component behaviors obtained by others [12,16] have been utilized to develop loss prediction models and fragility estimates for roof-to-wall connections and roof sheathings. However the laboratory conditions under which roof specimens are fabricated and tested can be a major source of uncertainty. This is because lab conditions fail to account for the variability due to actual construction practices which may significantly influence the resulting statistical parameters and probability distributions.

The current study seeks to add to the existing knowledge base on the performance of existing low-rise light framed wood structures exposed to high winds. Considering that there is a large portion of the existing inventory that has details similar to those contained in this study, the findings here will be relevant for evaluating risk and the need to retrofit. Furthermore, this performance data can be used to design appropriate retrofit schemes if and when necessary. To this end, this study looks to account for and quantify the variability in the structural behavior of two key components, namely the roof-to-wall connection and roof sheathing, in their as-built condition. A significant number of actual component specimens were made available for testing due to the scheduled demolition of four residential structures located on the campus of Clemson University. One hundred as-built roof-to-wall toenail connections were tested to determine in-situ uplift capacities and find a general connection behavior (i.e. force–displacement). Additionally, 34 as-built roof panels constructed with solid wood plank sheathing were harvested and tested for uplift capacity. Relevant probability models are proposed using these relatively large data sets. An analytical model for roof-to-wall toenail connections is also developed and presented to better facilitate the modeling and vulnerability assessment of roof systems exposed to high winds.

2. Experimental study

The experimental tests were carried out on roof components found in four identical houses located in the Douthit Hills residential community on the campus of Clemson University, Clemson, South Carolina, USA. The houses are typical residential wooden structures constructed 50–60 years ago. These gable roofed duplex houses, scheduled for demolition, offered an excellent opportunity to study the in-situ uplift capacity of an appreciable number of toe nail connections and also to collect roof panel specimens for testing the uplift capacity of sheathing in the laboratory. Fig. 1 shows a photo of one of the four houses having plan dimensions of 8.23 m (27 ft) wide by 20.73 m (68 ft) long. The roof frames were stick built using dimensional lumber and were made up of 38 × 140 mm (nominal 2 × 6 in.) or 38 × 89 mm (nominal 2 × 4 in.) horizontal ceiling joists and 38 × 140 mm (nominal 2 × 6) rafters. A layout of the structure and the roof framing is given in Fig. 2. Framing members are spaced at 0.41m (16 in.) on the center and every fourth rafter was reinforced using a collar tie. The rafters were placed at a 6:12 pitch and attached at their lower ends to the side of the ceiling joist by means of three 3.3 mm (0.131 in.) diameter, 63.5 mm (2.5 in.) long smooth shank 8-d common nails. The ceiling joist was attached to the wall top plate using either two or three 4.1 mm (0.161 in.) diameter, 89 mm ($3\frac{1}{2}$ in) long smooth shank 16-d common nails as illustrated in Fig. 3. The roof sheathing was made up of solid wooden planks of 19 mm thick by 140 mm wide (nominal 1 × 6 in.). Each plank was fastened using two 3.3 mm (0.131 in.) diameter, 63.5 mm (2.5 in.) long smooth shank 8-d common nails to each rafter. Asphalt shingles covered the sheathing planks and the building exterior was covered with brick veneer and vinyl siding. Visual inspection

Fig. 2. Typical roof framing plan of structure.

Fig. 3. Roof-to-wall connection detail.

of the framing members revealed the wood type to be Southern Yellow Pine (SYP).

2.1. Roof-to-top plate toenail connections

2.1.1. Experimental set up

Previous studies carried out cyclic or monotonic uplift tests on either full scale or reduced scale roof-to-top plate connections modeled in the laboratory. Seldom were uplift tests carried out on in-situ roof to wall toenail connections. Even when conducted, in-situ tests did not control load rate or load sequence and displacements were not monitored. One must further recognize that when tested in a group, the behavior of in-situ connections is significantly influenced by the load redistribution and sharing by the neighboring connections. Also the redundancy of the roofing system allows for stiffer connections to take higher loads than weaker connections. Indeed three to four connections on either side of a given connection can participate in load sharing where the percentage of load shared is inversely proportional to the distance from the connection considered and directly proportional to the stiffness of the connections themselves [19,20]. In the current study, the load redistribution effect on the perceived capacity of an individual connection is acknowledged by carrying out uplift tests on systems of four roof-to-top plate (ceiling joist to wall top plate) toenail connections. Furthermore, cyclic loading was applied in order to capture the hysteretic behavior of the connection at relatively low levels of deformation and thereby enable quantification of energy dissipation by the connection under an extreme wind load event. This result can be used to develop analytical models which mimic the behavior of toenail connections.

Fig. 4. Experimental setup for uplift tests.

The weak link in the vertical load path of these structures is considered to be the ceiling joist to top plate connection (not rafter to joist). This is because of the framing scheme used in the given structures. The detail, as presented in Fig. 3, shows that three 8-d nails fasten the rafter to ceiling joist and act in single shear while the toenail connections that attach the ceiling joist to top plate act in withdrawal. Hence the ceiling joist to top plate connection is considered to be the weak link and also represents typical toenail connections in other structures.

The test set up has two automated screw jacks mounted on a reaction frame. The jacks carry a spreader beam which applies equal deflection on a system of four connections as shown in Fig. 4. Load cells attached to the top flange of the spreader beam both transfer and measure the load going to each joist. The number of connections to be tested in a given system was limited by the capacities of the screw jacks and the size of the reaction frame. In order to exercise control over the influence from other structural, as well as non-structural components, the system of four connections was segmented from the other structural components and crossing members. The whole system was allowed to act as a unit by applying cyclic displacements via the spreader beam.