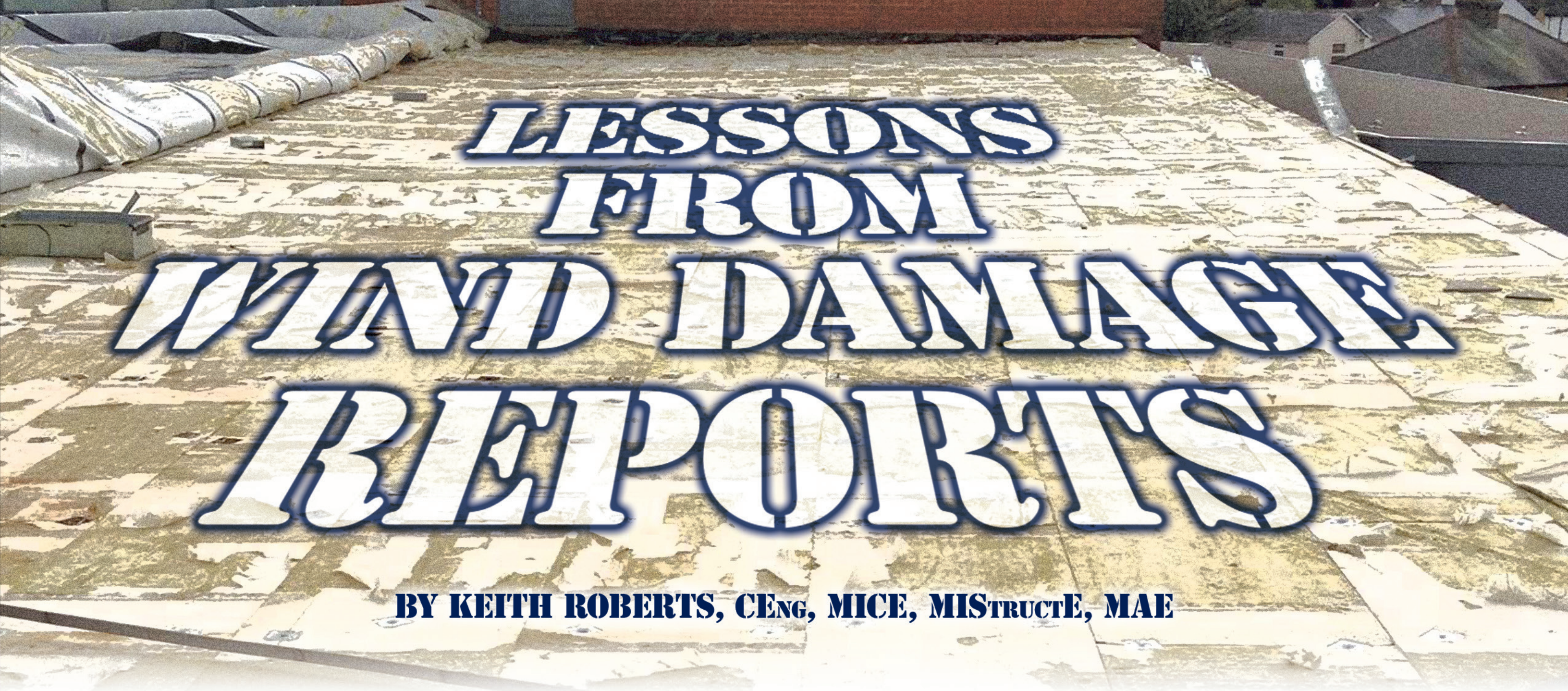

LESSONS FROM WIND DAMAGE REPORTS

BY KEITH ROBERTS, CEng, MICE, MIStructE, MAE

Editor's Note: This is a shortened version of a paper presented at the 31st RCI International Convention and Trade Show in March 2016 in Orlando, FL.

Technical investigation reports on wind damage to roofing and cladding can provide a wealth of useful information relevant to designers, researchers, manufacturers, contractors, and building owners. It is common to find multiple failures within roof systems, and often the challenge is to identify which link in the assembly broke first. Forensic investigations demand a methodical approach, piecing together the available evidence of the initial point of failure, which is often hidden from view.

Several case studies of investigations of wind-damaged roofs in the UK and Ireland are presented here, exploring alternative causation theories and developing options for strengthening and repair.

WIND ATTACHMENT DESIGN

Over the past 25 years, there have been three different standards used for calculating design wind pressures on buildings in the UK, each with its own factors, assumptions, and methodology. The changes in codes have led to confusion within the roofing and cladding industry and, on occasion, mistakes and oversight. The changes have had a negative effect, and it is not unusual during a wind damage investigation to find that no party has actually calculated the design wind pressures on the roof and checked the attachment strength.

The standard now used throughout Europe is EN 1991, Part 1.4, which was first introduced in 1999. This comes in two parts: the basic standard that is common across all 29 member countries of the European Union (EU), and a separate National Annex, which is specific for use in individual countries. Each member country has developed its own variations, often introducing significant differences and the requirement for local knowledge and experience. The designer has to use the two documents together and cross-reference both at the same time, which adds complexity.

Wind suction forces acting on the upper weathering skin of a roof are transferred from layer to layer down through the roof construction into the structural framework. Each fastener transfers the upward load to the next layer down. A useful analogy is that of a chain anchoring the upper weathering skin down to the support structure. If one link in the chain were to break, then potentially the outer sheets could become detached from the roof (*Figure 1*).

Calculations should be prepared to estimate the design wind suction load acting on each link in the chain, and then compared with the characteristic strength of the fastener to determine their factors of safety using the equation in *Equation 1.*

In the UK, the minimum acceptable factors of safety used for checking the attach-

$$w < \frac{f}{\gamma}$$

where:
w = design wind pressure
f = characteristic strength
γ = factor of safety

Equation 1.

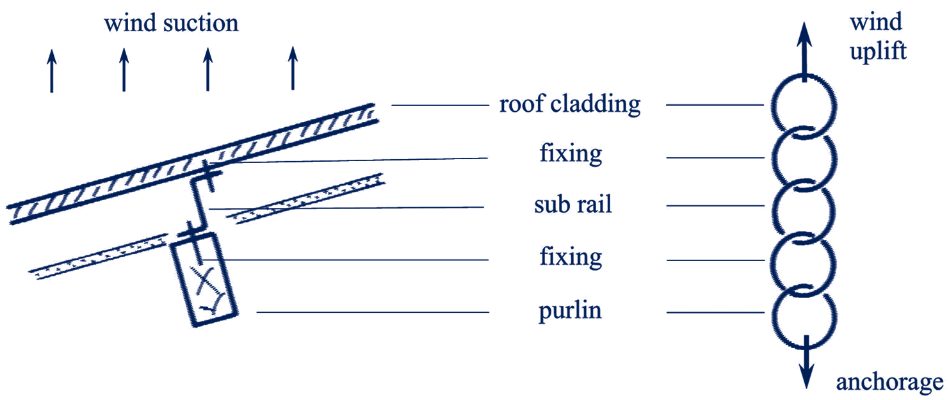

Figure 1 – The chain analogy for the attachment strength of a multi-layer roof system.

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Figure 2 – Detachment of aluminum standing seam roofing from windward verge of the Competition Pool.

Location	Dublin, Ireland
Building use	Aquatic center
Altitude, site exposure, topography	+74 m (240 ft.), severe, rural
Roof area	5,700 m^2 (61,000 sf)
Roof slope	Barrel vault 62 m wide, slope up to 20°
Roof type	Aluminum standing seam
Roof sub structure	Halters fixed to top hat rails, to saddles, through liner into purlins
Basic wind speed (hourly mean)	23 m/s (52 mph)
Recorded peak speed (hourly mean)	14 m/s (31 mph)
Design wind suction pressure in damage zone	-2.0 kN/m^2 ↑ (42 psf)
Extent of detachment	300 m^2 (3,200 sf) of standing seam 60 m (200 ft.) of parapet capping
Estimated financial loss	£10 million

Table 1 – Basic data for Case A.

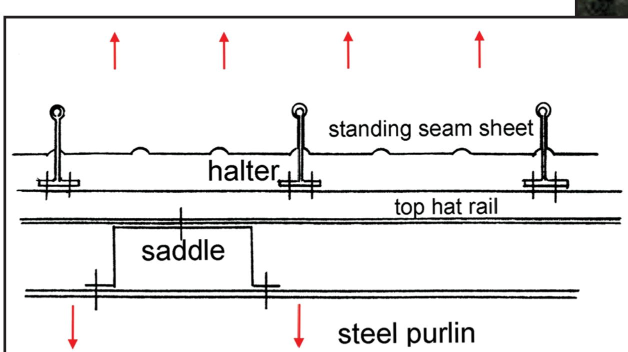

Figure 4 – Competition Pool roof assembly.

Figure 3 – Close-up of wind damage zone showing detached top hat rails and distorted saddles.

ment strength of profiled metal and single-ply membrane roof fasteners are 2.0 for pullout from steel or aluminum, 3.0 for pull-out from timber, and 4.0 for pullout from masonry/concrete. In the UK, a permissible strength approach is currently used in metal roofing standards. This is likely to change in the near future to a limit state approach using partial factors of safety.

CASE STUDY A: STANDING SEAM ROOF

On New Year's Day, 2005, a strong gale blew across southern Ireland from a southwesterly direction, resulting in an extensive area of lightweight aluminum standing-seam roofing becoming detached from the windward verge of an aquatic center and adjacent gym (*Figure 2*) and causing consequential impact damage to roof cladding and skylights downwind. The structures were evacuated safely without injury to members of the public or staff.

Roberts Consulting was contacted to investigate. Instructions were to examine the evidence relating to the wind damage and to identify causation. The instructions were received three months after the wind event, such that on arrival on site, much of the original roof construction and original damage had been disturbed. Consequently, the color photographs taken immediately after the storm became a vital record. The site inspection confirmed the as-built arrangement of the roof assembly and the details of the fasteners used.

The wind damage photographs showed that there had been a detachment between the steel top hat rail and the aluminum saddle at 900-mm (3-ft.) centers (*Figures 3*

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and *4*). In addition, there was upward distortion in the wide top plate of the saddle. Calculations were prepared to check the strength at each of the connections, and the conclusions are summarized in *Table 2*.

The calculations found that the local bending stress in the crown of the aluminum saddle was excessive, and that the factor of safety against the top hat rail to saddle fixing pulling out was 1.1, significantly less than the recommended minimum of 2.0. This is the same weakest link as observed in the photos of wind damage.

<table>
<tr><th>Element</th><th>Material</th><th>Design wind pressure kN/m² (psf)</th><th>Area loaded m² (sf)</th><th>Fastener number</th><th>Load / fastener kN (lbf)</th><th>Fastener strength kN (lbf)</th><th>Factor of safety</th><th>Satisfactory?</th></tr>
<tr><td>Standing seam</td><td>0.9-mm Aluminium</td><td rowspan="2">-2.0 ↑ (42)</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">-5.0 kN/m² (105 psf)</td><td rowspan="2">2.5</td><td rowspan="2">✔ Ordinance</td></tr>
<tr><td rowspan="2">Halter</td><td rowspan="2">Aluminum</td></tr>
<tr><td rowspan="2">-2.0 ↑ (42)</td><td rowspan="2">0.64 (6.9)</td><td rowspan="2">2</td><td rowspan="2">0.64 (145)</td><td rowspan="2">3.35 (753)</td><td rowspan="2">5.2</td><td rowspan="2">✔</td></tr>
<tr><td rowspan="2">Top hat rail</td><td rowspan="2">1.25-mm Galvanized Steel</td></tr>
<tr><td rowspan="2">-2.0 ↑ (42)</td><td rowspan="2">1.89 (20)</td><td rowspan="2">2</td><td rowspan="2">1.89 (420)</td><td rowspan="2">2.1 (472)</td><td rowspan="2">1.1</td><td rowspan="2">X</td></tr>
<tr><td rowspan="2">Saddle</td><td rowspan="2">2.0-mm Aluminium</td></tr>
<tr><td rowspan="2">-2.0 ↑ (42)</td><td rowspan="2">1.89 (20)</td><td rowspan="2">4</td><td rowspan="2">0.95 (210)</td><td rowspan="2">18 (4047)</td><td rowspan="2">19</td><td rowspan="2">✔</td></tr>
<tr><td>Purlin</td><td>10-mm Steel Flange</td></tr>
</table>

Table 2 – Summary of factors of safety for the Competition Pool roof assembly.

The adjacent verge cappings also became detached in the storm, and their means of attachment was closely examined. The aluminium capping had been held in place with rivets that had pulled through. The spacing of the rivet holes through the supporting cladding rail was measured, and the distances were found to be greater than the recommended 450 mm (18 in.). This was a further weakness in the roof assembly.

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Figure 5 – Second-floor roof membrane rolled back from western edge.

The original roofing contractor undertook to replace the area of detached roofing, both to make good the downwind isolated impact damage, and to strengthen the top hat rail to saddle and purlin connection by installing additional long screw fixings through the top hat rail directly into the steel purlin below. This repair scheme had a number of disadvantages, including puncturing the vapor control layer. Those advising the building owners considered the future condensation risks to be acceptable.

CASE STUDY B: SINGLE PLY MEMBRANE

On St. Jude's Day—September 28, 2013—a fast-moving, vigorous Atlantic depression brought very strong winds and heavy rain to southeast England, with winds gusting up to 36 m/s (80 mph). One modern building that suffered wind damage was a hotel in Chelmsford, to the northeast of London. Lengths of roof edging and single-ply membrane roofing became detached from the western side of the second floor roof and peeled back, resulting in debris falling to ground level (*Figure 5*). This led to the closure of the public highway immediately to the east of the building for a period of several days (*Table 3*).

An independent inspection of the roof was commissioned two months after the storm to examine the evidence of damage, to identify causation, and to advise on remedial work to remaining roofs. The roof system comprised a TPO single-ply membrane that was adhered to a tissue-faced mineral fiber insulation board, which in turn was screw fixed through the vapor control layer into a galvanized steel deck.

At the time of the inspection, temporary remedial works had been completed to enable the hotel to reopen. Much of the debris had been removed from site by the repair contractor and, fortunately, had been kept for examination in his local yard. The samples were closely examined to reveal an inadequate thickness and spacing of the adhesive bonding. Samples of the mineral wool insulation showed that the top tissue facing readily detached from the fibrous core and was not the specified insulation board with a "single-ply adhered facing." The wrong product had been supplied, which had not been identified by the roofing contractor, the supplier, or the other surveyors initially inspecting the wind damage.

Publish in *Interface*

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Submit articles or questions to Executive Editor Kristen Ammerman at 800-828-1902 or kammerman@rci-online.org.

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Location	Chelmsford, England
Building use	Hotel
Altitude, site exposure, topography	+25 m (82 ft.), sheltered, urban
Roof area	2,000 m^2 (21,500 sf)
Roof slope	Flat
Roof type	Single-ply membrane, adhered
Roof sub structure	Mineral wool thermal insulation, screw-fixed through vapor control layer into steel deck
Basic wind speed (hourly mean)	22 m/s (49 mph)
Recorded peak speed (hourly mean)	18 m/s (42 mph)
Design wind suction pressure in damage zone	-1.8 kN/m^2 ↑ (38 psf)
Extent of detachment	200 m^2 (2,150 sf) of single-ply membrane roofing and roof edge
Estimated financial loss	£1 million

Table 3 – Basic data for Case B.

The wind damage photos also showed that the roof edge had become detached. There were no record drawings of the initial construction, and so the as-built assembly was drawn up based on site measurements, the opening-up examination, and inspection of the debris in the contractor's yard. A short parapet had been constructed using two channel sections with an internal stud and no fixings joining the channels together. Under wind uplift pressure, the capping and support could lift upwards. From this, it was possible to determine the probable sequence of detachment along the western edge of the central roof in which a Z-section flashing rotated upwards, increasing the wind uplift pressure acting on the underside of the flashing and entering the upstand detail (*Figures* 6 and 7). This, in turn, caused the perimeter channel and studs to lift upwards, causing the single-ply membrane to peel back readily with the lack of adhesive restraint.

Within a month of the initial inspection, the second-floor roof was fully replaced with a new mechanically attached PVC single-ply membrane system. The third- and fourth-floor roofs were investigated and found to be of a similar construction, with areas of debonded single-ply membrane adjacent to the western edge. It was recommended that a new mechanically fixed PVC single-ply membrane should be overlaid over the existing membrane, with a new secure perimeter detail developed.

There were delays in carrying out this work, and over a six-month period, the extent of the delaminated zone increased, ultimately resulting in extensive ruckling or wrinkling. This evidence of further progressive damage persuaded the parties to mechanically fasten and overlay the third- and fourth-floor roofs, with work satisfactorily completed in the summer of 2014.

LESSONS LEARNED FROM WIND DAMAGE INVESTIGATIONS

Safety Comes First

Our first responsibility is to the safety of ourselves and of those around us, including members of the public. Roof consultants inspecting wind-damaged roofs should be experienced at working at heights and in wearing appropriate personal protective equipment. Particular care is required when working close to unprotected roof edges, often requiring the provision of a mobile platform or fixed scaffolding.

Immediately after a storm in which elements of a roof have come loose, a cordon should usually be set up at ground level to keep people away from high-risk areas where further pieces could fall and cause injury. This is particularly important in urban areas and around assembly buildings where people gather, such as schools and hospitals. Usually, these precautionary measures have been undertaken in advance of the arrival of the roof consultant.

Adopt a Scientific Approach

It is important to inspect the wind damage as soon as possible after the incident as possible, before the areas are modified, such as by the removal of loose elements or local emergency repairs. This often requires travel

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Figure 6 – Examination of upstand discovered top channel not fixed to internal stud.

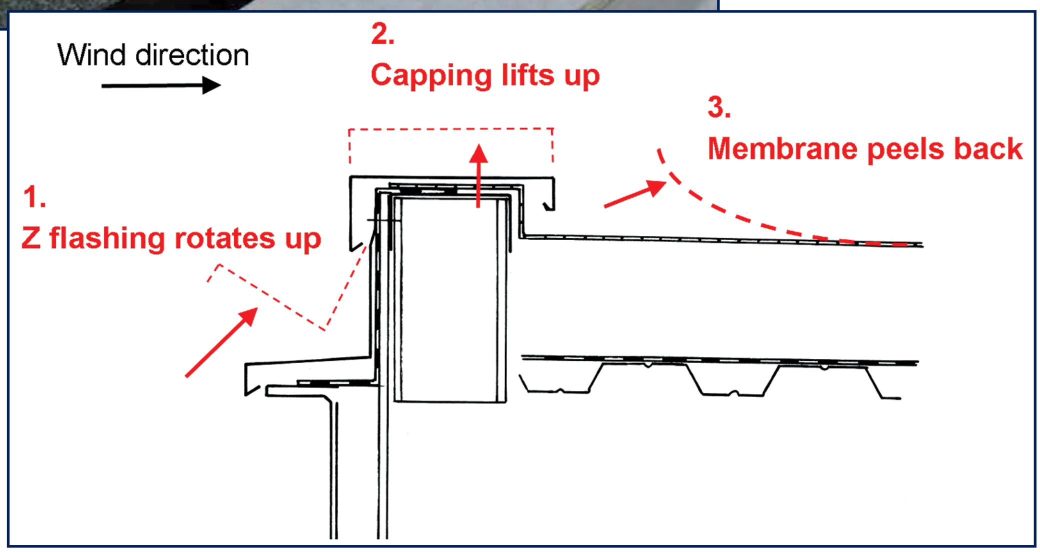

Figure 7 – Probable sequence of detachment of western half of second-floor roof.

at short notice, and the consultant should be prepared.

On first sight, the pattern of damage is often confusing, with multiple failures and impact damage caused by flying debris. The challenge is to identify the first link in the roof assembly that failed. A methodical approach should be adopted, following the good practice set out in the "Guide to Surveys and Inspections of Buildings" published in the UK by the Institution of Structural Engineers. Practical difficulties on site often mean that it is not always possible to gain access to all roof areas on the same day, and an adaptable approach is required to gather as much information in what is often only a short period of time at roof level.

Careful records of observations and sketches with site measurements are important, examining both the zone of detachment and any loose debris. Color photographs that are dated should include general views of the wind-damaged building, the surrounding topography as seen from roof level, and close-ups of the roof assembly—both damaged and undamaged. Where there is some movement in the roof, video recording can be of assistance. Collected samples of damaged elements and fasteners that can be removed should be properly labelled. They can be of great assistance for close examination and reference at the time of report writing, and later for presenting in meetings to assist in explaining likely modes of failure.

Eyewitness Information Can Be Useful

Reliable eyewitness evidence can be invaluable in determining the probable sequence of events. This should include informal discussions with security staff, maintenance workers, neighbors, and roof repair contractors, keeping a note of the names of the eyewitnesses. Closed-circuit security video records may also be of assistance.

Examine Weather Data

The meteorological data from the nearest recording station should include the hourly wind speeds and directions for the period leading up to and including the time of the reported damage. The wind speeds should include the hourly mean, as well as the maximum ten-minute and three-second gust wind speeds. Occasionally, the air temperature and rainfall data are also of assistance in assessing the strength of the components; for example, some artificial slates absorb water and lose flexural strength.

Commission Testing

Basic static screw and nail pullout strengths can be determined using screw jack equipment, either on site or on a lab bench. A first estimate of the degree of movement can be measured by pulling a flexible sheet by hand and measuring the applied load with a spring balance. Other

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test methods include the FM Global wind uplift field test, and laboratory tests of full-scale roof assemblies using compressed air bags to apply an upward loading that allows for changes in the shape of the roof cladding.

Prepare Calculations

To check the structural adequacy of mechanically fixed roof systems, calculations should be prepared to estimate the applied wind loads on the different links in the chain, transferring the upward wind loads down into the supporting structure and to assess their factors of safety. The summary given in Table 2 of the first case study is a good way to highlight the weakest link.

Within bonded multi-layer roof systems, the wind pressure acting on each layer is not the same. The layer with the greatest upward pressure, or the critical layer, is the first air-impermeable barrier from the underside of the roof. The critical layer could be a concrete roof deck, a vapor control layer laid over perforated metal decking, or a waterproofing layer above an unsealed metal deck and fibrous insulation. This should be considered by the roof consultant in assessing the applied wind loading on the roof system.

Undertake Desk Study

Any project drawings or specifications should be examined, together with copies of original manufacturers' literature relating to the claimed performance of the roofing system. This, in turn, requires access to a reference library with historical product literature. Ordinance survey maps are particularly useful in the UK for identifying the topography and exposure of the land around the site, which may give rise to unusual wind features. Enquiries into similar damage reports elsewhere—both nationally and internationally—may provide useful background information.

Prepare Report

The report should bring together the information collected and present the facts and discussion in a logical order with concise conclusions and clear recommendations. The use of photographs and line drawings is particularly helpful to the lay reader in illustrating where the failures probably occurred. Recognizing the commercially sensitive nature of some wind damage investigations, there is a need for matters to be dealt with on a strictly confidential basis.

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When instructed, the options for repairing or replacing the wind-damaged roofs should be identified, summarizing the advantages and disadvantages of each. From experience, there are occasions when the roof consultant cannot be confident of the precise reasons why the roof failed. On such occasions, there is a need for further examination, testing, and analysis to improve the understanding of the performance of the roof when subjected to strong winds.

CONCLUSIONS

A methodical approach should be adopted in gathering and recording the evidence of wind damage, in undertaking the desk study, and then producing the factual report. It is recognized that these time-consuming tasks often need to be completed promptly to enable repairs to be started and the building brought back into use.

There is a need to learn from experience and to avoid repeating mistakes. This recurred in Ireland in February 2014, when the roof of another aquatic center in County Wexford blew off, suffering the same mode of failure as the aquatic center in Dublin a decade before. The lessons from previous investigations hadn't been shared within the roofing community.

It is hoped that by sharing feedback from wind damage reports in an independent and constructive way, we can improve our common understanding of failure mechanisms, enabling us to design and build more reliable building envelopes that are better able to withstand the extremes of changing weather patterns in whatever country we practice.

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Keith Roberts

Keith Roberts is principal of Roberts Consulting, an independent firm of consulting engineers. He is a chartered civil and structural engineer who has investigated wind damage to more than 50 roofs in the UK and Ireland over the past 25 years, identifying the causes of the failure and working with the parties to agree on practical forms of repair or replacement. He is chairman of the CIB International Roofing Committee that examined roof reliability and is a member of RCI.

"Get a Roof, Get a Gun" Promo Offered by Roofing Contractor

Looking to stand out from the estimated 2000 other roofing companies scrambling to get business in Colorado, one company has started a promotion called "Get a Roof, Get a Gun." Every completed roof replacement and exterior repair from a hail or windstorm receives an AR-15 rifle.

WeatherProof Roofing & Exteriors' website says the company is offering the promotion through October 1 "because it symbolizes, at its core, who we are: True American Patriots… for patriots like us, its true representation is the high cost of freedom we enjoy…a well-armed population is the best defense for protecting your life, liberty, and happiness."

The company is partnering with a local gun club to run the appropriate background checks. In lieu of the AR-15, customers may choose a handgun or a $500 gift certificate to Cabela's.

Colorado State Rep. Rhonda Fields said, "It is very troublesome to me that someone would want to increase business by offering an incentive to get a new roof by getting a gun."

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