P 2.17

WIND EFFECTS ON ASPHALT SHINGLES

Timothy P. Marshall*, Scott J. Morrison, Richard F. Herzog, Jeffrey R. Green
Haag Engineering Co.
Irving, Texas

1. INTRODUCTION

Asphalt shingles have been utilized as a roofing material for more than one hundred years. The first asphalt shingles were manufactured in 1901 but were not mass produced until 1911 (Snoke 1941). Asphalt shingles were originally made from cotton rags that were coated with asphalt and surfaced with slate particles (McNulty 2000). In the early 1960s, glass fiber mats were introduced as the base material for asphalt shingles which made the shingles lighter and less apt to retain detrimental moisture (Cullen 1993). Relatively inexpensive asphalt along with advancements in mat and sealant technology quickly led to asphalt shingles becoming the primary choice for steep slope roofing. In 2009, asphalt shingles comprised 57 percent of the roofing market covering 138.5 million roofing squares (The Freedonia Group 2010). (Note: A square in roofing is 100 sq. ft. or 9.3 m^2.) Today, there are literally billions of roofing squares covered by asphalt shingles in the United States (Noone and Blanchard 1993).

Not surprising, a large percentage of steep slope roofing in hurricane prone regions is asphalt shingles because asphalt shingles are more economical than their tile or metal counterparts. Further, stringent building codes and standards have led to tougher demands on the asphalt shingle industry. Today, asphalt shingles can be rated for high wind zones up to 67 m s^{-1} (150 mph) as a three-second gust.

However, there remain problems at the basic level with the design, manufacture, installation, and durability of asphalt shingles. Assessments of asphalt shingle roofs by the authors after hurricanes have revealed deficiencies in each of these areas. Similar findings have been made by McDonald and Smith (1990) after Hurricane Hugo, Smith (1995) after Hurricane Andrew, Rash (2006) after Hurricane Ivan, and the Roofing Industry Committee on Weather Issues (RICOWI) (2006, 2007, and 2009) after Hurricanes Charley and Ivan, Katrina, and Ike, respectively.

Corresponding author address: Timothy P. Marshall, 4041 Bordeaux Circle, Flower Mound, TX 75022-7050. email: timpmarshall@cs.com

While wind damage to asphalt shingles is usually obvious (i.e. torn and missing shingles) there remain a number of issues with asphalt shingles (i.e. cupping, clawing, splitting, lack of bonding) which some people falsely attribute to wind. Thus, it is the subject of this paper to review and discuss the modes of wind damage to asphalt shingles.

2. WIND DAMAGE MECHANISM

Wind interacting with a roof is deflected over and around it. As a result, uplift pressures develop on the roof. However, uplift pressures are not uniform and are highest along the windward corners, rakes, eaves, and ridges (Fig. 1). It is at these locations that wind uplift damage initiates especially with asphalt shingles that are not well bonded (Fig. 2). Wind flow in these areas is quite turbulent. Thus, it is important that the roof covering receive additional anchorage in these high wind uplift regions. The Federal Emergency Management Agency (FEMA 2005) has published guidelines on how to attach asphalt shingles in these areas which involve the application of adhesive dollops along the roof edge and between the asphalt shingles in high wind zones.

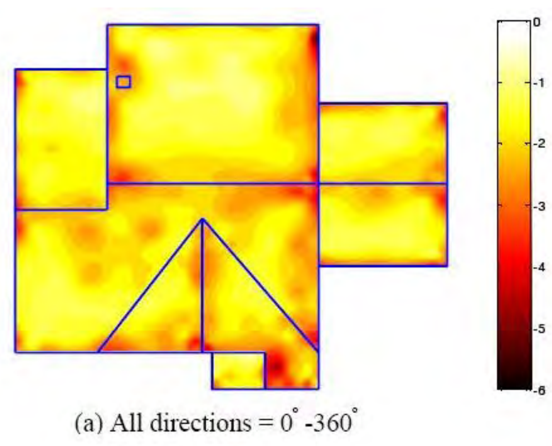

Figure 1. Peak negative uplift pressure coefficients (C_p) on a gable roof from a wind tunnel model. Wind directions were at 10 degree increments. From Liu et al. (2006)

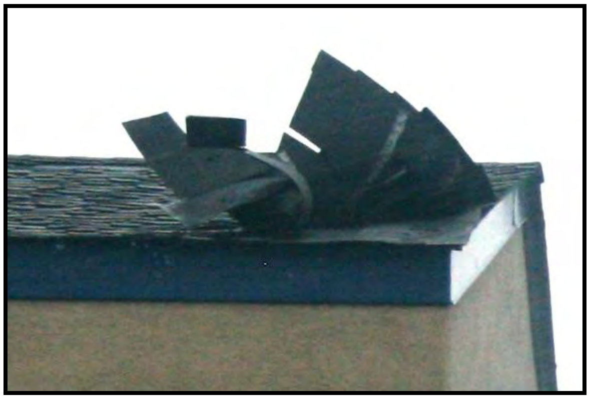

Figure 2. Uplift of asphalt shingles on the corner of a gable roof during Hurricane Gustav. Image by Tim Marshall.

One mechanism of asphalt shingle uplift is specific to the shingle itself. Peterka et al. (1997) and Jones et al. (1999) have shown that wind-induced uplift of shingles can be different from the mechanism that causes uplift on impervious roof sheathing. Due to small dimensions of the shingles and their pervious design, pressure variations across the shingle surfaces can be relatively small. Thus, it is the profile of the shingle that determines the extent of wind uplift. A critical part of the shingle is that region cantilevered downslope from the sealant strip (Fig. 3). Wind stagnates at the base of the shingle while aerodynamic uplift occurs on top of the shingle, a situation similar to what occurs on an aircraft wing. The resulting lift can deform the shingle, producing greater projected area and therefore, more lift (Fig. 4). Noone and Blanchard (1993) indicated: 1) the quality of fastener installation, 2) the strength of the sealant, and 3) the physical properties of the asphalt shingle (i.e. fastener pull-out strength and stiffness) are critical factors in resisting wind uplift damage.

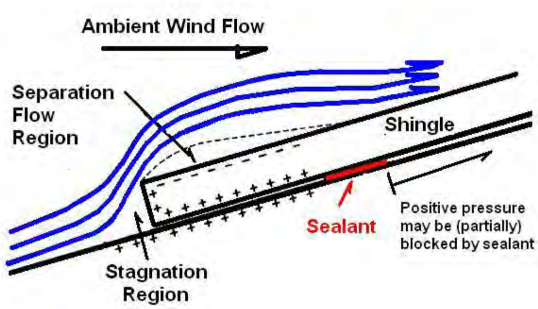

Figure 3. Idealized wind flow (blue lines) and resultant positive (plus signs) and negative pressures (minus signs) at the bottom edge of a shingle. From Peterka et al. (1997).

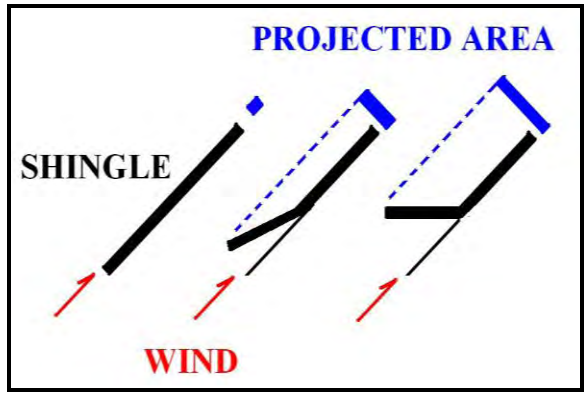

Figure 4. Idealized diagram showing the increase in the projected area (blue line) as the shingle is uplifted in the wind.

3. TYPES OF ASPHALT SHINGLES

The two most common types of strip asphalt shingles are three-tab and laminated (Fig. 5). Both shingle types are comprised of glass-fiber or paper mats that are saturated in hot asphalt and top coated with granules. With three-tab shingles, two joints are cut out of the bottom half of the shingle primarily as a design feature. Laminated shingles have a top laminate and a bottom laminate. The lower portion of the top laminate has trapezoidal-shaped cut-outs whereas the bottom laminate is a solid shingle. The bottom laminate is only half the width of the top laminate and is adhered to the lower portion on the back side of the top laminate. The design of the laminated shingle gives the appearance of wood shingles. Both shingle types have sealant strips.

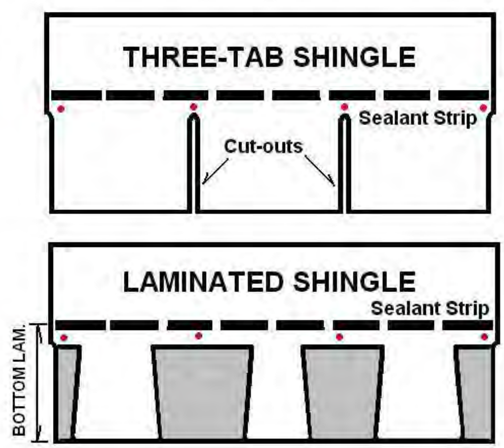

Figure 5. The two most common types of asphalt shingles are the three-tab and the laminated. At least four fasteners must be installed per shingle (standard application) as noted by locations of the red dots.

Other types of asphalt shingles include solid strip (without the cut-outs or laminates) and large format. Less common types are the T-lock, hexagonal, and three or more laminates. The interlocking shingles typically do not have sealant strips.

Shingles must be fastened properly to the roof in order to achieve the maximum wind resistance. In non-hurricane regions, four fasteners are required to secure three-tab and laminated shingles. However, in hurricane prone regions, some building codes require six fasteners per shingle. The vast majority of shingle manufacturers require that fasteners be installed below the sealant strip and above the cut-outs, and within one inch of the ends of the shingles. Fasteners must extend through the shingle as well as the underlying shingle. Fasteners also must be long enough to penetrate plywood and oriented strand board (OSB) roof decking. It is critical that fasteners be driven flush with the shingle surfaces and not over- or underdriven.

4. HURRICANE FRANCES STUDY

According to the Beven (2004) at the National Hurricane Center, the eye of Hurricane Frances made landfall on Hutchinson Island, FL as a Category 2 storm on the Saffir-Simpson scale around 0430 UTC on 5 September 2004 and traveled slowly west-northwest across the Florida peninsula. The Army Corps of Engineers (USACE) station at Port Mayaca reported sustained winds of 38 m s^{-1} (85 mph) at 0500 UTC, while a portable instrumented tower operated by the Florida Coastal Monitoring Program (FCMP) at Ft. Pierce reported 36 m s^{-1} (81 mph) sustained winds at 0402 UTC along with a peak gust of 48 m s^{-1} (107 mph).

Shortly after the hurricane, the lead author conducted a survey of roof damage along the eastern Florida coast. The purpose of the survey was to evaluate the performance of common roofing systems in strong winds. The survey was performed along the coastline via Highway A1A from Cocoa Beach to Jupiter Beach. Three coastal subdivisions were selected for examination of roof performance. These subdivisions were located in Vero Beach, Stuart, and Ft. Pierce.

The degrees of shingle damage were categorized as: (1) little to no damage, (2) between 10 and 50 percent damage, and (3) greater than 50 percent damage. A total of 280 asphalt roof coverings were evaluated. Of these, 129 roofs had three-tab shingles and the remaining 151 roofs had laminated type shingles. Many three-tab shingle roofs were installed in the straight-up or racking patterns whereas laminated shingles were installed in diagonal patterns. Table 1 summarizes the results of the survey:

TABLE 1
PERFORMANCE OF ASPHALT SHINGLES IN HURRICANE FRANCES

SHINGLE TYPE	Little to no Damage	10-50% Damage	>50% Damage	Total number of roofs
Three-tab	57 (44%)	11 (9%)	60 (47%)	129
Laminated	132 (87%)	6 (4%)	13 (9%)	151

Failures of the three-tab shingles typically occurred when the tabs were not bonded to the sealant strips and were lifted, breaking at the tops of the tabs. Failure was more likely in those tabs which bridged the butted end joints of underlying shingles. The result was a "zipper" like pattern of missing tabs that extended upslope from the eaves to the ridges (Fig. 6).

Figure 6. Wind damage to asphalt shingles installed in the racking or “straight-up” pattern after Hurricane Frances.

It was found that three-tab asphalt shingles did not perform as well as laminated shingles during the hurricane. Only 44 percent of roofs with three-tab shingles had little to no damage compared to 87 percent of roofs with laminated type asphalt shingles. This was due in part to lighter weights of the tabs and their design which acted like a flap on an aircraft wing. Once the sealant bond was broken, the tab would fold back and crease along the top of the tab. Multiple flipping of the tab in the wind eventually caused some tabs to tear and blow away.

A total of 11asphalt shingle roofs were selected for detailed examination. On 10 of the 11 roofs, the shingles had been fastened improperly with nails or staples installed in or above the sealant strips, thereby missing the underlying shingles. In some instances, fasteners interrupted the transfer of the sealant to the overlying shingle. The numbers of fasteners ranged from three to six per shingle.

Four primary modes of asphalt shingle failures occurred during Hurricane Frances: 1) creasing, 2) flipping, 3) tearing/removal, and 4) abrading from flying or falling debris (Fig. 7). It was not uncommon to find multiple modes of failure on a roof or slope. In some instances, entire shingles tore away when the fasteners pulled through the mats. Noone and Blanchard (1993) reported similar modes of failure with asphalt shingles during wind storms.

Figure 7. Various types of wind damage to asphalt shingles.

5. OTHER FACTORS THAT INFLUENCE SHINGLE FAILURE IN THE WIND

The authors have identified several factors that can lead to asphalt shingle failure during windstorms: 1) degree of weathering, 2) design, 3) quality of manufacture, and 4) quality of installation. A brief explanation of each of these issues follows.

a. Weathering of asphalt shingles

As asphalt ages, it dries out, shrinks, and cracks. Sealant strips beneath the shingles deteriorate, leading to lower wind resistance. The authors have found certain shingles where the sealant strip had little to no bond strength. Such shingles could be lifted easily by hand (Fig. 8). RICOWI (2009) found that roofs installed in the last ten years appeared to perform better than older roofs in their damage assessment after Hurricane Ike.

According to the National Association of Home Builders (NAHB 2007), the expected life of asphalt shingles is 20 years. Of course, there can be wide variance in expected life depending on the type of shingle, quality of installation, extent of attic ventilation, geographic location, etc.

Dupuis and Graham (2002) conducted laboratory tests on various three-tab shingles and found that heat and moisture affect tear strength, leading to premature cracking and less wind uplift resistance. They also indicate that darker shingles experience higher thermal loads and deteriorate more quickly than lighter-colored shingles.

Figure 8. This aged tab had little sealant bond strength and could be easily lifted by hand. Note the crazed cracks on the shingle surface.

b. Design deficiencies with asphalt shingles

The cut-out design in the three-tab shingle makes them more prone to flipping in the wind after sealant failure. However, the authors have found other shingle designs that are particularly prone to wind damage. One manufacturer makes a three-tab shingle with a small, rectangular tab adhered to the top of the shingle. This rectangular tab prevents sealant on the bottom side of the overlying tab from bonding fully to the underlying tabs. Also, an air gap is created between rectangular tabs allowing wind to get underneath them. The result is the uplift and removal of the tabs at relatively low wind speeds (Fig. 9).

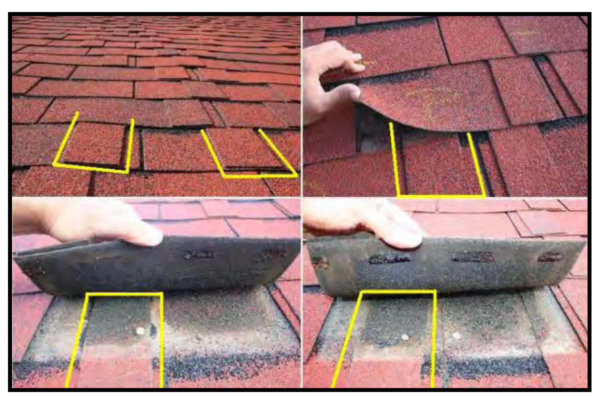

Figure 9. Rectangular tabs (outlined) adhered to the tops of the shingles prevented full contact of the overlying tabs and created air gaps between the tabs.

Certain shingles have the sealant strip on the smooth, bottom side of the shingle rather than on the top. The authors have noticed that these shingles often do not bond well to the underlying shingles. The sealant is supposed to bond to the rough granule surface; but instead, the sealant becomes contaminated with loose granules. Part of the problem can be an insufficient amount of sealant. We have noticed that shingles bond better when the sealant strip is on the rough granule surface and bonds to the smooth surface on the bottom of the overlying shingle.

c. Manufacturing problems with asphalt shingles

There are various roofing industry standards that measure physical properties of asphalt shingles with regard to wind uplift resistance. One organization providing asphalt shingle specifications is the American Society of Testing and Materials (ASTM 2010). The ASTM D 3161 standard involves subjecting asphalt shingle test panels to wind speeds generated by a fan between 27 m s^{-1} to 49 m s^{-1} (60 to 110 mph) for a period of two hours. In order to pass this test, no free portions of the shingles shall lift enough to stand upright or bend back on itself. Also, the sealing feature must remain intact. However, as Shaw (1991) points out, the weakness in this test is that it uses constant wind speed whereas natural wind varies in intensity, duration, direction, and turbulence. Also, the test is conducted on new shingles.

The ASTM D 3462 standard has three main parts. The first part measures tear strength of glass fiber mat shingles. The minimum tear resistance needed to pass this test is 1700 g. Koontz (2007) conducted tests on 13 new shingles and found that eight shingles (three three-tabs and five laminated) failed the tear strength portion of this test. The second part measures fastener pull-through resistance. It requires a minimum pull-through force of a fastener for both one and two layers of shingle material. One layer is required to have a pull-through resistance of 20.0 lbf, and two layers must have a pull-through resistance of 30.0 lbf. The remaining part measures physical properties of the shingle to include the minimum net mass of the glass fiber mat. A net mass of 1.35 lbs/100 ft^2 is required to pass this test.

The ASTM D 6381 standard measures resistance of the sealed shingle to an applied force. A shingle specimen is heat-conditioned for 16 hours and then pulled apart. The uplift force shall be equal or greater than the calculated uplift force for the corresponding wind speed classification in UL 2390. Shingles are designated as CLASS D, G, or H if the sealed product can resist winds up to 40, 54 and 67 m s^{-1} (90, 120, and 150 mph), respectively. However, as Koontz (2007) notes, compliance with ASTM standards does not insure a quality product. Such standards are the goal of manufacturers and yet they represent minimum requirements. Noone and Blanchard (1993) also point out that if the sealants are too strong, they can promote shingle splitting whereas weak sealants can lead to shingle removal during low wind speeds. McDonald and Smith (1990) indicated that asphalt shingle performance in Hurricane Hugo was governed primarily by effectiveness of tab seals.

d. Installation problems with asphalt shingles

Another factor in wind resistance is how well the asphalt shingles are fastened to the roof deck. The authors frequently have found first shingle courses are not bonded to the starter shingles. This condition occurs when the starter shingles are not installed correctly (with the tabs cut off such that the sealant strip is placed at the roof edge.) Thus, the first shingle course is not bonded to the roof and can be removed in relatively low wind speeds (Fig. 10). Such shingles can also be lifted easily with a finger.

Figure 10. Loss of first tab course from Hurricane Ike as the tabs were not sealed down due to improper installation of the starter shingles as shown by inset.

High fastening also can make asphalt shingles more susceptible to being removed in the wind. Smith and Millen (1999) conducted wind tunnel tests on asphalt shingles and concluded that fasteners that were installed improperly can increase wind related damage when the tabs are not sealed. In their tests, nails were installed one inch above the fastener line such that the nails penetrated only one shingle. Such high nailing also can lead to shingle slippage.

Koontz (2007) found that when a fastener is placed at the proper location, fastener pull-through resistance approximately doubles from that when a fastener is improperly placed.

Shingle manufacturers require that fasteners be driven flush to the shingle surfaces and be installed in the correct locations. Underdriven fasteners can prevent the sealant strip from contacting overlying shingles. As a result, overlying shingles remain elevated and the fasteners eventually protrude through it. Typically, sealant that does not bond remains smooth. Dirt and debris can accumulate on the sealant rendering it ineffective (Fig. 11). Overdriven fasteners can dimple the shingles also preventing sealant transfer or cut through the shingles. Wind would not pull out the fasteners and leave the shingles intact.

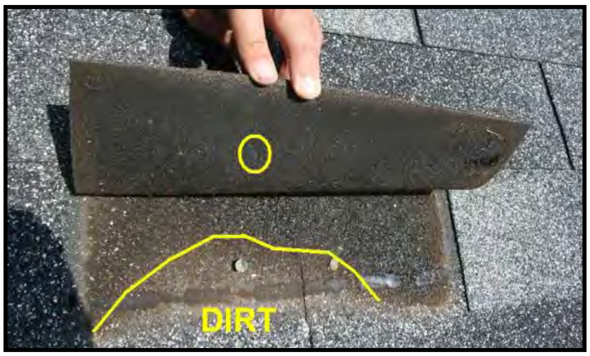

Figure 11. Elevated nail (note shadow) prevented this tab from bonding to the sealant strip. Note the dirt residue and smooth sealant on the underlying shingle and lack of sealant transfer to the bottom side of the overlying tab. The yellow circle highlights the indentation of the nail head in the bottom of the overlying tab.

Fasteners also must be long enough to penetrate the plywood or OSB roof decking. Longer fasteners are needed to attach ridge tabs, especially when installed over high profile plastic or fabric type ridge vents. The authors have found many wind damaged ridge shingles because the fasteners were too short (Fig. 12).

Figure 12. Loss of ridge tabs due to insufficient fastener length (inset).

6. WHAT IS NOT WIND DAMAGE

There are a number of shingle anomalies that are not caused by wind but can be mistaken for wind damage. Ribble et al. (1993) described many of these anomalies.

Cupping and clawing occurs slowly and progressively as the shingles shrink. Cupping results when the top portions of shingles shrink more than their bottoms, causing the unrestrained corners to curl upward. Clawing is the opposite of cupping and involves the corners curling downward (Fig. 13).

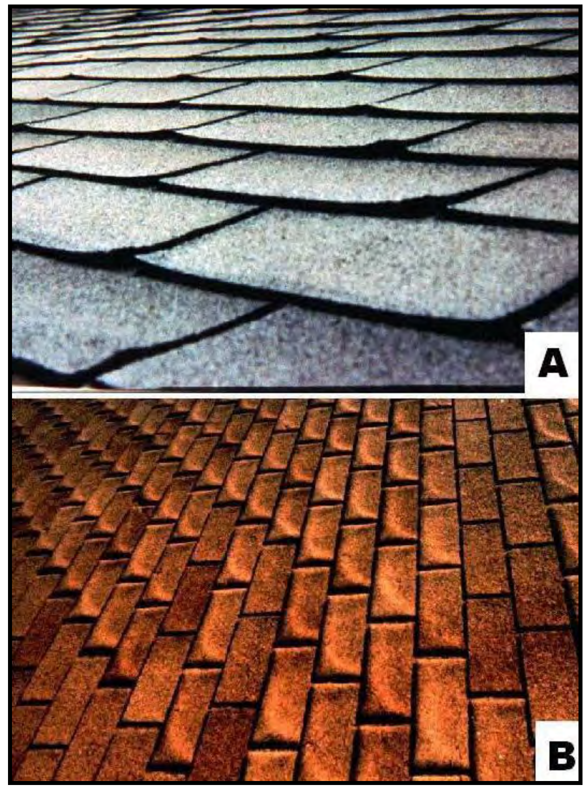

Figure 13. Examples of cupping (A) and clawing (B) of asphalt shingles. These conditions are not caused by storm effects.

Shingle splitting is relatively common, especially with glass fiber mat type shingles. According to Koontz (1990) and (2007), this failure mode is a combination of three factors: 1) a lack of sufficient tensile strength in the fiberglass mat, 2) thermal expansion and contraction, and 3) full adhesion of the self-sealer strip over the end joints. These factors combine to split shingles as they shrink. Shingle splitting is not caused by wind.

Horizontal splits occur as the shingle shrinks between the two lines of anchorage. The middle of the shingle is fastened mechanically to the roof deck while the bottom edge is secured with sealant. Horizontal splitting occurs between the two lines of restraint.

Vertical splits occur as the top shingles shrink over the butted joints on underlying shingles. On shingles installed in racking or straight-up patterns, splits extend vertically upslope. On shingles installed in a diagonal manner, splits are curved, extending upslope on overlapping portions of the shingles. Generally, torn shingle pieces remain bonded to the underlying shingles. In some instances, shear failure occurs in the sealant and the overlying shingle does not split. Occasionally, curved and round splits occur as a shingle tears around the underlying sealant dollops. In some instances, shingle corners become elevated (Fig. 14).

Figure 14. Examples of shingle splitting: a) horizontal, b) vertical, c) curved, and d) rounded. Such splitting is not caused by wind.

Shingles frequently are not bonded to the roof where they overlap an adjacent shingle. Poor adhesion of the sealant strip in combination with cyclic thermal expansion and contraction along the long dimension of the shingle causes the unbonded condition. Eventually, dirt and debris render the seal ineffective. The authors have found this condition on roofs around the U.S., and not just in hurricane prone regions.

The pattern of unbonded shingles depends on the manner in which the shingles were installed. Shingles installed in a racking or straight-up pattern typically have alternating overlaps not bonded to the underlying shingles. By comparison, shingles installed diagonally typically have left or right overlaps not bonded to the underlying shingles. Usually, unbonded overlaps can be found on each directional slope. Wind does not come from multiple directions with just enough force to unbond the shingle overlaps on different slopes. Refer to Figures 15 through 18.

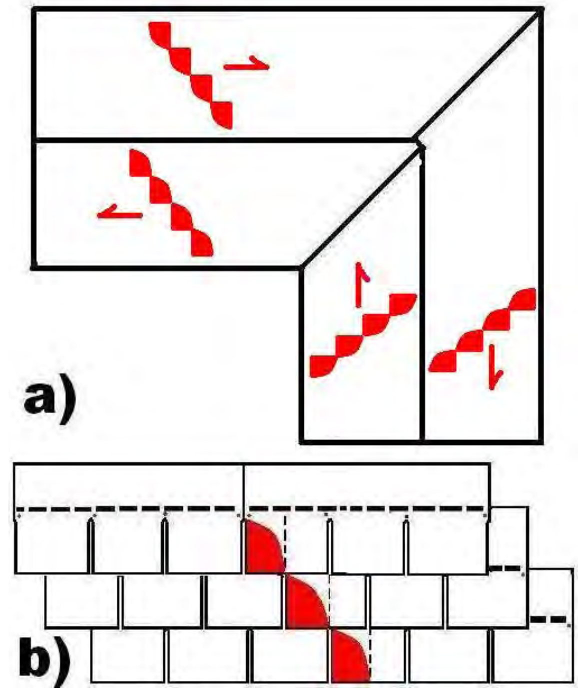

Figure 15. Diagonal pattern of shingle overlaps not bonded to the roof: a) roof plan showing open laps (arrows) pointing in different directions, and b) idealized diagram showing red shaded region where tabs could be lifted unimpeded by hand. This pattern extends diagonally upslope depending on the manner in which these shingles were installed.

Figure 16. Roof in Norman, OK where overlaps were not bonded to the underlying shingles on each directional slope (indicated). This condition was not wind-caused.

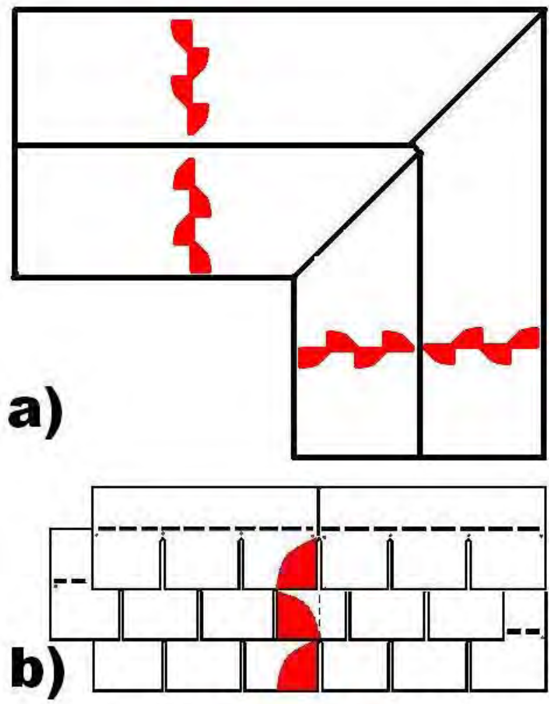

Figure 17. Straight-up pattern of shingle overlaps that are not bonded to the roof: a) roof plan showing alternating overlaps not bonded to the roof on each directional slope, and b) idealized diagram showing red shaded region where tabs were not bonded to the underlying shingles. This pattern extends vertically upslope in the manner in which these shingles were installed.

Figure 18. Roof in Minneapolis, MN where overlaps were not bonded to the underlying shingles on directional slopes (indicated). This phenomenon was not wind-caused.

7. MECHANICALLY-CAUSED DAMAGE

Occasionally, the authors have found other forms of roof damage inconsistent with wind damage. There have been instances where shingle pieces have been torn away and left near the shingles. In certain instances, the damage was not intentional, (i.e. caused by rubbing tree limbs or squirrels). In other instances, the damage was intentional, in an attempt to simulate wind damage. There are a number of characteristics that distinguish intentional damage to a roof from wind caused damage.

Intentional damage to the roof usually involves recognizable patterns. In many instances, the right or left corners of shingles/tabs are removed instead of the entire shingle/tab. Also, shingle damage tends to be concentrated in walkable areas of a roof, away from roof edges (Fig. 19). Sometimes, shingles are broken and torn away removing portions of the sealant strip indicating the shingle was well bonded. Close examination of the sealant strip can reveal impressions of tool marks used to pry up the shingles. Occasionally, the roof slope containing the damage does not correlate with wind direction. A plot of the damage on a roof plan diagram can better show such patterns.

What is not damaged by wind is just as important as what is damaged. The authors have found intentional damage to shingles when television antennas, satellite dishes, gutters, etc. were not damaged. As mentioned earlier, there are usually areas on the roof where shingles never had bonded such as along the first shingle course. The force needed to break a bonded field shingle would be greater than that needed to break a shingle with no bond.

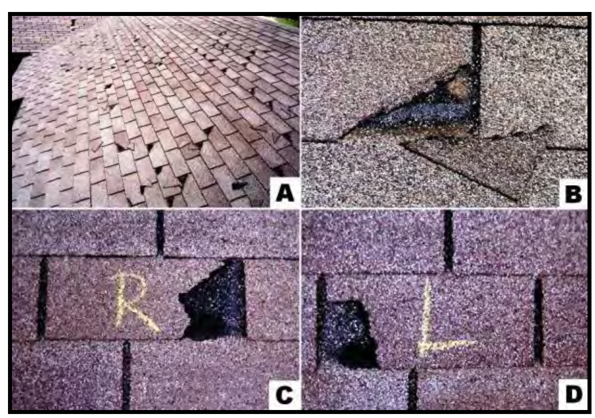

Figure 19. Intentional damage to roofs to simulate wind damage: a) broken corners upslope away from roof edge, b) broken corner left nearby, c) torn right edge of tab, and d) torn left edge of tab.

8. SHINGLE REPAIRS

Asphalt shingles can be assessed for wind damage on a slope-by-slope basis. Repairs can be made to individual shingles or groups of shingles by standard insert techniques, or roofing on entire slopes can be removed and replaced. The choice to repair or replace a roof or slope is typically based on economics.

Unbonded shingles can be sealed in accordance with the Asphalt Roofing Manufacturers Association (ARMA 2006) guidelines. For three-tab shingles, dollops of asphalt roofing cement, about the size of a quarter coin, can be placed on the underlying shingle to secure the lower corners of the overlying tabs. For laminated shingles, four dollops of asphalt roofing cement can be placed on the underlying shingles to secure the bottom edges of the overlying shingles. The dollops are placed 2.5 cm (1 in.) inwards from the ends of the overlying shingles with equal space between.

Uplift tests were performed by the authors on a building roof that was not damaged by Hurricane Ike. Strengths of the shingle sealant were determined by pulling upward on sealed shingles using a specially made metal bracket that was inserted beneath the bottom edges of the shingles and using a dynamometer (digital force gauge) to measure the uplift force (Fig. 20).

After the shingles were mechanically unbonded, they were sealed with two common types of sealant. Sealing included both the standard-size dollops and .64 cm (1/4 in.) wide continuous beads. After a 30-day cure time, the shingles were pulled again. Strengths of the dollops and continuous beads both exceeded the original sealant strengths. Average strengths of the dollops exceeded existing sealant strengths by more than 70 percent while the average strengths of continuous beads exceeded existing sealant strengths by more than 400 percent. In some instances, the bond between the repaired shingles was so strong that uplifting tore the underlying shingles.

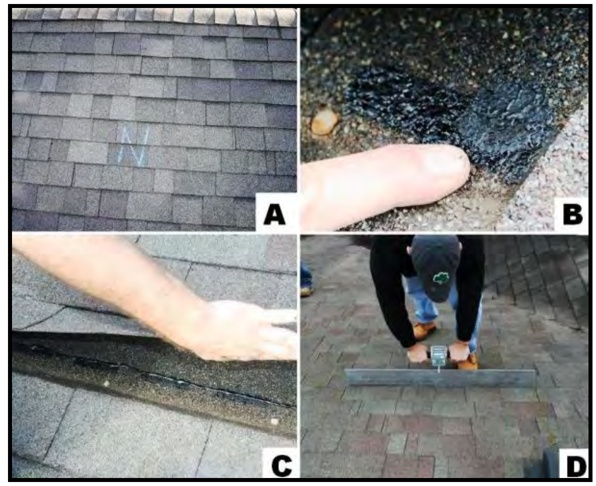

Figure 20. Pull tests on laminated asphalt shingles: a) undamaged shingles, b) dollop of asphalt plastic cement applied under shingle, c) bead of asphalt plastic cement applied under shingle, and d) pull test after 30 days.

9. SUMMARY

In this paper, we have reviewed how wind uplifts and damages asphalt shingle roofing. Usually, wind damage is obvious with a combination of uplifted and creased, flipped, and removed shingles. Flying debris impact might damage other shingles. Wind damage typically is concentrated on the windward sides of a roof, especially along eaves, ridges, and tops of valleys. Shingles with little or no bond are especially prone to being lifted and damaged by wind.

We discussed how there are several factors that affect uplift resistance of asphalt shingles, including type of shingle, design, quality of manufacture, quality of installation, and degree of weathering. Field damage assessments after Hurricane Frances showed that laminated type shingles outperformed three-tab shingles in wind resistance. Thus, if three-tab shingles continue to be utilized in hurricane-prone regions, they should receive additional attachments as shown in FEMA fact sheet number 20.

We also have discussed certain issues with asphalt shingles not caused by wind. These include cupping, clawing, and shingle splitting. Also, shingle overlaps frequently are not bonded due to thermal contraction and expansion stresses as well as sealant deterioration. The lack of shingle bond also depends on how the shingles were installed as well as the quantity and quality of the sealant. Occasionally, we have found roofs damaged intentionally to simulate wind damage. However, careful examination of the roof can yield clues that the damage is not consistent with wind effects.

Finally, we have discussed repair techniques and showed how adhesive placed under unbonded shingles actually can provide greater wind uplift resistance than the original sealant.

10. ACKNOWLEDGEMENTS

The authors would like to thank the following reviewers: Stoney Kirkpatrick, Emily McDonald, John Stewart, and David Teasdale.

11. REFERENCES

American Society of Testing and Materials, 2010: Various roofing standards. [Available online at: http://www.astm.org/Standard/index.shtml]

Asphalt Roofing Manufacturers Association, 2006: *Residential Asphalt Roofing Manual*, 123 pp.

Beven, J., 2004: Tropical Cyclone Report. Hurricane Frances: 25 August – 8 September 2004, National Hurricane Center, 28 pp. [Available online at: http://www.nhc.noaa.gov/pdf/TCR-AL062004_Frances.pdf.]

Cullen, W., 1993: Research and performance experience of asphalt shingles, *10th Conf. on Roofing Technology*, Gaithersburg, MD, 6-12. [Available online at: http://docserver.nrca.net/pdfs/technical/1815.pdf.]

Dupuis, R. M. and M. S. Graham, 2002: The effects of moisture and hear on the tear strength of glass fiber-reinforced asphalt shingles. *12th Intl. Roofing and Waterproofing Conference*, Orlando, FL, 14pp. [Available online at: http://docserver.nrca.net:8080/technical/7880.pdf.]

Federal Emergency Management Agency, 2005: Asphalt shingle roofing for high-wind regions, Tech. Fact Sheet 20, 2 pp. [Available online at: http:// www.flash.org/resources/files/HGCC_Fact20.pdf.]

Jones, J., R. Metz, C. W. Harper, 1999: ARMA wind uplift load model for assessing asphalt shingle performance. *Proc. Fourth Intl. Symposium on Roofing Tech.,* Gaithersburg, MD, 180-184. [Available online at: http://docserver.nrca.net/pdfs/technical/5832.pdf.]

Koontz, J. D., 1990, Fiberglass Shingles – Shingle splitting problem observed in a number of western applications. *Western Roofing* [Available online at: http://www.jdkoontz.com/articles/shingles.pdf.]

____________, 2007: Performance attributes of fiberglass shingles, *Interface*, 23 – 30. [Available online at: http:www.rci-online.org/interface/2007-07-koontz.pdf.]

Liu, Z., D. O. Prevatt, L. D. Aponte, T. A. Reinhold, K. R. Gurley, and F. J. Masters, 2006: Wind load determination using field data and wind tunnel studies on residential buildings, *Fourth LACCEI International Latin American and Caribbean Conf. for Engineering and Technology,* 10 pp. [Available online at: http://www.davidoprevatt.com/wp.../uploads/2008/.../whm197_prevatt-laccei-06.pdf.]

McDonald, J. R., and T. L. Smith, 1990: *Performance of roofing systems in Hurricane Hugo*, Institute for Disaster Research, 42 pp.

McNulty, R. A., 2000: Asphalt roofing shingles – composition, performance, function, and standards, *Interface*, 20-23. [Available online at: http://www.rci-online.org/interface/2000-01-mcnulty.pdf.]

National Association of Home Builders, 2007: *Study of the life expectancy of home components*, 19 pp. [Available online from: http://www.nahb.org/page.aspx/generic/sectionID=152]

Noone, M. J., and W. K. Blanchard, 1993: Asphalt shingles – A century of success and improvement, *10th Conf. on Roofing Technology*, Gaithersburg, MD, 23-33. [Available online at: http://docserver.nrca.net/pdfs/technical/1817.pdf.]

Peterka, J.A., Cermak, J.E., Cochran, L.S., Cochran, B.C., Hosoya, N., Derickson, R.G., Harper, C., Jones, J. and Metz, B., 1997: "Wind Uplift Model for Asphalt Shingles., *Jour. of Architectural Engineering*, Amer. Soc. of Civil Engineers, Vol. 3, No. 4, 147-155. [Available online at: http://cedb.asce.org/cgi/WWWdisplay.cgi?9705505.]

Rash, D., 2006: Three-tab shingle performance during Hurricane Ivan, *Interface*, 5-11. [Available online at: http://www.rci-online.org/interface/2006-04-rash.pdf.]

Ribble, R., D. Summers, R. Olson, and J. Goodman, 1993: From generation to generation: Issues and problems facing the steep slope roofing industry, *10th Conf. on Roofing Technology*, Gaithersburg, MD, 1-5. [Available online at: http://docserver.nrca.net/pdfs/technical/1814.pdf]

Roofing Industry Committee on Weather Issues, 2006: *Hurricanes Charley and Ivan wind investigation report*, Oak Ridge National Laboratory, 260 pp. [Available online at: http://www.ricowi.com/docs/reports/RICOWI_Katrina_Report.pdf.]

____________________________________, 2007: *Hurricane Katrina wind investigation report*, Oak Ridge National Laboratory, 260 pp. [Available online at: http://www.ricowi.com/docs/reports/RICOWI_Ivan_Charley_Report.pdf.]

___________________________________, 2009: *Hurricane Ike wind investigation report*, Oak Ridge National Laboratory, 364 pp. [Available online at: http://www.ricowi.com/docs/reports/RICOWI_Ike_Report.pdf.]

Shaw, D. E., 1991: ARMAs new approach for evaluation of asphalt shingle wind resistance, *Third International Symposium on Roofing Technology*, Gaithersburg, MD, 216-221. [Available online at: http:// docserver.nrca.net/pdfs/technical/375.pdf.]

Smith, T. L., 1995: Improving wind performance of asphalt shingles: Lessons from Hurricane Andrew, *Proc. 11th Conf. on Roofing Technology*, Gaithersburg, MD, 39-48. [Available online at: http://docserver.nrca.net/pdfs/technical/4463.pdf.]

Smith, T. L., and M. Millen, 1999: Influence on nail locations on wind resistance of unsealed asphalt shingles. *Proc. 11th Conf. on Roofing Technology*, Gaithersburg, MD, 98-111. [Available online at: http://docserver.nrca.net/pdfs/technical/6862.pdf.]

Snoke, H. R., 1941: Asphalt-prepared roll roofings and shingles. Report BMS70, National Bureau of Standards.

The Freedonia Group, 2010: Roofing, 379. [Available online at: http://www.housingzone.com/proremodeler/article/CA672