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Aerodynamic Devices for Mitigation of Wind Damage Risk

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ABSTRACT

Different from a conventional wisdom of damage risk mitigation by increasing structural resistance capacity, an aerodynamic approach seeks to mitigate damage risk at the source by reducing the load demand generated by wind. A recent such example is a series of patented aerodynamic roof edge devices designed to minimize uplifts generated by edge vortices. They are being evaluated by full-scale testing in the RenaissanceRe Wall of Wind at Florida International University. Comparative tests of roof gravel scouring show that aerodynamic edge devices increase damage (scouring) threshold speed by at least a factor of 2 compared to conventional roof edge products. Consistent with this result, pressure measurements indicate a reduction in uplift pressures of up to 75% in the roof corner area for the aerodynamic edge configuration relative to the conventional edge shapes.

INTRODUCTION

Amid recent hurricane losses and insurance debates in the United States, mitigation of damage risk becomes one of the central topics that tend to garner the attention of everyone concerned.

Structural mitigation methods that increase component resistance capacities have been sought after for many decades for applications on new constructions and for retrofit of existing buildings. Relatively successful examples include ring-shank nails and hurricane rafter straps, etc. However, there are two inherent shortcomings in the structural mitigation approach. First, its application for retrofit is intrusive to the structure and often requires evacuation of occupants and contents. Second, it does not eliminate the cause of damage, which is the load induced by wind. Hence, resistance capacity needs to be strengthened on each of the many links along the load path from roof to foundation; else, some weak link is left in the chain that may become the next starting point of failure. These factors limit its success in application for loss mitigation. Partly due to a lack of cost-effective mitigation methods, particularly ones for retrofit of the existing building stock, avoidable losses continue to occur in severe storms.

As an alternative to increasing structural capacity, the aerodynamic approach seeks to reduce the load generated by wind, thus mitigating damage risk at the source while being non-intrusive to the structure. One of the potential applications of this approach is associated with the conical corner vortices and cylindrical edge vortices generated along roof edges and the resulting extreme uplift loads. Engineers and other practitioners have noted the frequent wind damage experienced in roof edge areas (e.g., FM 1985, IBHS 1999 [1] and [2], and Baskaran et. al. 2007; also see Figs. 1 to 3). Researchers have documented the severity of the vortex-induced uplift observed on flat roofs (e.g., Stathopoulos 1987, Kramer and Gerhardt 1989, Gerhardt and

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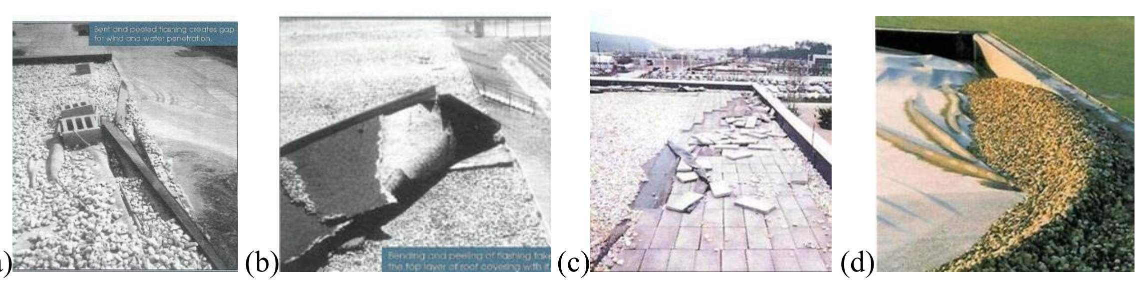
Kramer 1992, Mehta and Levitan 1992, Cochran and Cermak 1992, Cochran et. al. 1993, Lin et. al. 1995, Lin and Surry 1998, Whalen et. al. 1998, Banks and Meroney 2001, etc.). Some also explored a variety of roof edge configurations or devices to suppress vortex and reduce uplift with varying degrees of aerodynamic effectiveness and architectural practicality (e.g., Lin and Surry 1993, Tieleman et. al. 1994, Surry and Lin 1995, Cochran et. al. 1995, Cochran and English 1997, Wu 2000, Banks et. al. 2001, Phillips 2003, Kopp et. al. 2005, and Franchini et. al. 2005).

Aiming to bring research results into real-life applications for damage risk mitigation, this paper examines a recent full-scale study of a series of prototype devices primarily derived from Lin and Surry (1993) and Surry and Lin (1995) in the RenaissanceRe Wall of Wind test facility (Blessing 2007, Leatherman et. al. 2007), which has a cross-sectional wind area of 24 ft wide by 16 ft high (7.3 m by 4.8 m) and a mean wind speed of up to about 125 mph (56 m/s). The comparative study included gravel scouring and pressure tests for full-scale conventional and aerodynamic edge configurations or devices on a 10 ft (3 m) cube-shaped building. The implication of load reduction by aerodynamic devices for economic loss mitigation is briefly discussed.

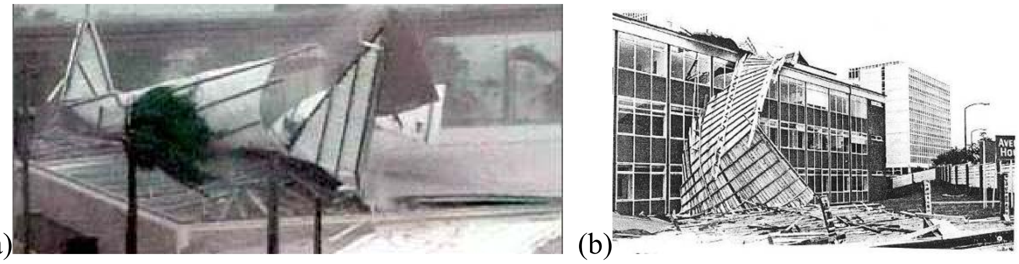
BACKGROUND OF STUDY

Wind damage initiated at roof corners and edges appears to be the single most dominant cause for frequent loss occurrences as exemplified in FM 1985, IBHS 1999 [1] and [2], and FEMA 2004 and 2007. Damage to roof corners and edges (Fig. 1) starts at relatively low wind speeds, well before wind-borne debris becomes a major threat to breach glazed areas such as windows and glass doors at higher wind speeds, at which roof corner and edge initiated large scale damage (Fig. 2) continues to contribute to the overall losses. The roof ballast scour and membrane damage shown in Figs. 1(c) and 1(d) was caused by thunderstorm wind known to be far below hurricane force. Fig. 3(a) shows an example of typical scour patterns on a high-rise building during a modest storm. A wind tunnel study by Kind and Wardlaw (1984) investigated the effects of parapet height on roof gravel scour and blow-off under the influence of corner



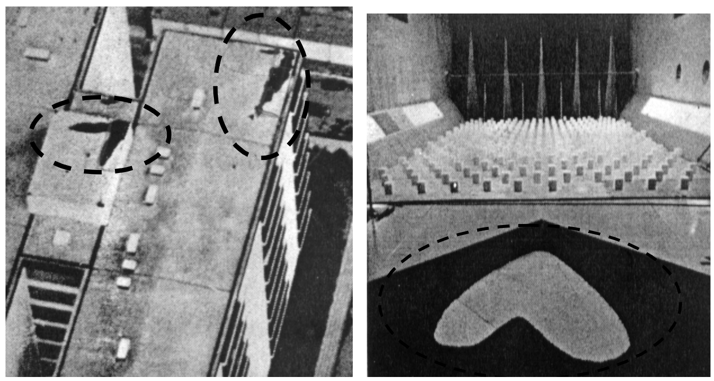
(a) (b) (c) (d)

Fig. 1. Strong edge vortices cause gravel scour and other damage in modest wind events (a and b. FM 1985; c. W.P. Hickman Co.; d. UK Building Research Establishment)



(a) (b)

Fig. 2. (a) Roof damage initiated from windward edge (NBC News 2005); (b) Damage to roof with a conventional edge system, detached along the windward edge (Cook 1990)



(a) (b)

Fig 3. (a) Roof ballast scour on a high-rise building; (b) Wind tunnel study of parapet effects on roof gravel scouring (both from Kind and Wardlaw 1984)

vortices as depicted in Fig. 3(b). Damage statistics from various sources below further illustrate the extent of the roof edge vulnerability problems.

A Factory Mutual Research Corporation study (FM 1985) determined that 79% of the flat roof failures occurred at the edge. Discussing a US wind design standard for roof edge systems (ANSI/SPRI ES-1), a Southern Building magazine article (1999, Jan.-Feb. issue) revealed that 80% of construction litigation involved water damage, and 90% of the damage, or about 72% of total, began with wind and water leaks at the roof edge. Metal-Era Corporation, one of the largest low-slope roofing manufacturers, provides that nearly 75% of all incidents of roof blow-off occur at the roof edge (http://www.advanced-roofing.com/productsservices/metalera.htm). A preliminary report of post-storm surveys of the 2004 hurricanes by IBHS (2004) also indicated that 70-80% of all peeling of shingles and sheathing was initiated at the edge or corner regions. These damage statistics paint a consistent picture of the continued problems associated with roof edge performance. Solution to the problems lies in research results that are applicable in practice.

The initial concept of the aerodynamic roof edges studied herein was developed through understanding the dynamics of wind flows over buildings. Wind tunnel model-scale tests were carried out to verify the initial concept (Lin & Surry 1993, and Surry & Lin 1995). Practical devices configured to be attached to actual buildings were later developed and tested at 1/4-scale in a wind tunnel against a conventional roof edge product as described in the examples below.

Examples of roof pressures previously measured on model-scale buildings are shown in Fig. 4, where uplift pressures measured in the area near the windward roof corner under the pair of vortices are illustrated for both conventional and aerodynamic edge shapes. The worst uplift pressures located near the roof corner for the conventional roof edge were reduced by about 75%, or a factor of 4, when aerodynamic roof edge shape was used (Surry & Lin 1995).

Examples of model-scale roof ballast scour tests are shown in Fig. 5, where granular cat food was used to simulate roof gravel according to dynamic similarity requirements. The 1/4-scale models with traditional and aerodynamic edge products were tested side by side in a wind tunnel under exactly the same conditions. Scour occurred for the conventional edge shape, as seen in the picture, while the “roof materials” were calm and intact for the aerodynamic edge.

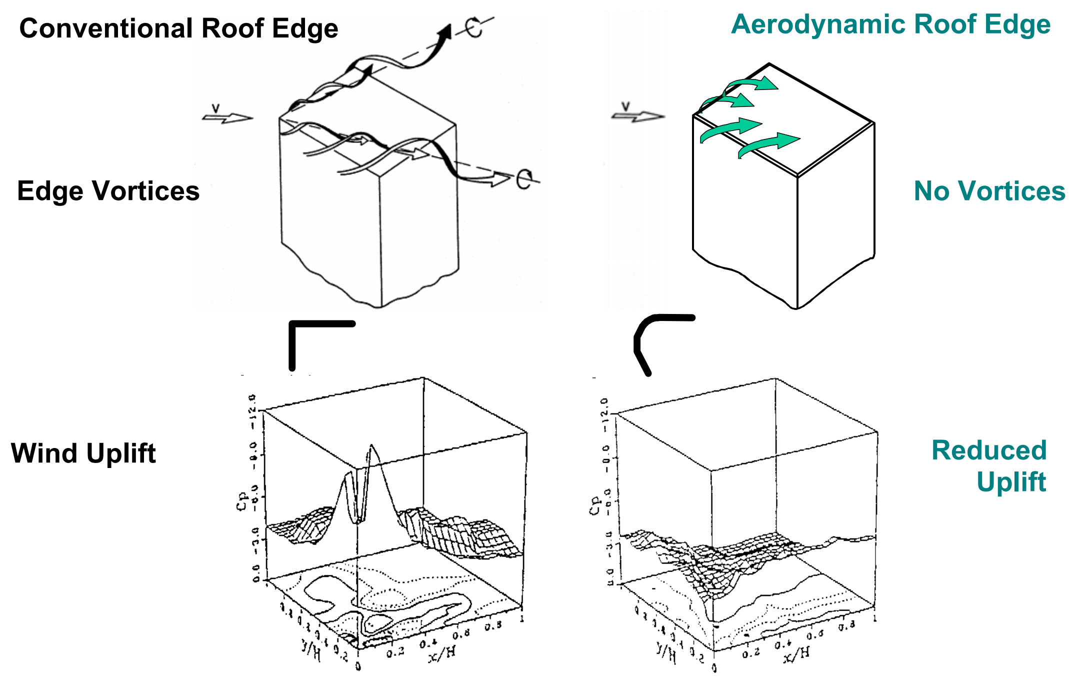


Fig. 4. Roof uplift pressures measured in wind tunnel model-scale tests

Fig. 5. Wind tunnel test of gravel scour on Aerodynamic edge (left) and Conventional edge

From these wind tunnel model-scale tests, it was evident that the concept of aerodynamic roof edges provides a promising effective means for damage mitigation through vortex suppression and wind load reduction. To validate the core functionality and effectiveness of full-sized aerodynamic roof edge prototypes, full-scale pressure measurement and roof ballast scouring tests were carried out in the RenaissanceRe Wall of Wind as described below.

FULL-SCALE TESTS

RenaissanceRe Wall of Wind (Fig. 6) is a full-scale facility designed for destructive wind tests, which generate flying debris and thus would not be suitable in conventional facilities such as in wind tunnels. The RenaissanceRe Wall of Wind has a cross-sectional wind area of 24 ft wide by 16 ft high (7.3 m by 4.8 m) and a mean wind speed of up to about 125 mph (56 m/s) (Leatherman et. al. 2007). The wind profile and turbulence characteristics are still a subject under investigation; however, the present comparative study emphasizes the relative performances between conventional and aerodynamic edge configurations, which is expected to rely less on the exact flow characteristics. The study included gravel scouring and pressure tests for real-size prototypes or products on a 10 ft (3 m) cube-shaped structure as shown in Fig. 6.

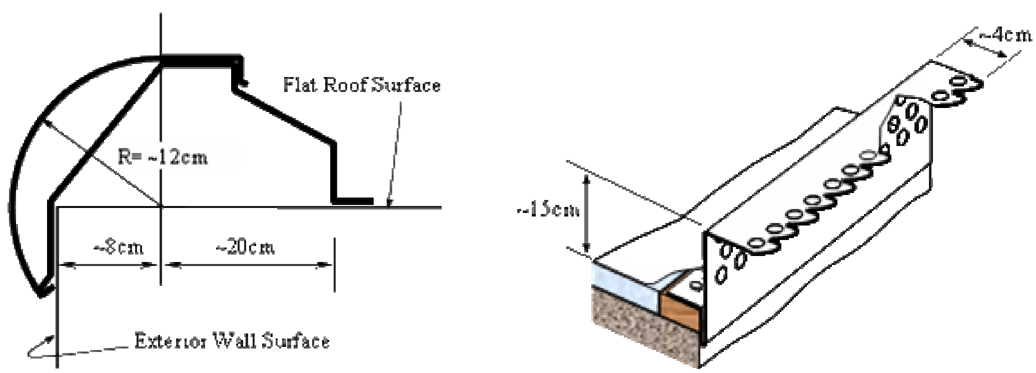
(a)  (b) 

Fig. 6. (a) RenaissanceRe Wall of Wind; (b) Test structure at 45^{o} to the wind

Two aerodynamic edge prototypes for flat roofs were tested, namely an AeroEdge™ cap and an AeroEdge™ screen as sketched in Fig. 7. Two conventional edge products (Fig. 8) were also tested for comparison. One is the prevailing conventional type that represents at least 75% of the market, namely the traditional fascia. Another is the drain-through gravel stop, which appears like an AeroEdge™ screen design while in fact it is not, for lack of vortex suppression functionality, as shown below. AeroEdge™ screen has about 50% porosity while the drain-through has less than 30% porosity.

<u>a. Roof Ballast Dislodging Tests</u>

Roof gravel scouring tests, as other destructive tests, are not just a visualization or show of force, but also provide the most direct quantification of damage threshold wind speed when it is properly defined and recorded as done by Kind and Wardlaw (1984). In this study, scouring threshold wind speed was defined as the wind speed at which gravel aggregate starts to be swept and displaced to the extent that an observable area of roof surface is exposed. A 2-inch (5.1 cm) layer of river gravel, which is widely used throughout the United States as aggregate ballast for flat roofs, was used in these tests. The nominal gravel diameter is about 0.5 inch (1.3 cm). Fig. 9 shows the wind scour of gravel aggregate at a wind speed of 74 mph (33 m/s) for the traditional fascia and for the drain-through gravel stop, respectively, in comparison with the two AeroEdge™ prototypes shown in Fig. 10. A scour pattern caused by a pair of conical corner vortices is clearly visible at this wind speed for both conventional types. In fact, video records of the tests show that scouring actually starts at about 62 mph (28 m/s), where a small portion of roof ballast was dislodged and the roof deck was exposed. There was no scouring for the two aerodynamic prototypes.



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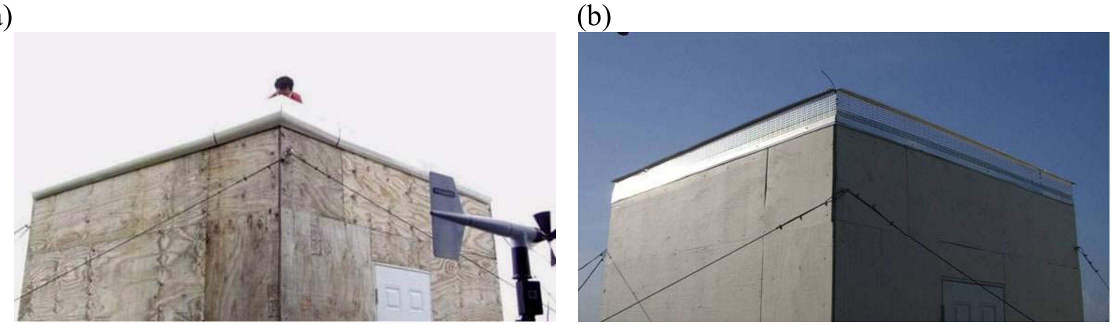
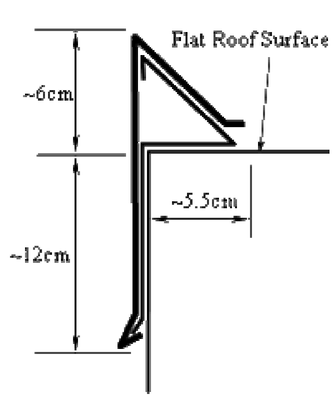
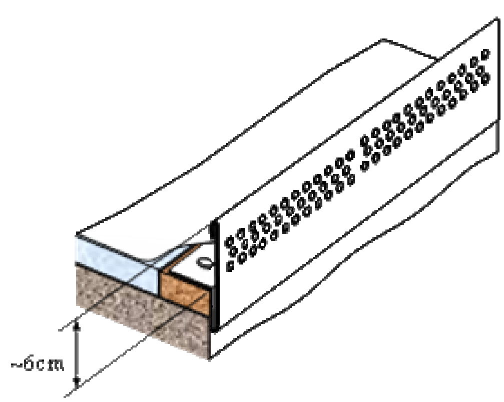


Fig. 7. Aerodynamic prototypes tested: (a) AeroEdge™ cap; (b) AeroEdge™ screen; not to scale





(a) (b)

Fig. 8. Conventional products tested: (a) Traditional fascia; (b) Drain-through gravel stop

(a)  (b) 

Fig. 9. Gravel scour recorded for conventional products at a wind speed of 74 mph (38 m/s) for a cornering wind of 45^o: (a) Traditional fascia; (b) Drain-through gravel stop

(a)  (b) 

Fig 10. No scour observed for aerodynamic prototypes at a wind speed of 74 mph (38 m/s) for a cornering wind of 45^o: (a) AeroEdge™ cap; (b) AeroEdge™ screen

Figs. 11 and 12 show scour at 125 mph (56 m/s) for the traditional fascia in comparison with the results for the AeroEdge™ screen for the wind directions of 45^o and 30^o, respectively. Substantial roof area was cleared of ballast by the vortices for the traditional fascia, whereas no scour or displacement of gravel aggregate on the roof occurred with the AeroEdge™ screen.

(a)  (b) 

Fig 11. Comparison of scouring at a wind speed of 125 mph (56 m/s) for a cornering wind of 45^o: (a) Traditional fascia; (b) AeroEdge™ screen

(a)  (b) 

Fig 12. Comparison of scour at a wind speed of 125 mph (56 m/s) for a cornering wind of 30^o toward the farther windward side: (a) Traditional fascia; (b) AeroEdge™ screen

In short, for the gravel size and roof height tested, the scour threshold wind speed is about 62 mph (28 m/s) for the two conventional roof edge products tested and is at least 125 mph (56 m/s) for the AeroEdge™ screen since no scour was observed at this wind speed yet. That is, the AeroEdge™ screen at least doubles the damage threshold wind speed over the conventional types. This is further illustrated in Fig. 13, where the functional relationship is extended for other gravel diameters according to a formula described by Kind and Wardlaw (1984).

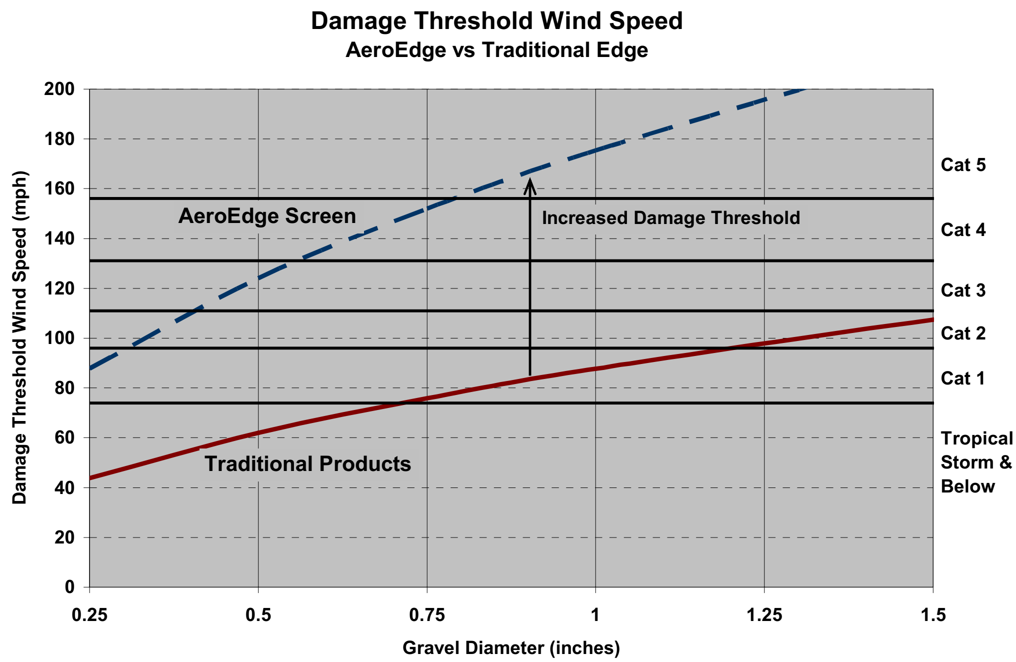


Fig 13. Comparative scour threshold wind speeds as functions of gravel diameter between the conventional edge products and the AeroEdge™ screen

This improvement in ballast dislodging threshold achieved by AeroEdge™ designs can be interpreted to mean that aerodynamic edges reduce damage effects of hurricane wind on the foremost important roof edge areas by 3 to 4 hurricane categories on the Saffir-Simpson scale compared to conventional designs, as illustrated in Fig. 13. This would mean significant reduction of potential economic loss given the fact that over 70% of past wind damage initiated from roof edge areas, as discussed earlier. A brief example for economic analysis is given later.

b. Roof Uplift Pressure Tests

In parallel with the gravel scour tests, pressure measurements were also carried out for the two conventional products and for the AeroEdge™ screen prototype. The same roof without any edge product installed was also tested for comparison as a well-studied baseline case for which we know almost exactly where the conical vortex lies (e.g., Lin et. al. 1995). Fig. 14 depicts its trace with a thickened line emanating from the roof corner and also indicates pressure tap locations designed to lie around the vortex trace.

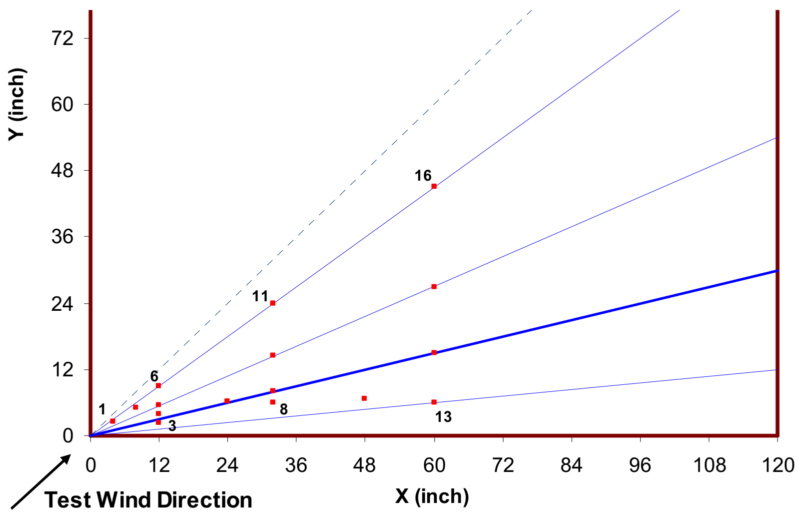


Fig. 14. Pressure tap layout for full-scale uplift pressure measurements

Peak pressure coefficients are presented in Fig. 15 for the cornering wind of 45°, which is one of the worst wind directions. The pressures for the AeroEdge™ screen appear to be much flatter than the non-aerodynamic configurations. This indicates that there is no pronounced vortex structure in the instrumented corner-edge area for AeroEdge™ screen, while for the non-aerodynamic configurations a vortex structure is detected in the same area. This observation is markedly consistent with the scouring test results described above. Quantitative comparisons of the pressure coefficients show that AeroEdge™ screen substantially reduces the worst uplift pressure near the corner area. For example, at Tap 3, which is a location near one of the vortices, the magnitude of the pressure coefficient is reduced from 18.3 for the original edge shape or so-called baseline case, to 4.6 for the AeroEdge™ screen. This is a reduction of 75% or by a factor of 4.

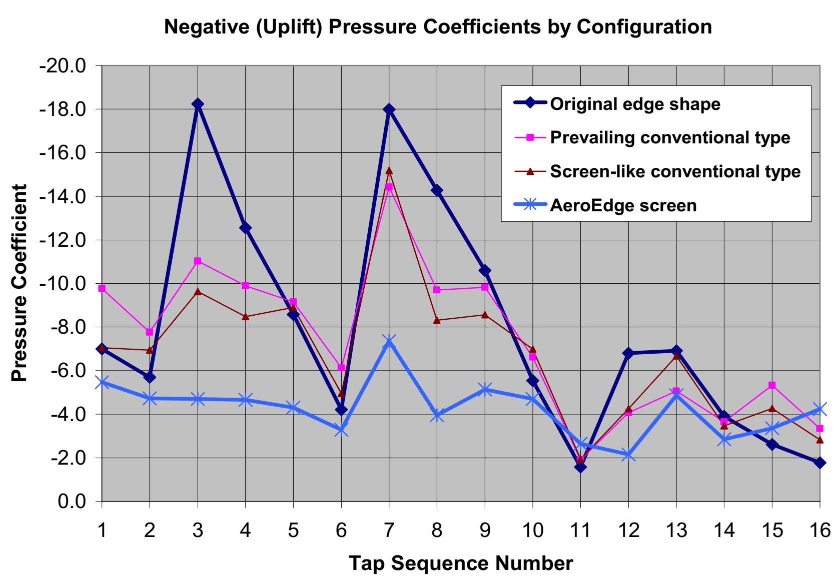


Fig. 15. Peak uplift pressure coefficients measured for various edge configurations

This reduction in uplift pressure is also consistent with the improvement in scour wind speed threshold, considering that pressure is proportional to the square of wind speed. Again, this is a very significant reduction in that it means the effects of hurricane wind are reduced by 3-4 categories in the roof edge areas, where most of hurricane wind damage to buildings initiates.

For the conventional products, the measured worst uplift pressures are also substantially higher than that for the AeroEdge™ screen, by about a factor of 2. However, the test results shown may have missed the worst uplift pressures present on the roof under the corner vortices, where very steep pressure gradients exist between adjacent taps for all non-AeroEdge™ cases. This can be seen in Fig. 15 for recorded pressure coefficients across the row of Taps 3 to 6 or across the row of Taps 8 to 11. Spatial patterns of uplift pressures shown earlier in Fig. 4 for a classic baseline case also clearly illustrates such steep pressure gradients under the roof corner vortices. Since the exact locations of the worst uplift pressures were previously known only for the well-studied baseline case, and the number of pressure taps was limited to a total of 16, it was less likely to have captured the worst uplift pressures for the other two non-AeroEdge™ cases that also exhibit steep pressure gradients as seen in Fig. 15. To this end, gravel scour tests have a clear advantage in capturing the previously unknown critical details associated with the modified conical vortices such as their existence, location and strength, etc. The gravel aggregate uniformly covers the entire roof without omitting any particular location, regardless of where the vortices and the worst uplift pressures are being shifted by any roof edge device.

As shown earlier in Fig. 4, previous wind tunnel scale-model pressure tests on shapes similar to AeroEdge™ cap here yielded uplift pressure reduction nearly identical to the 75% achieved here by AeroEdge™ screen and demonstrated that the conical vortices are being suppressed with aerodynamic edge caps.

In brief, AeroEdge™ designs can potentially reduce critical uplift pressures on the roof by 75% or by a factor of 4. This is equivalent to a reduction of wind damage effects in the roof edge areas by a factor of 2 in wind speed, or roughly by 3-4 hurricane categories on the Saffir-Simpson scale, in a consistent trend with the results of roof gravel scouring tests where scouring threshold wind speed increases by at least a factor of 2 with AeroEdge™ screen.

DISCUSSIONS

a. Vortex Suppression

From the roof gravel scouring tests, it appears that the conical corner vortices, known to induce strong scour and high suction on the roof under cornering winds, are being suppressed either by rounding the sharp roof edge (AeroEdge™ cap) or by diverting flows in the separation zone over the roof edge (AeroEdge™ screen). Present full-scale and previous model-scale pressure tests provide further evidence to support this judgment, showing significant reduction of roof suction. A planned flow visualization test carried out with water spray, in conjunction with wind-driven rain simulation, will further reveal the flow structure and mechanism associated with vortex suppression.

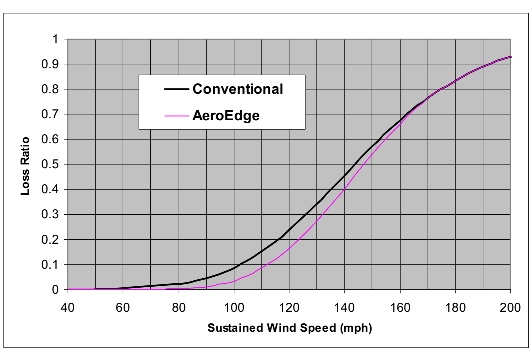
For the conventional edge products tested (i.e. Traditional fascia and Drain-though gravel stop), gravel scour and thus organized vortex is evident. Although the Drain-through gravel stop is perforated, the porosity is insufficient to divert enough air flow to effect vortex suppression. With their structural attributes essentially resembling a straight sharp edge, the conventional edge products appear to perform just like one. They seem to yield comparable vortex strengths for a given wind speed. Note that the scouring threshold speed for these products is as low as only half the speed where none or little gravel movement has been observed for the aerodynamic configurations, while the worst uplift pressure measured for the sharp edge baseline case is about 4 times that of the aerodynamic configurations, keeping in mind that pressure is proportional to square of wind speed. For a direct comparison of worst pressures between the conventional products and aerodynamic configurations, it will be interesting to use a denser grid of pressure taps to confidently capture the worst uplift pressure on the roof with the conventional products where the traces of the vortices may be shifted by the raised edges while their strength may still be maintained.

b. Potential Loss Reduction

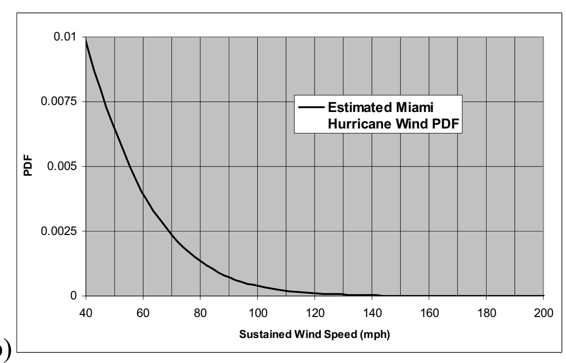
While it is not the intention for this paper to give a comprehensive economic analysis, an example of loss reduction analysis is given here to gauge the potential economic benefit brought by aerodynamic devices in loss reduction.

A reduction in uplift load in the roof edge area for a given wind speed provides a reduction in both the probability and severity of damage to the roof cover, roof deck and roof framing in that area, and damage in adjacent area from tearing and other progressive failure behaviors. To a lesser extent damage will also be reduced for components in the path of uplift load being transferred to the foundation, such as roof-to-wall connections. This reduction in damageability is equivalent to the increase of damage threshold wind speed for given component capacities for uplift loads, as demonstrated earlier with roof ballast as part of the roof cover.

Reduction of overall monetary damage for a building, due to attenuations in component damageability, is reflected in a non-uniform shift of a damage function towards higher wind speeds for AeroEdge™ compared to conventional edge. For example, in Fig. 16(a), expected loss ratio reductions are shown for an average building, as estimated from a generic vulnerability model. Damage functions describe the expected loss ratio as function of wind speed, and are completed with loss ratio probability distributions at given wind speeds.



(a)



(b)

Fig 16. (a) Modeled vulnerability functions for an average building with/without AeroEdge™; (b) Approximate wind speed distribution for Miami area

For example, as illustrated for Miami, integrating the damage functions with a local hurricane wind speed model, as shown in Fig. 16(b), yields expected hurricane loss costs derived for specific building configurations with and without AeroEdge™ respectively, as included in Table 1. The expected annual loss cost for the building with AeroEdge™ is \$5.76 per \$1000 value, compared to \$11.96 without AeroEdge™. This represents a reduction of 52% in averaged annual loss. Table 1 also includes examples for Charleston, SC, and Newport, RI (roughly representing geographic area indicated in the column only for the percentage loss reduction). The percentage of loss reduction is higher for these areas relative to Miami since these areas are expected to experience fewer extreme high wind events that are beyond the protection of edge devices *alone*. In these extreme winds, other parts of the building start to incur damage. A more sophisticated vulnerability and economic analysis is under way with further refinement and verification of some of the assumptions used here.

Table 1. Estimated loss reduction by AeroEdge™ for an average commercial building

LossCost	**Miami, FL** (Southeast Florida Coast)	**Charleston, SC** (Gulf & Lower East Coast up to NC)	**Newport, RI** (Upper East Coast & Inland)
Conventional	\$11.96	\$5.53	\$2.02
Roof AeroEdge	\$5.76	\$2.02	\$0.47
Loss Reduction	**52%**	**63%**	**77%**

CONCLUDING REMARKS

Aerodynamic roof edge devices designed to minimize uplifts generated by corner and edge vortices are tested using a full-scale experimental regime. Comparative tests of roof gravel scour show that aerodynamic edge devices increase the damage (scouring) threshold wind speed by at least a factor of 2 compared to conventional edge products, which is equivalent to an increase of 3 to 4 hurricane categories on the Saffir-Simpson scale. Pressure measurements indicate reductions in uplift pressure of up to 75% in the roof corner area for the aerodynamic configuration compared to the conventional edge shapes. Potential hurricane loss reduction due to wind load reduction through the use of aerodynamic devices is expected to be significant, as showcased by a simple analysis on expected losses with and without the use of aerodynamic devices.

Being simple, economic, and non-intrusive, aerodynamic edge devices reduce wind loads and mitigate damage risk at the source. They provide not just an alternative to structural mitigation methods, but a comparatively cost-effective solution to the roof edge damage problem widely experienced during high winds.

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