

Uplift Capacity of Polyurea-Coated Light-Frame Rafter to Top Plate Connections

David J. Alldredge¹; John A. Gilbert, M.ASCE²; Houssam A. Toutanji, F.ASCE³; Thomas Lavin⁴; and Madhan S. Balasubramanyam⁵

Abstract: This paper demonstrates the potential for using field-applied structural coatings to reinforce traditional framing members and standard building ties, thereby providing an improved and continuous foundation to roof load pathway. Tension tests were performed on light-frame rafter to top plate connections, some of which were reinforced with a hurricane tie, to establish how much of a difference a polyurea coating made as the joints between the stud and top plate, and top plate and rafter, were loaded to failure. The tests indicate that polyurea provides universal strengthening compared with hurricane ties with the added advantage that members and joints can be protected from a multitude of threats, including corrosion attributable to moisture, damage attributable to flood; and, with self-extinguishing properties fire. The addition of the coatings allowed both unreinforced and reinforced configurations to withstand higher loads (200–400% more). In general, the polyurea delayed the onset of failure and significantly strengthened every configuration by increasing the amount of work/energy required to pull it apart; in some cases, by almost 800%. DOI: 10.1061/(ASCE)MT.1943-5533.0000492. © 2012 American Society of Civil Engineers.

CE Database subject heading: Coastal structures; Polymer; Coating; Wood structures; Structural behavior; Connections; Frames.

Author keywords: Coastal structures; Polymer coating; Wood structures; Structural behavior; Fastening ties.

Introduction

Fifty percent of the U.S. population lives within 50 miles of the coast in trillions of dollars of insured property (Insurance Institute for Business and Home Safety 2009). It is evident that significant problems exist in coastal buildings and there is a need for new water-resistant building materials and techniques that can reinforce new and existing structures while providing safety for building occupants. Federal Emergency Management Agency technical notes and bulletins outline many of these problems, including flood hazard information and recommendations for reconstruction practices (FEMA 2005), the structural needs for occupant safety and the criteria for designing hurricane and tornado safe rooms (FEMA 2008a), material ratings for common building materials and evidence of the need for Class 5 water-resistant materials (FEMA 2008b), and recommendations for home construction in storm pathways (FEMA 2010).

In their *Home Builder's Guide to Coastal Construction*, FEMA stresses the need for wall to sill plate reinforcement, foundation to shear wall reinforcement, and the development of continuous foundation to roof load pathways (FEMA 2010). It highlights problems with practices, e.g., used to tie and strengthen framing members to the foundation or roof or framing member to framing member.

The facts are that an enormous number of coastal homes were built before hurricane ties became standard or lie in areas in which code requirements are less stringent. The estimated loss (in 2008 dollars) from Hurricanes Andrew, Katrina, and Ike alone was 81.6 billion dollars (Insurance Institute for Business and Home Safety 2009). Roof cover damage was the largest, most frequent source of nonsurge failures.

In a study funded by the National Science Foundation, researchers collected data over a three-day period following Hurricane Katrina regarding wind damage to wood-frame structures along the U.S. Gulf Coast (van de Lindt et al. 2007). A total of 27 case studies, ranging from entire subdivisions to individual wood-frame structures, were examined in detail. According to the authors, most of the structures inspected lacked strengthening elements such as ties and straps, and a noticeable number of the hurricane ties examined lacked nails. Historically, these types of problems motivated researchers to seek viable alternatives to strengthen the building envelope.

Researchers from Clemson Univ., for example, studied the uplift capacity of rafter-to-top plate joints made with a variety of connection methods, including toe nailing, hurricane straps, and epoxy adhesives (Reed et al. 1997). In their research, the authors found that when compared with what they call "small straps," the epoxy adhesive provided a comparable uplift capacity. Their results demonstrated that the addition of straps or epoxy provided a significant increase in capacity when compared with a joint that was toe nailed only.

A disadvantage to applying epoxy, either by gluing the rafter directly to the top plate in new construction or by retrofitting an

¹Doctoral Student, Dept. of Mechanical and Aerospace Engineering, Univ. of Alabama in Huntsville, Huntsville, AL 35899. E-mail: alldredge_david@yahoo.com

²Professor of Mechanical Engineering; Dept. of Mechanical and Aerospace Engineering, Univ. of Alabama in Huntsville, Huntsville, AL 35899 (corresponding author). E-mail: jag@eng.uah.edu

³Professor of Civil Engineering, Dept. of Civil and Environmental Engineering, Univ. of Alabama in Huntsville, Huntsville, AL 35899. E-mail: toutanji@eng.uah.edu

⁴President, Soems, Inc., 10 Canterbury Lane, Watchung, NJ 07069. E-mail: tlavin@salu.org

⁵Research Engineer, Propulsion Research Center, Univ. of Alabama in Huntsville, Huntsville, AL 35899. E-mail: madhanb@uah.edu

Note. This manuscript was submitted on August 29, 2011; approved on January 26, 2012; published online on January 28, 2012. Discussion period open until February 1, 2013; separate discussions must be submitted for individual papers. This paper is part of the *Journal of Materials in Civil Engineering*, Vol. 24, No. 9, September 1, 2012. © ASCE, ISSN 0899-1561/2012/9-1201-1210/\$25.00.

existing structure by adding wooden blocks, is that these processes are time-consuming. A faster and potentially better approach was suggested by the current authors, who explored the potential of spraying polyurea onto framing members (Alldredge et al. 2011).

This paper demonstrates the potential for using field-applied structural coatings to reinforce traditional framing members and standard building ties, thereby providing an improved and continuous foundation to roof load pathway. Tension tests were performed on light-frame rafter to top plate connections, some of which were reinforced with a hurricane tie, to establish how much of a difference a polyurea coating made as the joints between the stud and top plate, and top plate and rafter, were loaded to failure.

Materials and Methods

Polyurea

Polyurea is a high-strength polymer with scalable and predictable material characteristics that can be sprayed onto a substrate to make it waterproof. The polymer has a variable gel time; tensile strengths in commercially available materials vary from 13.8 to 34.5 MPa with inversely related elongation rates. It can be field applied with a brush, a high-temperature pump applicator, or a low-temperature, low-pressure dispenser (Polyurea Development Association 2011).

The first reference to polyurea came in 1948 when researchers discovered that these compounds had far superior thermal properties and extremely high melting points compared with other polymer systems such as polyesters, linear polyethylene, polyurethanes, and polyamides (Hill and Walker 1948). In the early 1980s, discoveries and advancements in elastomeric polymer chemistry resulted in polyureas that could be used to produce automotive body panels through reaction injection molding (RIM) (Grigsby and Dominguez 1986). But the typical gel times (2–3) of these compounds made it very difficult to spray them using conventional techniques.

Although work was done in the 1970s with modified polyamines and high levels of plasticizers and solvents to achieve a spray system for coating work (Rowton 1977), poor field performance was noted and this technology never gained acceptance. However, by 1990, modifications were made to slow the effective reactivities of the polyureas developed for RIM so that the compounds could be sprayed without compromising their unique characteristics and performance properties (Primeaux 2000).

Nowadays, polyurea is used for applications ranging from truck bed liners to explosive blast resistant walls. Thin layers of polyurea have been shown to increase blast resistance of carbon fiber foam composites (Bahei-El-Din and Dvorak 2007), and polyurea

coatings have been used to improve the energy absorption of syntactic foams (Panduranga et al. 2007). Because polyurea strain hardens under load (Roland et al. 2007), the U.S. military has employed it to coat and harden field buildings against explosive blast (Moradi et al. 2008), and membrane catcher systems have been developed to protect building occupants from secondary debris resulting from blast pressure (Moradi et al. 2010).

Test Program

A framing connection was selected for testing and a licensed carpenter contracted to make several rafter top plate model joint constructions (subsequently referred to as the “configuration”) from southern pine. As illustrated in Fig. 1(a), a vertical 2 by 4 stud was nailed to the bottom of a doubled top plate using two 16 d \times 3.5-in. nails. Then, a 2 by 8 rafter having a birdsmouth was toe nailed to the top plate using four 12 d \times 3.25-in.-long nails. For reference purposes, the birdsmouth connection exceeded the fastener schedule included in the 2009 international building code, which calls for using three 8 d \times 2.5-in.-long nails (International Code Council 2009).

In some cases, the configuration was reinforced by using a Simpson LTS12 hurricane tie fastened between the stud and the rafter with 14 4 d \times 1.5-in. nails [see Fig. 1(b)]. Fourteen 4 d nails were used, as opposed to 12 10 d nails as recommended, to anchor the tie to avoid splitting the stud. For reference, according to the manufacturer, when properly installed, the LTS12 is designed to withstand a maximum allowable lift load of 3.2 kN (Simpson Strong Ties 2011).

Loads were applied in the vertical direction in an attempt either to pull the stud away from the top plate or fail the toe-nail joint between the rafter and the top plate. During construction, no attempts were made to control the orientation and coarseness of the grain structure in the configurations, and these varied widely for different structural members. In the rafter joint shown in Fig. 1(a), for example, the grain runs in a direction perpendicular to the applied load, whereas the grain structure in the vertical stud runs parallel to it.

During loading, it was assumed that the rafter lifts directly upward from the vertical stud and top plate, thereby placing both joints in tension. Because of its location, the hurricane strap is subjected to eccentric loading.

Standard nailed configurations, with and without the metal hurricane tie, were used to define control standards. While testing the configurations, the reinforcement effects caused by plywood sheathing that may be nailed to the top plate and the stud were neglected.

Polyurea was then sprayed on similar configurations continuously around the stud and up and around the top plate and rafter.



Fig. 1. Basic framing connection: (a) constructed; (b) reinforced with a hurricane tie



Fig. 2. Configurations coated with polyurea before subjecting them to uniaxial tension: (a) black; (b) white

For most retrofitting applications, the top plate to stud will not be available in the soffit. In this case, only the rafter to top plate can be easily coated.

As illustrated in Fig. 2, two different types of polyurea were employed: (1) a black version having a relatively large elongation (800%) and low elastic modulus (179 MPa), and (2) a white version having a relatively low elongation (200%) and high elastic modulus (483 MPa). The tensile strengths of the black and white polyureas were 16.0 and 15.2 MPa, respectively.

Results

Thickness Measurements

The thickness of the polyurea coatings varied throughout a configuration and from configuration to configuration. An average value of the coating thickness was obtained for all of the coated configurations by making measurements: (1) across the thickness of the rafter at a point located midway between the centerline of the upper hole and the upper surface of the top plate, and (2) across the smaller dimension of the lower 2 by 4 at a point located midway between the centerline of the lower hole and the lower surface of the top plate. The average thicknesses for the black and white coatings were 2.0 and 2.4 mm, respectively.

Pull-Strap Tests

As illustrated in Fig. 2(b), the configurations were initially placed in uniaxial tension by passing Kevlar straps through two 2.34-cm-diameter holes drilled in the 2 by 4 and rafter. Each hole was reinforced using a 3.8-cm-long section of aluminum pipe. The 98-kN-capacity MTS testing machine used to conduct the tests was equipped with a load cell; and, comparisons and observations were made between uncoated and coated specimens that were pulled in deflection controlled tests at a rate of 1.27 cm/min.

A net deflection for each configuration was calculated by subtracting the deflection in the pull straps from that measured for the crossheads. The deflection in the pull straps was computed on the basis of Fig. 3, which shows a load deflection plot obtained by placing a 50cm long segment of one of the pull straps in tension.

A calibration factor, C , of $6 \mu\epsilon/\text{N}$ was obtained for the case when a 2.54-cm-long segment of the strap was subjected to a 4.45-N load by fitting a linear curve through the data in Fig. 3 over the load range observed during the test program (0 to 9790 N).

Referring to the configuration shown in Fig. 2(b), each side of the upper and lower straps carries one-half of the total load. Hence, the total deflection in the pull straps is

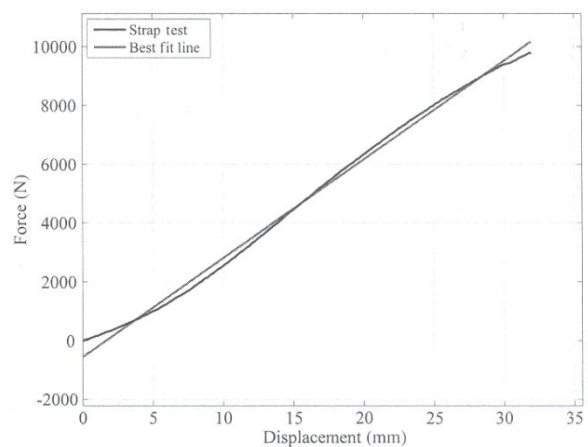


Fig. 3. Load versus deflection plot for a 50-cm-long Kevlar pull strap

$$\delta_{\text{straps}} = \frac{PCL}{4} \quad (1)$$

In Eq. (1), P is the load and L is the total length of all straps used to pull on the configuration (approximately 55.9 cm).

The strain energy, U , is equal in magnitude to the area under the load/deflection plot. For the configuration at hand

$$U_{\text{straps}} = \frac{P^2 CL}{8} \quad (2)$$

"Standards" for Unreinforced and Reinforced Joints in Uncoated Configurations

Fig. 4 shows plots of load versus total deflection (of the configuration and the pull straps) corresponding to three uncoated specimens. Two of the configurations were unreinforced (without tie), whereas one was reinforced with a hurricane tie. The scale on the vertical axis was kept constant in all of the plots presented in this paper so that direct visual comparisons can be made.

One of the uncoated configurations without the tie failed gradually as the nails in the top plate pulled out of the stud [see Fig. 5(a)]. This configuration, which held a maximum load equal to 1850 N, was considered the "standard" for 2 by 4 end nail failure; i.e., pull-out between the stud and top plate in an unreinforced configuration.

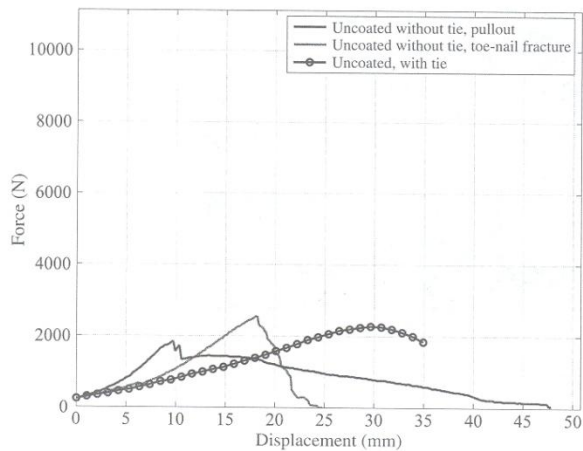


Fig. 4. Load versus deflection plots for uncoated specimens; see legend and Figs. 5 and 7 for details

In contrast, the other uncoated configuration without the tie held a higher load (2562 N) and failed relatively quickly as the toe-nailed joint between the rafter and top plate fractured and gave way [see Fig. 5(b)]. This was considered a “best-case” scenario and the “standard” for toe-nail rafter failure, i.e., failure of the toe-nail joint between the top plate and rafter in an uncoated configuration.

Because nail pullout occurred in every other initial pull test except for this one, further analysis was conducted to understand why. Inspection of the lower joints in the specimens shown in Figs. (5a–b) revealed that all nails were driven vertically through the top plate into the stud. But Fig. 6 shows the grain structures in the studs. The ring patterns indicate that both studs were centrally cut; however, the relatively coarse grain structure observed in Fig. 6(a) resulted in end nail failure [see Fig. 5(a)], whereas the unusually fine grain structure observed in Fig. 6(b) resulted in toe-nail rafter failure [see Fig. 5(b)].

The joint between the stud and top plate in the configuration shown in Fig. 5(b) was subsequently tested by placing pull straps over the top plate and through the hole in the stud (see Fig. 7). The partial configuration held 2998 N, substantially higher than the load applied to fail the toe-nail joint.

Fig. 4 also includes a typical load versus deflection plot of an uncoated configuration that was reinforced with a Simpson LTS12 hurricane tie. As illustrated in Figs. (8a–b), failure occurred when the tie deformed as the nail farthest away from it pulled out of the stud. The specimen held a maximum load equal to 2277 N, which was considered “standard” for pullout failure of an uncoated, reinforced configuration.

2 by 4 End Nail Failure in Unreinforced Specimens

Fig. 9 shows the load/deflection plots obtained for the unreinforced standard along with those for typical unreinforced configurations coated with black and white polyurea.

The configuration that was coated with black polyurea held a maximum load of 3621 N and, as shown from the plot, failed

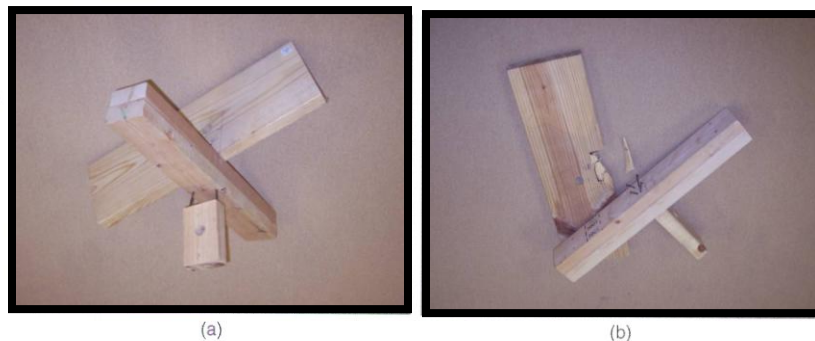


Fig. 5. Unreinforced configuration failure: (a) gradually as a result of 2 by 4 end nail failure; (b) abruptly as a result of toe-nail rafter failure



Fig. 6. Grain structure in the stud: (a) coarse and weaker; (b) fine

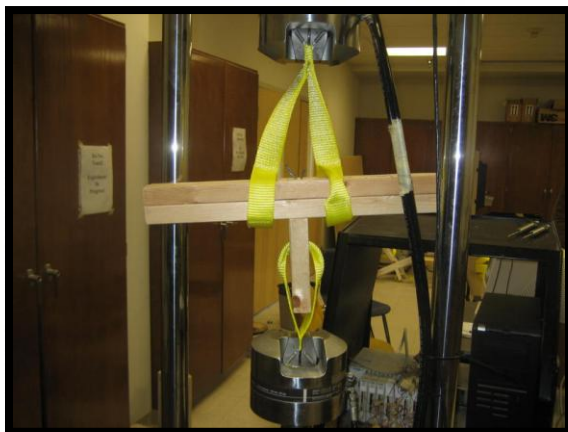


Fig. 7. Partial configuration shown in Fig. 5(b) retested for 2 by 4 end nail failure

relatively slowly. As shown in Fig. 10(a), a thin layer of wood fibers fractured in the top plate as the nails in the stud loosened and the coating stretched.

In contrast, the configuration coated with white polyurea held a maximum load of 7624 N and, as shown Fig. 10(b), abruptly failed when the wood fibers fractured in the top plate.

Although the white polyurea coating was on average slightly thicker than the black, the tensile strength of the black polyurea is slightly higher than that of the white. So, the superior performance of the white coating was attributed to the higher stiffness ratio between the polyurea and the wood and a better bond between the two. The higher stiffness ratio associated with the white polyurea forces more stress into the coating, thereby stiffening the overall configuration relative to that coated with the black version. This is evident in Fig. 9, where the slope associated with the white version is higher than the slope associated with the black version.

The superior bonding associated with the white polyurea was attributed to greater penetration into the wood substrate. A comparison of the specimens shown in Fig. 10 revealed that the fracture plane associated with the black polyurea [see Fig. 10(a)] is very close to the surface as opposed to that associated with the white polyurea, which lies deep within the wood grain [see Fig. 10(b)].

An observation was made during a close inspection of the coated unreinforced configurations. Fig. 11 shows the grain structure in the top plates of two different unreinforced configurations

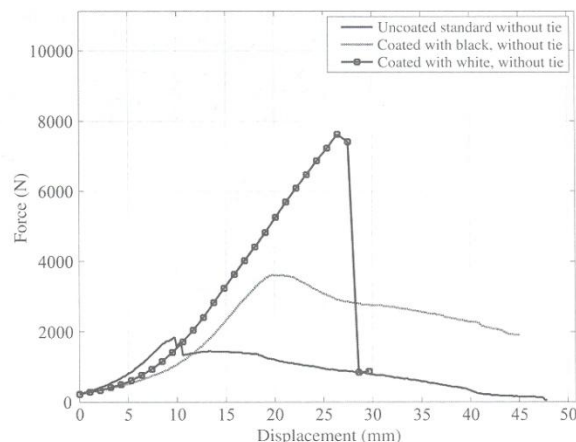


Fig. 9. Load versus deflection plots for 2 by 4 end nail failure in the uncoated unreinforced standard and coated unreinforced configurations

that were both coated with white polyurea. These configurations had very similar load/deflection plots, but the configuration in Fig. 11(a) held 7019 N, whereas the one in Fig. 11(b) [described previously and shown in Fig. 10(b)] held 7624 N. The difference is partially attributed to the orientation of the grain structure in the lower 2 by 4 that comprises the top plate. When the grain is oriented vertically [see Fig. 11(a)] parallel to the nail surface, the joint is relatively weak as compared with when the grain is oriented horizontally [see Fig. 11(b)] perpendicular to the nail surface.

2 by 4 End Nail Failure in Reinforced Specimens

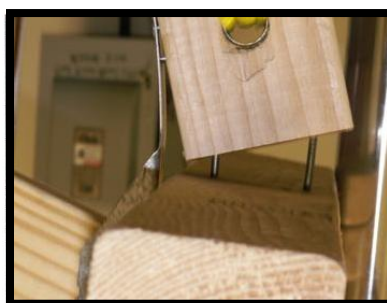
Fig. 12 shows the load/deflection plot obtained for the reinforced standard along with those for typical reinforced configurations coated with black and white polyurea.

The configuration that was coated with black polyurea held a maximum load of 5738 N. As illustrated in Fig. 13(a), the wood fibers, diametrically opposed to the hurricane tie and along the sides of the stud, fractured in the lower member of the top plate. Then while the coating stretched, the nails in the stud loosened.

In contrast, the sample coated with white polyurea held a maximum load of 9906 N. As illustrated in Fig. 13(b), the configuration abruptly failed when the wood fibers, diametrically opposed to the hurricane tie and along the sides of the stud, fractured in the lower member of the top plate.



(a)



(b)

Fig. 8. Failure of reinforced configuration occurred when nail farthest from tie pulled out of stud



Fig. 10. 2 by 4 end nail failure: (a) occurred relatively slowly in black-coated, unreinforced configuration; (b) failed quickly in white-coated configuration after wood fibers fractured in top plate

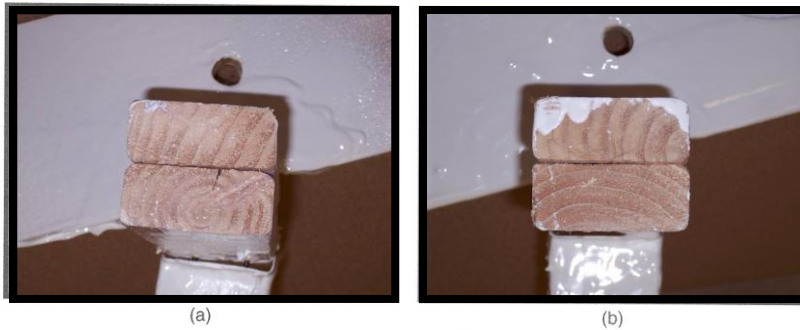


Fig. 11. Orientation of the grain in the lower member of the top plate: (a) weaker when oriented vertically; (b) oriented horizontally

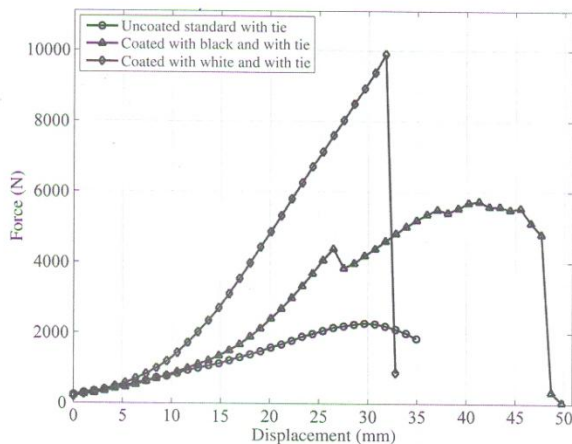


Fig. 12. Load versus deflection plots for 2 by 4 end nail failure in the uncoated reinforced standard and coated reinforced configurations

It is clear by looking at the slopes of the plots shown in Fig. 12 that the coatings stiffen the configuration, the white much more so than the black. Although the white-coated configuration holds more load, the black-coated configuration is able to sustain more deformation.

The secondary peak observed at a deflection of approximately 2.54 cm in the curve associated with the black-coated configuration was seen in every test conducted on configurations of this type. The peak may correspond to the fracture that takes place in the wood and, if so, could provide some insight into the relative bond strength associated with the two polyurea coatings. Assuming that the wood fibers fracture in the white-coated configuration at failure, the bond strength associated with the white coating is more than twice of that associated with the black.

Anomalies

During the initial pull test program, two coated configurations held substantially lower loads than those reported previously: (1) an unreinforced configuration coated with black polyurea, and (2) a reinforced configuration coated with white polyurea. The load/deflection curves obtained for these cases are plotted in Fig. 14 along with those corresponding to their stronger counterparts.

Inspection of these weaker specimens revealed that the polyurea felt sticky and failure occurred in the polyurea itself as opposed to within the wood fibers. This problem was attributed to incomplete mixing, which most likely occurred when one of the canisters in the spray gun ran dry before the other. Although the peak load is very different for the weak and strong specimens, for a given polyurea, the shapes of the curves are similar.

Summary of 2 by 4 End Nail Failure

Fig. 15 includes load/deflection plots corresponding to pullout for all six cases tested: (1) an unreinforced configuration,



Fig. 13. Coated reinforced configurations failure when wood fibers fractured in top plate: (a) relatively slowly; (b) quickly

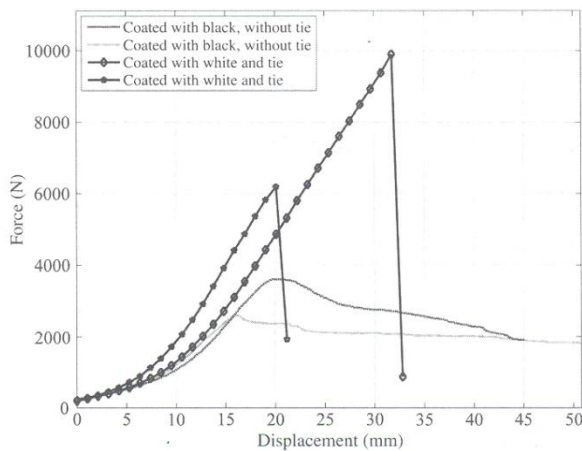


Fig. 14. Load versus deflection plots for 2 by 4 end nail failure in similar specimens that withstood very different peak loads

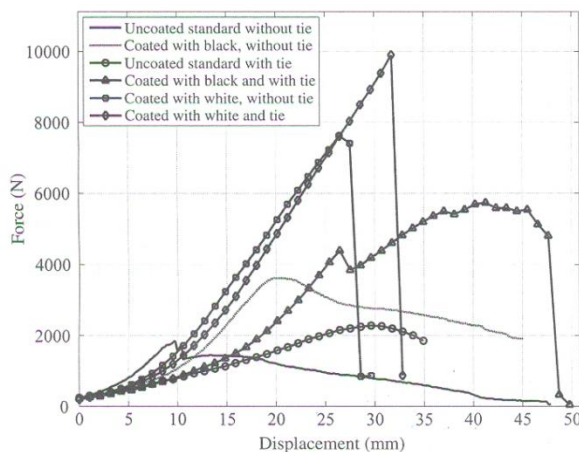


Fig. 15. Load versus deflection plots for 2 by 4 end nail failure in six different configurations

(2) a configuration reinforced with a hurricane tie, (3) an unreinforced configuration coated with black polyurea, (4) an unreinforced configuration coated with white polyurea, (5) a reinforced configuration coated with black polyurea, and (6) a reinforced configuration coated with white polyurea.

Table 1 lists the maximum loads that these six different configurations took along with the value of total deflection at which they occurred and the total strain energy required to achieve the maximum load condition. The net deflection and strain energy for each configuration was obtained by subtracting the values associated with the pull straps [see Eqs. (1)–(2)].

Table 2 lists the multiplication factors associated with coated specimens computed by taking the value found for a given quantity and dividing it by the value determined for its standard counterpart. The net strain energy is equal to the work done as the load is slowly applied and represents the amount of energy required to bring each configuration to the maximum load condition.

Toe-Nail Rafter Failure in Unreinforced Specimens

As noted previously, all specimens except for one failed as the nails in the top plate pulled out of the stud. As illustrated in Fig. 16(a), the other partial configurations that did not include a hurricane tie were tested by placing pull straps over the top plate and through the hole in the rafter. Fig. 16(b) shows how the toe-nail joint failed in the coated specimens as a crack developed and propagated along the rafter. This was notably different from the failure that occurred in the standard [described previously and shown in Fig 5(b)] in which the wood surrounding the nails fractured.

Summary of Toe-Nail Rafter Failure

Fig. 17 shows plots of load versus total deflection (of the configuration and the pull straps) corresponding to toe-nail fracture for an uncoated standard and configurations coated with black and white polyurea.

Table 3 lists the maximum loads that these three different configurations took along with the value of total deflection at which they occurred and the total strain energy required to achieve the maximum load condition. The net deflection and strain energy for each configuration was obtained by subtracting the values associated with the pull straps [see Eqs. (1)–(2)].

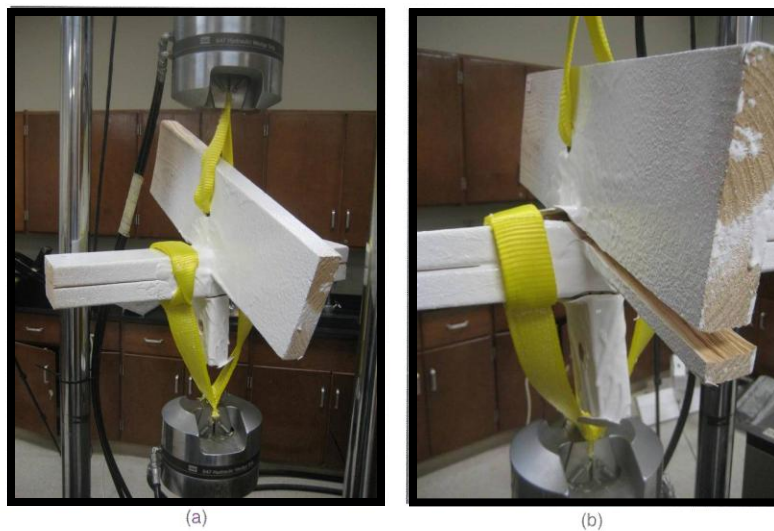
Table 4 lists the multiplication factors associated with coated specimens computed by taking the value found for a given quantity and dividing it by the value determined for its standard counterpart.

Table 1. Tabulated Results for 2 by 4 End Nail Failure in Six Different Configurations

| Configuration status | Maximum load (P_{max}) (N) | Total deflection at P_{max} (mm) | Deflection at P_{max} (mm) | Total strain energy to P_{max} (N mm) | Strain energy to P_{max} (N mm) |
|-------------------------------|--------------------------------|------------------------------------|------------------------------|---|-----------------------------------|
| Uncoated standard without tie | 1,850 | 9.7 | 8.1 | 8,699 | 7,231 |
| Uncoated standard with tie | 2,277 | 29.7 | 27.7 | 35,814 | 33,668 |
| Coated with black without tie | 3,621 | 19.8 | 16.8 | 28,810 | 23,274 |
| Coated with white without tie | 7,624 | 26.4 | 20.1 | 81,571 | 57,167 |
| Coated with black and tie | 5,738 | 41.4 | 36.6 | 113,544 | 99,648 |
| Coated with white and tie | 9,901 | 31.8 | 23.4 | 121,340 | 80,102 |

Table 2. Multiplication Factors; 2 by 4 End Nail Failure in Coated Configurations

| Configuration status | Load (P_{max}) with respect to standard | Total deflection at P_{max} with respect to standard | Deflection at P_{max} with respect to standard | Total strain energy to P_{max} with respect to standard | Strain energy to P_{max} with respect to standard |
|-------------------------------|---|--|--|---|---|
| Coated with black without tie | 1.96 | 2.05 | 2.07 | 3.31 | 3.21 |
| Coated with white without tie | 4.12 | 2.74 | 2.47 | 9.38 | 7.87 |
| Coated with black and tie | 2.52 | 1.39 | 1.32 | 3.17 | 2.96 |
| Coated with white and tie | 4.35 | 1.07 | 0.84 | 3.39 | 2.38 |

**Fig. 16.** Partial coated configurations retested: (a) to evaluate toe-nail after failure; (b) a crack developed in the rafter

Discussion

Referring to Tables 1–4, many factors could have contributed to deviations and potential errors in the values determined for deflection and strain energy, such as variations in wood grain and structure, kinks in the straps, elongation of the holes at the attachment points, variations in strap length, and differences in construction and the manner in which failure took place. But the results presented for peak load are indisputable.

It is clear from the tabulated data that the addition of a polyurea coating allowed both the unreinforced and reinforced configurations to withstand a greater load. Results for nail pullout indicate that when compared with their uncoated counterparts, the black-coated configurations were approximately twice as strong, whereas the white-coated configurations were four times as strong. The follow-up tests conducted to evaluate toe-nail fracture show that when compared with their uncoated counterpart, the black-coated

configurations were three times as strong, whereas the white-coated configurations were four times as strong.

A review of the load/deflection plots revealed that the peaks corresponding to the maximum load in the unreinforced coated configurations always occurred at a greater deflection than those corresponding to their uncoated counterparts. Thus, the addition of a polyurea coating delayed the onset of failure, allowing the unreinforced configurations to sustain more deflection before they reached their peak loads. Results for nail pullout and toe-nail fracture indicate that when compared with their uncoated counterpart, the coated configurations can sustain anywhere from two to three times as much deflection.

The fact that it can take almost eight times more energy to bring a coated unreinforced configuration to the peak load as compared with that required to bring an uncoated unreinforced configuration to the same condition is staggering. Even when the configuration is reinforced, the strain energy associated with the coated

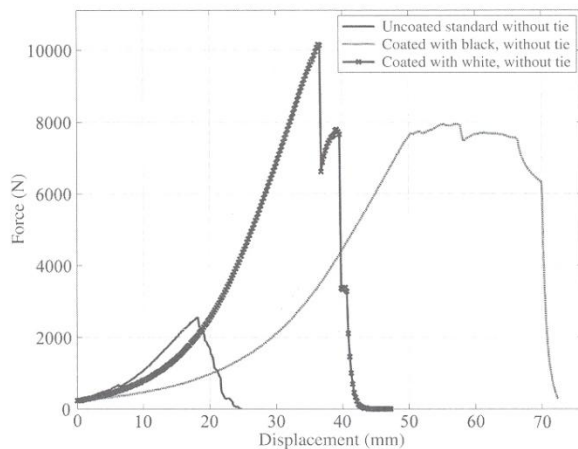


Fig. 17. Load versus deflection plots for toe-nail rafter failure of the uncoated unreinforced standard and unreinforced configurations coated with black and white polyurea

configurations is more than double that associated with their uncoated counterparts. Significantly, the polyurea strengthened both the unreinforced and reinforced configurations by increasing the amount of work/energy required to pull them apart.

Because nearly all hurricane straps are made of galvanized steel, there is limited design flexibility from a materials standpoint. This makes it difficult to design a configuration that can readily adapt in real time to withstand sustained winds or wind gusts. Referring again to the plots, the differences in the peaks and shapes associated with the coated configurations show that the failure mode of the unreinforced and reinforced configurations can be controlled by using different types of polyurea. The configuration can be designed to fail at a higher peak load in a relatively brittle fashion or at a lower load in a relatively ductile manner. If this knowledge can be harnessed and used to advantage, polyurea coatings may revolutionize how construction in hurricane-prone regions is done.

The hurricane tie, as installed, only increased the peak load of the unreinforced configuration by approximately 25% and allowed the configuration to deflect three times as much before the maximum load was achieved. Significantly, it has been shown that, when used in combination with a hurricane tie, a polyurea coating substantially enhanced the structural performance even when the strap alone does little to strengthen the uncoated joint.

In contrast to existing metal hurricane ties that are designed to withstand a specific loading, a polyurea coating provides more universal strengthening with the added advantage that members and joints can be protected from a multitude of threats, such as corrosion attributable to moisture and damage attributable to flood and, with self-extinguishing properties, fire.

Conclusions

In conclusion, a licensed carpenter was contracted to construct several rafter top plate model joint connections. Tension tests were performed on these configurations, some of which were reinforced with a hurricane tie, to establish how much of a difference a polyurea coating made as the joints between the stud and top plate, and top plate and rafter, were loaded to failure.

The addition of the coating allowed both unreinforced and reinforced configurations to withstand higher loads (200–400% more). In general, the polyurea delayed the onset of failure and significantly strengthened every configuration by increasing the amount of work/energy required to pull it apart, in some cases, by almost 800%. Tests showed that the failure mode can be controlled by using different types of polyurea, and results indicate that the commercial applications of using polyurea to strengthen structures in hurricane prone areas could be enormous. Polyurea provides universal strengthening compared with hurricane ties with the added advantage that members and joints can be protected from a multitude of threats, including corrosion attributable to moisture, damage attributable to flood, and, with self-extinguishing properties, fire.

Although it is evident from the results summarized in Tables 2 and 4 that the load-carrying capacities of the specimens reinforced with the polyurea coatings were higher than those without them, only one specimen was tested and reported for each configuration. Because the connection strengths of wood members can be highly variable, more tests are needed before one can quantify the reported strength gains with confidence. Also, because the tests performed were static in nature, additional work should be done to address things such as fatigue strength and long-term performance.

Acknowledgements

The authors would like to thank the U.S. Dept. of Commerce for supporting this research under NOAA SBIR Phase I and Phase II contract No. WC133R-09-CN-0108. They would also like to thank Mr. Rajesh Vuddandam for his help with running the pull tests and

Table 3. Tabulated Results for Toe-Nail Rafter Failure in Three Different Unreinforced Configurations

| Configuration status | Maximum load (P_{max}) (N) | Total deflection at P_{max} (mm) | Deflection at P_{max} (mm) | Total strain energy to P_{max} (N mm) | Strain energy to P_{max} (N mm) |
|-------------------------------|--------------------------------|------------------------------------|------------------------------|---|-----------------------------------|
| Uncoated standard without tie | 2,562 | 18.3 | 16.3 | 20,788 | 18,077 |
| Coated with black without tie | 7,949 | 55.1 | 48.5 | 155,798 | 129,248 |
| Coated with white without tie | 10,164 | 36.3 | 27.7 | 119,306 | 75,922 |

Table 4. Multiplication Factors; Toe-Nail Rafter Failure in Unreinforced Coated Configurations

| Configuration status | Load (P_{max}) with regard to standard | Total deflection at P_{max} with regard to standard | Deflection at P_{max} with regard to standard | Total strain energy to P_{max} with regard to standard | Strain energy to P_{max} with regard to standard |
|-------------------------------|--|---|---|--|--|
| Coated with black without tie | 3.10 | 3.01 | 3.00 | 7.49 | 7.17 |
| Coated with white without tie | 3.97 | 1.99 | 1.72 | 5.74 | 4.21 |

acquiring data at the Univ. of Alabama in Huntsville and Mr. John Becker, president of Creative Material Technologies, for helping to select the polyureas used in this study. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the Dept. of Commerce.

References

- Allredge, D. J., Gilbert, J. A., Toutanji, H., Lavin, T., and Balasubramanyam, M. (2011). "Structural enhancement of framing members using polyurea." *Mechanics of Time-Dependent Materials and Processes in Conventional and Multifunctional Materials*, Vol. 3, Conf. Proc. of the Society for Experimental Mechanics Series, 99999, Society for Experimental Mechanics (SEM), Bethel, CT, 49–63.
- Bahei-El-Din, Y. A., and Dvorak, G. J. (2007). "Behavior of sandwich plates reinforced with polyurethane/polyurea interlayers under blast loads." *J. Sandwich Struct. Mater.*, 9(3), 261–281.
- FEMA. (2005). "Reconstruction guidance using Hurricane Katrina surge inundation and ABFE maps." (http://www.fema.gov/pdf/hazard/flood/recoverydata/katrina/katrina_reconstruction.pdf).
- FEMA. (2008a). "Design and construction guidance for community safe rooms." Washington, DC, 361.
- FEMA. (2008b). "Flood damage-resistant materials requirements for buildings located in special flood hazard areas in accordance with the national flood insurance program." *Technical Bulletin 2*, Washington, DC.
- FEMA. (2010). "Home builder's guide to coastal construction." P-499, Washington, DC.
- Grigsby, R. A., and Dominguez, R. J. G. (1986). "Polyurea RIM—A versatile high performance material." *J. Elastomers Plast.*, 18(2), 71–84.
- Hill, R., and Walker, E. E. (1948). "Trend of crystalline melting points in homologous series of aliphatic polymers." *J. Polym. Sci.*, 3(5), 609–630.
- Insurance Institute for Business and Home Safety. (2009). "Hurricane Ike, nature's force vs. structural strength." (<http://www.disastersafety.org/research/article?articleId=4449>), (Aug. 28, 2011).
- International Code Council. (2009). "International building code: General construction requirements." (http://publicecodes.citation.com/ncod/ibc/2009/ibc_2009_23_sec004_par030.htm), (Aug. 28, 2011).
- Moradi, L. G., Davidson, J. S., and Dinan, R. J. (2008). "Resistance of polymer retrofit concrete masonry walls to lateral pressure." *J. Perform. Constr. Facil.*, 22(3), 131–142.
- Moradi, L. G., Dinan, R. J., Bewick, B. T., and Davidson, J. S. (2010). "Resistance of concrete masonry walls with membrane atcher systems." *AFRL-RX-TY-TP-2010-0090*, Air Force Research Laboratory Materials and Manufacturing Directorate, Wright-Patterson Air Force Base, OH.
- Panduranga, R., Shivakumar, K. N., and Russell, L. Jr. (2007). "Energy absorption performance of eco-core—A syntactic foam." *48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 8, 7670–7678.
- Polyurea Development Association. (2011). (<http://www.pda-online.org/Content.asp>), (Aug. 28, 2011).
- Primeaux, D. J., II (2000). "Evolution of polyurea 'spray.'" *Building on the Future, PDA 1st Annual Meeting*, pp. 1–36. (<http://www.primeauxassociates.com/wp-content/uploads/2011/11/PP11.pdf>), (Aug. 28, 2011).
- Reed, T. D., Rosowsky, D. V., and Schiff, S. D. (1997). "Uplift capacity of light—Frame rafter to top plate connections." *J. Archit. Eng.*, 3(4), 156–163.
- Roland, C. M., Twigg, J. N., Vu, Y., and Mott, P. H. (2007). "High strain rate mechanical behavior of polyurea." *Polymer*, 48(2), 574–578.
- Rowton, R. L. (1977). "Cyanoethylated Polyoxypolypropylenepolyamines: Polymer formers of unique reactivity." *J. Elastomers Plast.*, 9(4), 365–375.
- Simpson Strong Ties. (2011). "LTS/MTS/HTS twist straps." (<http://www.strongtie.com/products/connectors/LTS-MTS-HTS.asp>), (Aug. 28, 2011).
- van de Lindt, J. W., Graettinger, A., Gupta, R., Skaggs, T., Pryor, S., and Fridley, K. J. (2007). "Performance of wood-frame structures during Hurricane Katrina." *J. Perform. Constr. Facil.*, 21(2), 108–116.