

Lesson Learned from Hurricane Wind Investigations of Low-slope Roof Assemblies—A Researcher Prospective

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Keywords

Roofs, hurricanes, edges, internal pressure, resistance, dynamic test, wind loads

Abstract

Wind-induced failure is one of the major contributors to insurance claims, and it is increasing. To address these growing concerns, the Roofing Industry Committee on Weather Issues (RICOWI) started a wind investigation program (WIP) to investigate the field performance of roof assemblies after Hurricanes Charley, Katrina, Ike and Ivan and factually describe roof assembly performance, as well as modes of damage. As part of this program, this paper focuses on the investigation of low-slope roof assemblies. The objective is not to present several photographs and information related to specific roof configurations. Rather, efforts were made to scrutinize photographs and field observations toward developing a generic relationship to benefit the North American roofing industry. This paper amalgamates the findings from all four hurricanes in three important take-home messages that are found to be critical in the failure of the roof systems as follows:

- 1) Understanding the wind aerodynamics on roof edges
- 2) Effect of the internal pressure buildup on roof failures

3) Need for wind-resistance design of rooftop equipment

The paper also extends and broadens the roofing knowledge base by comparing and contrasting the lesson learned from these hurricanes regarding wind-uplift performance, with the research progress made during the past two decades in North America.

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As a professional engineer, Bas Baskaran is the group leader for the Performance of Roofing System and Insulation Sub-program at the National Research Council of Canada. His research focuses on wind effects on building envelopes through experiments and computer modeling. He also acts as adjunct professor at the University of Ottawa. He has authored and/or co-authored more than 200 research articles regarding wind effects on buildings. He is a principal research officer for the North American-based industry consortia, Special Interest Group For the Dynamic Evaluation of Roofing Systems (SIGDERS). He is a member of RICOWI, RCI Inc., American Society of Civil Engineers, SPRI and CIB [Construction Industries Board?] technical committees. He received his bachelor's degree in engineering from Annamalai University, Madras, India, and his master's degree in engineering and doctorate from Concordia University, Montreal. Both research topics focused on the wind effects on buildings and earned a best dissertation award from the Canadian Society of Civil Engineers.

David L. Roodvoets

David Roodvoets is an independent consultant. He is past chairman of RICOWI, SPRI technical director and a member of the Cool Roof Rating Council's (CRRC's) board of directors. Previously, he was employed as an associate development scientist for The Dow Chemical Co., Midland, Mich., and technical director for the T. Clear Corp., Hamilton, Ohio. Roodvoets has been involved with research on all facets of roof systems. He has worked with major research institutions and conducted extensive wind tunnel testing of roof systems. Recently, he has worked on developing fire and wind standards for vegetative roofs; ventilation requirements for attics and cathedral ceilings; and RICOWI's hurricane investigations. He presented a paper at the 2008 RCI Building Envelope Symposium and was published in *Construction Specifier* magazine. He is a member of CRRC, RICOWI, International Code Council, ASTM, American Society of Heating, Refrigerating and Air-conditioning Engineers, Construction Specifications Institute and emeritus SPRI.

Introduction

Natural wind hazards, such as typhoons and hurricanes, have been dramatic during the past decade, incurring losses of life and property damage. Figure 1 [National Oceanic and Atmospheric Administration (NOAA), 2010] shows the trend of the damage amounts of the most costly hurricanes in the U.S. Hurricanes Hugo and Andrew created awareness of roof failures. There were concerns that the truth of the failures' causes and the product types that failed were distorted (Cook and Soltani, 1993, Smith et al., 1992). Following these storm events, two workshops were devoted to identify and discuss roof wind-uplift issues and solutions (ORNL, 1989). One of the outcomes of

these workshops resulted in the establishment of the Roofing Industry Committee on Wind Issues (RICOWI). An additional outcome was the formation of the Special Interest Group for Dynamic Evaluation of Roofing Assemblies (SIGDERS), a North American roofing consortium. During early 2000, RICOWI widened its focus from wind to weather and became the Roofing Industry Committee on Weather Issues.

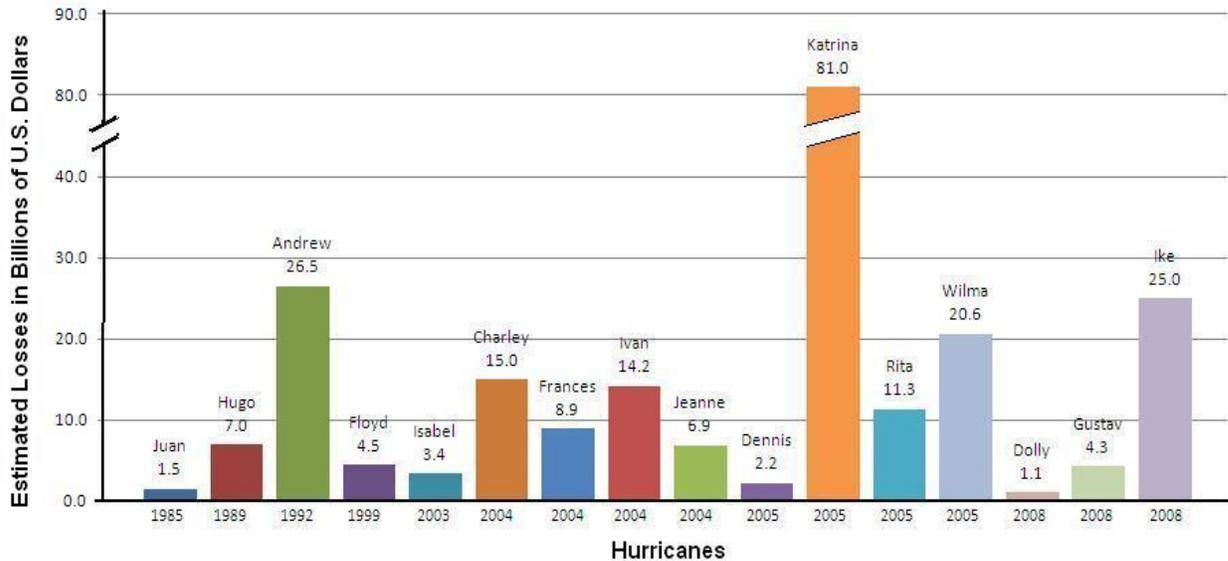


Figure 1. Historical Data for the Estimated Loss Resulting From Hurricanes (Source: NOAA)

RICOWI consists of 13 sponsors representing the major roofing associations and 63 affiliates representing general interested parties (visit www.ricowi.com for current membership details). RICOWI started a wind investigation program (WIP) with the following mission:

- (1) To investigate the field performance of roof assemblies after major wind storm events
- (2) To factually describe roof assembly performance and modes of damage
- (3) To formally report the results for substantiated wind speed

Keys to the RICOWI investigations are that investigation teams are balanced, unbiased and trained in wind damage assessment (Baskaran et al., 1997). As shown in Figure 1, there were four major hurricanes after Andrew and their categories ranged from 2 to 4. High wind speeds and severe damage are expected for Category 5 hurricanes.

- Charley (Category 4) made landfall near the Punta Gorda-Port Charlotte area of Florida Friday, Aug. 13, 2004. Charley was the first storm to meet the RICOWI WIP criteria of “greater than 95 mph (153 kpmh) sustained wind speeds over a populated area.” Seven teams involving a total of 39 professionals fanned out over the area to document damage to low-slope and steep-slope roof systems.
- Ivan (Category 2) made landfall Sept. 16, 2004, west of Pensacola, Fla. Five teams (21 professionals) conducted an extensive wind damage investigation, again looking at low-slope and steep-slope roof systems. The personnel gained valuable experience in the Charley investigation, which is reflected in the Ivan investigation.
- Katrina (Category 4) made landfall Aug. 29, 2005, near Grand Isle, La., and traveled almost due north across New Orleans. Hurricane wind hammered the coastline from Houma, La., to Pensacola, Fla. The severe flooding problems in New Orleans made it almost impossible for the investigating teams to function inside the city. Therefore, the WIP investigations were conducted in areas east of the city. The six teams covered the coastal areas from Bay Saint Louis, Miss., on the west to Pascagoula, Miss., on the east. Twenty-five professionals documented damage to low-slope and steep-slope roof systems.

- Ike (Category 3) made landfall Sept. 13, 2008, at Galveston, Texas. Seven teams involving a total of 29 professionals documented damage to low- and steep-slope roof systems.

Observations from the RICOWI WIP Database

RICOWI teams investigated low-slope and steep-slope roofs. As the only one of its kind, the total cash and in-kind budget was approximately \$1.5 million for the RICOWI investigations. This paper focuses on the investigations of more than 200 buildings with low-slope roofs. RICOWI teams collected specific information on each building examined, including type of structure (use or occupancy), wall construction, roof type, roof slope, building dimensions, roof deck, insulation, construction and roof attachment method. All inspections were documented during the investigations using standard forms, and failure modes were photographed. At the end of each investigation day, reports were completed and provided to the administrator. A feedback session also occurred so teams could follow up on interesting leads. Although teams typically worked from the highest wind-damaged areas to the less wind-damage areas, there was no attempt to get randomized data. Toward the end of the investigations, writers who were members of the investigation teams developed final reports from the data (RICOWI, 2006, 2007 and 2009). These reports are available for free download at the RICOWI website, www.ricowi.com.

For buildings with low-slope roof configurations, Figure 2 shows the building classification according to the building height and roof type. Buildings were divided into two groups: low-rise building and high-rise building. ASCE 7 - 2010 and NBCC (2010)

classify buildings with roof eave heights less than 60 feet (19 m) as low-rise buildings. Using this criteria, it is clear a majority of the RICOWI investigations fell under low-rise buildings.

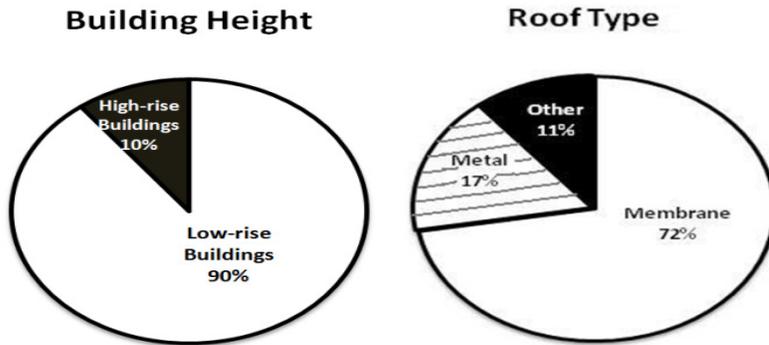


Figure 2. Building and Roofing Types Classification from the RICOWI Database

As shown in Figure 2, a majority of the investigated roofs also had membranes as the waterproofing component; about 17 percent had metal roofs and of the others, 11 percent of the majority were spray polyurethane foam roofs. Figure 3 groups the intensity of the damage into four categories for low-rise and high-rise buildings. A majority of buildings had damage less than 25 percent of the roof area. Total failure, damage greater than 75 percent of the roof area, was observed on about 20 percent of low- and high-rise buildings inspected.

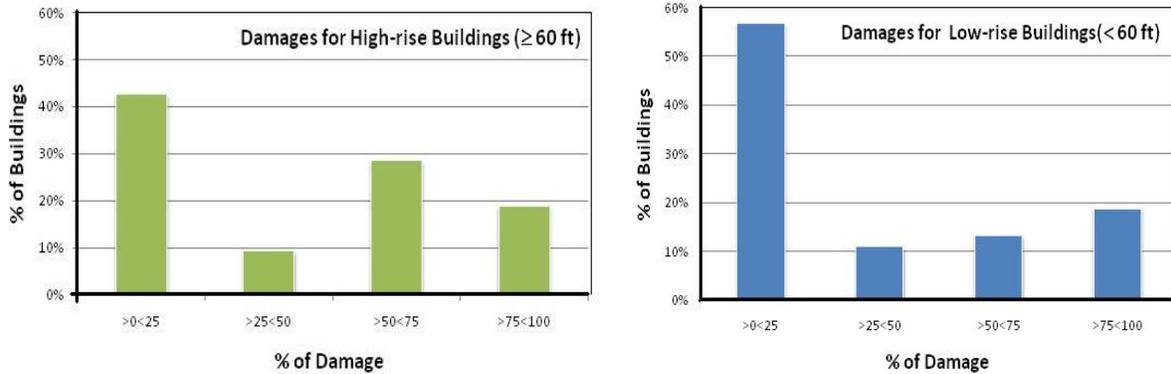


Figure 3. Damage Severity Classification from the RICOWI Database

From these observations, it can be said that even with high hurricane wind speeds, the damage mostly was partial failures of the building envelope components rather than complete system failures. This was one of the encouraging observations for the engineering community because of the fact that future prevention of these failures are possible by applying sound engineering principles and design methodologies while controlling the quality of the workmanship in the field. However, one should note though the damage was less than 25 percent on 50 percent of the buildings, all had water ingress failure leading to building content damage.

Water damage is the major cause of insurance claims and increased costs. Figure 1 encapsulates this in the case of Hurricane Katrina as the estimated cost exceeds \$80 billion, mainly because of the water surge damage. Nearly all damage from the other hurricanes was wind-induced failures in contrast to Hurricane Katrina where the damage was a combination of water and wind-induced failures. Wind-induced failure is one of the major contributors to insurance claims, and it is increasing. Therefore, understanding how to prevent wind damage by establishing engineering standards or standard practices will allow designers to design roofs that can resist high winds.

Present Contribution

The objective of the paper is not to present several photographs and information related to specific roof configurations. Rather, efforts were made to scrutinize all these photographs and field observations toward developing a relationship with the existing science in the wind and roofing fields. A segment of the findings already was presented in our previous paper (Baskaran et al, 2007) by focusing only on the Hurricane Charley investigation. Limited case studies were selected for this paper.

For each scenario, scientific documentation is first presented, followed by discussing how the field observation reflects the fundamental principles. Based on this exercise, correlations are developed for roof wind design. In addition, wind design data from the North American codes and standards are compared to show the effects of science and field observations on durable roof design. With these illustrations, this paper offers recommendations to advance the roof system wind-resistance design for hurricane-prone regions.

Roof Edge Wind Aerodynamics and Failure Investigations

Wind flow around buildings creates pressure and suction on the building envelope (Figure 4). As the building obstructs the flow movement, pressures are induced on the windward side, and as the flow separates from the side walls, suction is created. For roof assemblies, most suction is induced because of flow separation from the edges. However, depending on the building aspect ratio (i.e., for slender building in which the length of the roof is much longer than the width) the flow can reattach over the roof along its length and induce pressure on the roof surface. Moreover, depending on

rooftop obstructions, wind flow gets modified and develops complexities in the flow aerodynamics.

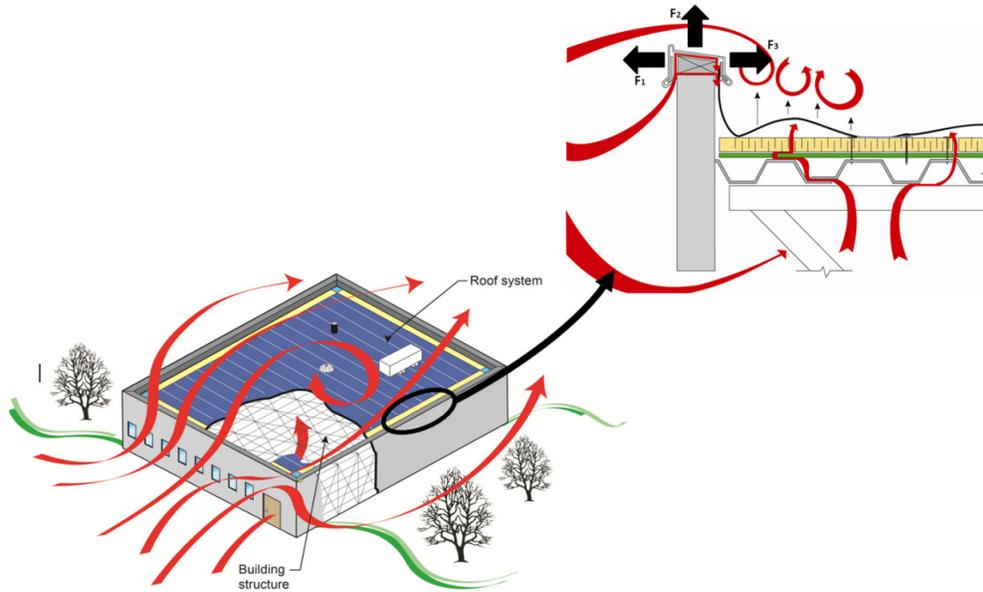


Figure 4. Wind Aerodynamics on Roof Edges and Induced Forces

As shown in Figure 4, this complex wind aerodynamics can be simplified into three force segments as follows

- F1 is the outward force acting on the edge system because of the positive pressure. Basically, this force can unlock the coping from the cleat and lead into edge failure.
- F2 is the uplift force acting on the whole edge system because of the strong flow separation. This can cause complete failure of the edge system by initiating the failure on the weakest link.
- F3 is the force caused on the edge system because of membrane behavior. This can be predominant in the case of mechanically attached systems where the

membrane billows and flutters between the mechanical attachment, and also in the case of loose-laid systems where the membrane can be exposed to wind as a result of ballast displacement. Additional discussions on this issue will be presented in Figure 7.

Figure 4 shows these three forces simply are acting as perpendicular components to the surface. However, these three forces are not the only vectors; all force vectors can vary in time, as well as along the surface of the edge system.

Figure 5 shows typical failures observed during the Hurricane Charley investigation. Edge failure is seen in PVC, polymer-modified bitumen and TPO systems. This demonstrates these types of failures are not dependent on the membrane type. In all three cases, the roof membrane is not damaged and the weakest link is the edge system. The PVC and polymer-modified bitumen roof failures mainly result from the wind-induced outward force, F_1 , as discussed previously. There is no cleat installed in these two systems and, therefore, the wind outward forces lifted the coping. The TPO roof had a cleat but because of weak interlock with the coping, it could not resist the wind forces.

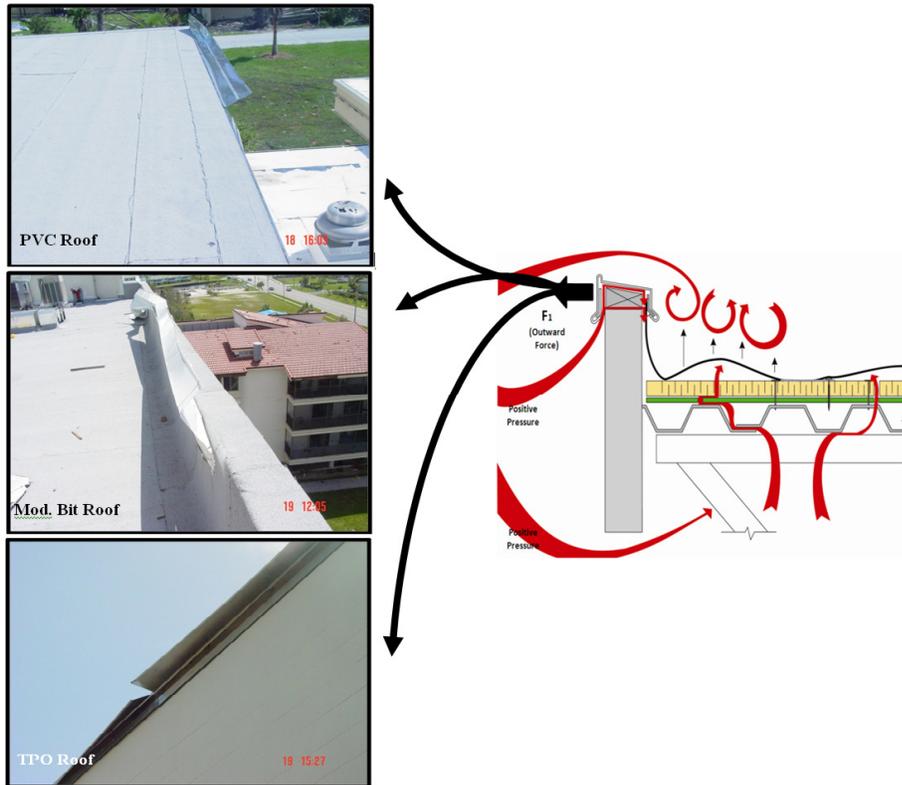


Figure 5. Failure of Roof Edge Because of Wind-uplift Force

Figure 6 shows the typical failure resulting from wind-uplift forces on the edges as the only failure observed for this TPO roof. The mechanically attached roof system was in good condition, and the rooftop equipment was not damaged. There were only a few membrane punctures because of edge metal debris. As shown in the figure, poor attachment of the metal caused the edge to be the weakest link for the wind uplift forces. In the case of the ballasted EPDM roof, there was major system failure as a result of the failures of the edge. The uplift force completely dislodged the edge system.



Figure 6. Roof Edge Failures due to Wind Uplift Force

Figure 7 demonstrates how the positive internal pressure can lead to roof failure. The loose-laid EPDM roof assembly had a parapet of 4.5 feet (1.4 m) high with a well-designed and installed edge system. However, at the wall/roof junction, there was a gap of more than 0.5 inches (127 mm) along the length of the roof (220ft [67 m]). During the field investigation, it was noticed strong air currents were emerging along that gap. This internal positive pressure lifted the loose-laid membrane along the edge and displaced the stone ballast. The exposed membrane experienced tension when it was subjected to wind uplift. Because the membrane tear resistance was lower than the strength of the edge metal, the membrane ruptured and led to roof failure.

Figure 8 shows the failure of a PVC mechanically attached roof. The failed section had one full sheet and two half sheets. During the failure investigation, it was noticed the edge metal was attached using nails at 3 inches (9 mm) on center.

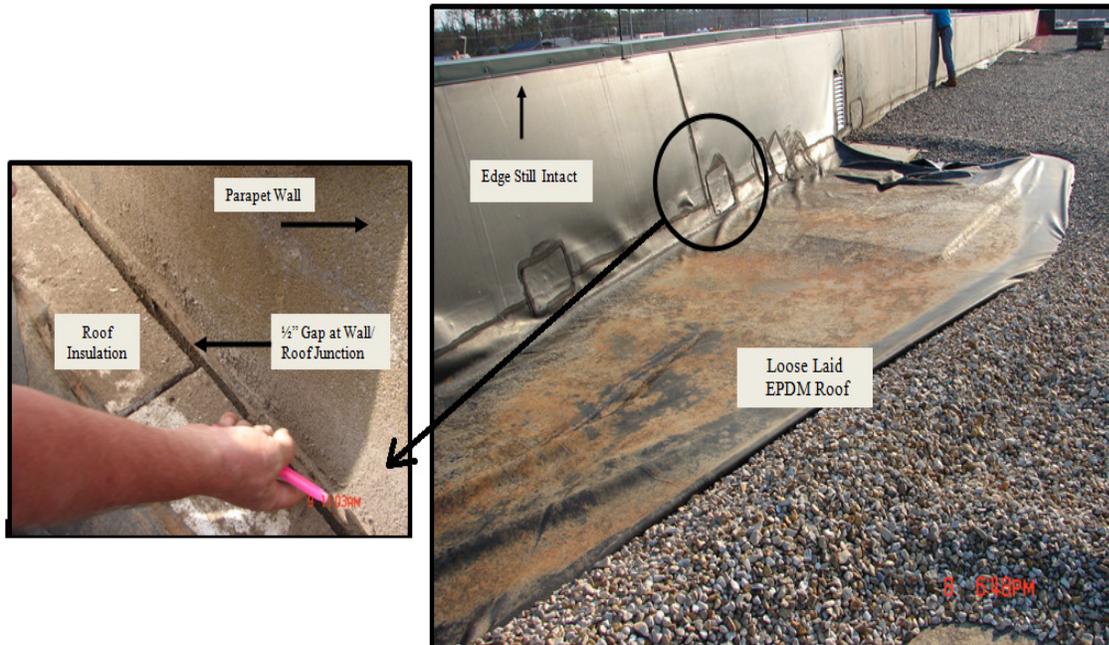


Figure 7. Failure of Roof Edge due to Membrane Pull

The membrane and coping remained intact. Membrane tear around the membrane metal plate was evident as was the bending of the plates. This indicates the weakest link for this roof system was the membrane having tear resistance lower than the wind-uplift forces. The membrane's failure caused the roof segment's failure. Closer examination revealed that slippage of the roof membrane from the attachment plate led to loss of compression between the roof membrane, insulation substrate and fastening elements and ultimately to the membrane failure by way of tear spread around the fastener shaft. Similar observations of failure modes also were noticed during dynamic

wind-uplift testing (Gerhardt et al, 1989 and Kramer, 1995). However, static tests did not produce this effect on the membrane, and, therefore, did not reveal the weakest link of the system's wind-uplift resistance.



Figure 8. Failure of Roof Edge Because of Combined Forces

State of the Art of the Roof Edge Design

Perimeters and corners of low-slope roofs have been recognized as the roof areas most vulnerable to wind damage. Failure continues to occur at these locations because design and installation practices can be inadequate. RICOWI investigation database shows one of four roof failures was a result of the failure of the edge. Before 2004, there were no code requirements for roof edge attachment. This has been corrected with the addition of ANSI/SPRI/ES-1 (SPRI, 2010) as a code requirement in the International Building Code. Presentations have shown that with a minimal increase in the installation

cost, major improvements in the resistance of the roof edges can be achieved. (LeClare, 2010).

The negative forces at the perimeter must be resisted by adequate mechanical attachment and/or bonding of the roof membrane to the substrate. Many designs allow pressurization of the underside of the roof system, which significantly adds to the loads that must be resisted. The characteristics of the load to be resisted are dynamic, and most tests used to evaluate roof systems are static or quasi static. Current test methods, such as ANSI/SPRI ES -1, only focus on the vertical force and/or outward force in evaluating the mechanical attachment. None of the existing test methods simulate the membrane peel forces. In current testing, the first mechanical failure (screw withdrawal) or separation of the membrane stops the test. In nature, roofs survive with small amounts of initial failure if the peel forces are resisted. If the peel forces are resisted, catastrophic damage is less likely. Neither the National Building Code of Canada (NBCC 2010) nor the widely used U.S. wind standard ASCE 7-2010 specifies wind load requirements for the roof edges. All the existing wind-uplift standards (CSA A 123-21-10, ETAG-2006, FM 4474-2005, NBI 160 and UL 580) are applicable only for the roof assembly; therefore, it is clear there are two major limitations in current testing and design requirements:

- 1) There are no requirements for peel loads at the roof edge.
- 2) There is no consensus-based test method that can simulate simultaneously all the wind-induced peel and uplift forces on the roof edges.

A collaborative research project has been initiated at the National Research Council of Canada to address these two major issues.

Recommendation from Field Investigation by the Present Study

“It is recommended that roof edges should be designed and installed as a system rather than as separate components. The design should be based on the well-established engineering procedure that the edge system resistance should be greater than the design load.”

Building Internal Pressure Buildups and Its Effects on the Roof System

Figure 9 presents the effect of sudden internal pressure buildup and its effects on a built-up roof (BUR) system. Several failures were noted during the hurricane investigation. The school building in the photos was 40 feet (12.2 m) high and designated as one of the hurricane shelters. The service door of the school gym, being the weakest link, caved inward during wind flow interaction with the building. A drain directly above this area lifted and broke bonds in the system. The roof systems failed primarily in the top perlite insulation layers as the weakest point. Insulation fasteners mostly were intact; although part of the coping was blown off, coping loss likely is not the cause of the roof damage. The sudden envelope failure increased the internal pressure of the gym as high as the external wind pressure. In turn, the roof assembly was subjected to the internal push and external pull forces. Design wind pressure on a roof is the algebraic sum of the external pressure and internal pressure across the roof assembly. It can be presented as follows:

$$p = I_w q (C_e C_g C_p - C_e C_{gi} C_{pi}) \text{ lbf/ft}^2 \quad \text{NBCC (1)}$$

$$p = 0.00256 K_z K_{zt} K_d V^2 I (G C_p - G C_i) \text{ lbf/ft}^2 \quad \text{ASCE (2)}$$

$C_e C_{gi} C_{pi}$ and GC_i are the internal pressure components, respectively, according to NBCC and ASCE. The magnitudes of these internal co-efficients depend on the distribution of the openings and air leakage paths in the building envelope.



Figure 9. Effect of a Sudden Internal Pressure Build up and its Impact on a Roofing System

Authors' previous publication (Baskaran et al 2007) documented such failure observations from Hurricane Charley and provided design recommendations based on ASCE 7 and NBCC 2010. These recommendations mainly focused on the design

aspect of the load calculation. In other words, it was suggested the internal pressure buildup can increase the roof failure probability. Probabilities of window cladding failures are high in hurricane prone regions, and such failures significantly can increase the internal pressure that can lead to roof uplift failures. It is recommended that designers allow provisions to account for such failures during the design and selection of the roof system. This can be achieved by classifying the building as Category 3 as per NBCC 2010 or partially enclosed building as per ASCE 7-07.

In examining several of such failures, it has been observed that the intensity of the internal pressure buildup is time-dependent. As shown in Figure 8, the failure of the service door caused the pressure buildup, and this excessive pressure will equalize with the internal volume of the building in time. Pressure equalization time depends on the building volume size, magnitude of the pressure buildup and duration of the external wind gusts. The extension of the roof failure is directly related to the pressure equalization time and intensity. This clearly can be seen in Figure 8; the membrane peel was stopped after a certain distance from the roof edge. The role of the roof divider acting as a peel stopper also is interesting. This is evident from the fact that the extent of the peel is much longer along the length compared with the roof's width. This mainly is because of the divider, which was running across the roof width, preventing the additional peeling. Structural roof design can be simplified as shown in equation 3:

$$\text{System Resistance (S.R)} > \text{Load Requirement (L.R)} \quad (3)$$

System rating can be obtained by subjecting roof mock-ups under static (FM 4474 or UL 1897) or dynamic (CSA A123.21-10 or ETAG 2006) test methods. From the system rating, one can obtain its resistance by dividing the rating using the appropriate safety factor. Load requirements can be established as per the NBCC (2010) or ASCE 7-10. The recommendation after Hurricane Charley focused on the load requirement by increasing the design load to account for the sudden internal pressure buildup. Additional investigation, such as the one previously discussed (Figure 8), offers an alternate design option in terms of roof system resistance as follows.

Recommendations from Field Investigation by the Present Study

“When there is a probability of building envelope failure such as the service door, it is recommended that peel stop design be incorporated as part of the roofing design. The peel stopper location along the length and width of the roof mainly depends on the size of sudden opening. It is recommended that peel stoppers can be installed at a distance 3 times that of the size of the sudden openings from the roof edge.”

Rooftop Unit Failure and Its Effects on the Roof System

Figure 10 shows the complete failure of a mechanical unit and its effects on the roof assembly. The retail building with gravel-surfaced BUR is 35 feet (10.7 m) high. There was a penthouse on the roof, and it was 15 feet (4.6 m) high above the main roof level. The penthouse had a mechanical unit, which was held in place with metal L angles and attached using nails. Failure of the nail attachment caused the blow-off of the mechanical unit, which caused the major punctures on the penthouse roof.

Subsequent wind flow dynamics caused the mechanical unit to come apart, which affected the main roof by puncturing the membrane at several locations. The debris path is evident from the figure, as well as the propagation of membrane puncture failures, until the debris left the roof surface.



Figure 10. Complete Blow-off of a Mechanical Unit and its Effects on a Roof System

Figure 11 shows partial failure of several mechanical units. This two-level roof had loose-laid EPDM on the lower level and mechanically attached PVC roof on the upper level. Both roof systems performed well during the wind event. The bases of the mechanical units and encircled paver still were in place. However, as shown in the figure, for missing metal covers, most of the units temporarily were repaired with plywood. The metal debris from the units caused several punctures to the single-ply membrane where some were temporarily patched and some were unnoticed. Similar to the previous case study, the trail of punctures was observed across the roof surface,

ending at the roof perimeter. These are classic examples of the rooftop unit becoming the weakest link for wind forces and failure of that resistance link in a roof assembly leads to roof system failure.

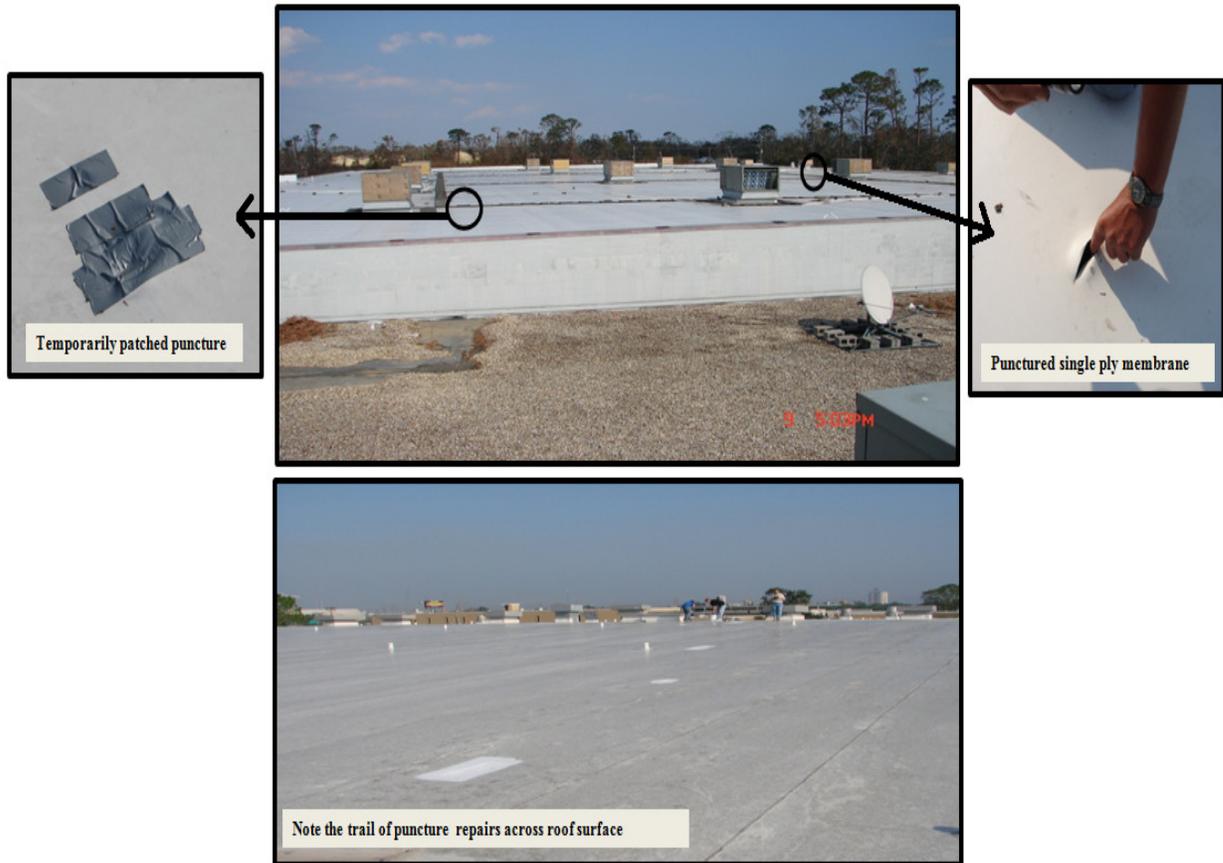


Figure 11. Partial Blow-off of Several HVAC Units and its Effects on a Roof System

Similar to the previous two case studies (roof edges and internal pressure), rooftop equipment failures are not dependent on the membrane attachment method nor the type of membrane used. Authors also reported success stories of the surviving rooftop equipment in the previous publication (Baskaran et al, 2007).

Recommendation from Field Investigation by the Present Study

“In comparing and contrasting the failed scenarios with the survivals, two generic recommendations can be summarized: (1) Roof design should include integrating roof top equipment with the structural element of the building and the design should be verified with experimental data, at the minimum for common attachment methods; and (2) Roof top mechanical equipment should be certified for wind uplift resistance.”

Concluding Remarks

This paper presented an overall view of RICOWI’s wind investigation program and its findings. As one of its kind, the \$1.5 million program investigated and documented roof system performance from Hurricanes Charley, Ivan, Katrina and Ike. Reports containing factual data are available for free download from the RICOWI website. This paper amalgamated the findings from all four hurricanes into three important take-home messages that were found to be critical in the roof systems’ failure as follows:

- 1) Understanding the wind aerodynamics on roof edges
- 2) Effects of the internal pressure buildup on roof failures
- 3) Need for wind-resistance design of rooftop equipment

With these illustrations, this paper offered recommendations to advance the roof system durability for hurricane-prone regions.

Acknowledgement

The presented research is being carried out for a consortium—Special Interest Group for Dynamic Evaluation of Roofing Systems (SIGDERS). SIGDERS was formed from a

group of partners who were interested in roof design. These partners included Atlas Roofing Corp., Canadian General-Tower Ltd., Canadian Roofing Contractors' Association, Carlisle SynTec Inc., Dow Roofing Systems, Duro-Last ® Roofing Inc., Firestone Building Products Co. LLC, GAF-Elk Materials Corp., IKO Industries Ltd., Johns Manville Inc., National Roofing Contractors Association, OMG Roofing Products, Public Works and Government Services Canada, RCI Inc., Sika Sarnafil, Soprema Canada Inc., Tremco Inc. and Trufast Corp.

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