Lessons Learned from Failures of the Building Envelope in Windstorms

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Abstract: Lessons learned from failures of the building envelope in windstorms are encapsulated in three principal findings. The building envelope is crucial to the performance of buildings in windstorms. Windborne debris is decisive in shaping the performance of the building envelope. Design attention should be given to postimpact behavior of building-envelope systems. Reviews of damage documentation, insurance records, and computer simulations of building failures establish the importance of the building envelope to satisfactory building performance. These reviews also establish the decisive role of windborne debris in causing damage. The imperative for considering the postimpact behavior of building envelope systems is discussed, and innovative glazing products that meet new design criteria are presented. It is concluded that the building envelope should be given status equal to the principal structural frame in terms of design attention.

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Introduction

The writer has been immersed for 33 years in hundreds of damage investigations, extensive research and publication activity, many building-code writing actions, and numerous design undertakings, all involving the performance of building envelopes in windstorms. These experiences are summarized for this paper as lessons learned from building envelope failures. The lessons can be summarized in three principal findings: the building envelope is crucial to the performance of buildings in windstorms, windborne debris is decisive in shaping the performance of the building envelope, and design attention should be given to postimpact behavior of building envelope systems. Each of these lessons is discussed below.

The Building Envelope Is Crucial

Research at three levels clearly establishes the paramount importance of the building envelope to satisfactory performance of buildings in windstorms. The first level of research, field documentation following windstorm events, reveals how quickly damage escalates with the first loss of a cladding component, be it a panel of roof sheathing, a broken window, or a door. The house shown in Fig. 1 illustrates this escalation. The immediate result of failures of windows and doors was an increase in internal pressure. This occurrence, in combination with overall roof uplift pressures, initiated a chain of events that included removal of roof sheathing, wind and rain entering the building, and the beginning of progressive failure of the building frame. Exposure of the interior of the building and its contents to wind and rain greatly magnified the cost of damage.

A second level of research involves assessing insurance records. Analysis reveals a dramatic increase in total insured loss when the physical damage includes breaching of the building envelope. Work by Sparks et al. (1994) relates wind speed and damage claims for residences. Results of this research clearly show an increase in the size of claims at a wind speed where the building envelope is compromised (Fig. 2). A loss magnifier (overall building loss minus damage to external facilities, divided by the cost of damage to the roof and wall envelopes) increases from two to nine above wind speeds identified with loss of sheathing. Roof and wall envelope losses begin to increase rapidly at about 145 mi/h (65 m/s) in building code terms, indicating major failures of these components. This wind speed is moderately higher than building-code–specified wind speeds in hurricane-prone regions. At wind speeds near and above this level, the rate of increase of the average total loss is much larger than the rate of increase of the component losses. The relationship between building-envelope failure and the magnifying of total loss is so dramatic that Sparks et al. (1994) advocates designing the building envelope for wind speeds associated with collapse-limit-state loads for the structural system.

Finally, a third level of research involves theory-based computer models that have been developed to assess the progressive failures of buildings in windstorms. These sophisticated models are commonly employed to project windstorm damage for emergency planning and for establishing insurance rates. Some of these models replicate the progressive damage to buildings as the winds of a hurricane increase, change direction, and instigate windborne debris. The most prominent of these models, HAZUS Wind (Minor and Schneider 2002), addresses possible sequences of progressive failure for specific building types. The potential weak links in the chains of structural strength are identified for a specific type of building. For a residence, the weak links may be shingle-to-sheathing connections, sheathing-to-rafter connections,

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Fig. 1. Building envelope damage may result in total insured loss

rafter-to-top plate connections, top plate-to-stud connections, stud-to-bottom plate connections, and bottom plate-to-foundation connections. Each connection is assigned a range of possible strengths (e.g., a "toe-nailed" strength and a "hurricane clip" strength for a rafter-to-wall connection). In addition, ranges of strengths for other building components—such as windows, doors, skylights, wall panels, and the structural frame—are defined. When all significant failure points and their ranges of strengths have been listed, thousands of possible damage sequences may be defined, depending on selections of connection strength combinations. For example, if the rafter-to-top plate connection is a hurricane clip, the failure point may be forced to the sheathing-to-rafter connection. If the rafter-to-top plate link is a toe-nailed connection, the failure point may be prove to be the rafter-to-top plate connection. The interesting result of thousands of computer simulations using various combinations of all connection and component strengths reveals that, for most building types, insured losses become total through damage to the building envelope and subsequent immediate effects long before the principal structural frame fails. This observation is common in application to most building types and reinforces observations regarding the importance of the building envelope.

Windborne Debris is Decisive

As early as 1972, investigators at Texas Tech University observed that windborne debris plays a major role in damaging the building envelope (Minor et al. 1972). In ensuing years, other investigators, as well as building code officials, have come to the same conclusion. Reports of Hurricane Alicia (Houston, Tex., 1983), Hurricane Hugo (Carolinas, 1989), and Hurricane Andrew (south Florida, 1992) cite windborne debris as a major contributor to loss totals. Specifically, *Proceedings of the Specialty Conference: Hurricane Alicia: One Year Later* (Kareem 1985) contains several papers that conclude that the blow-off of roof gravel was instrumental in causing window-glass damage to high-rise buildings in downtown Houston (Fig. 3). Behr and Minor (1994) conclude that windborne debris was a major factor in damage to glass in multistory buildings in south Florida during Hurricane Andrew (Fig. 4). Sparks et al. (1994) attributes most of the damage to the building envelope of residences to windborne debris. Finally, four major investigations following Hurricane Andrew highlighted windborne debris as a major cause of property damage (Dade County 1992a, 1992b; FEMA 1992; WERC 1992). The loss magnifier defined by Sparks et al. (1994) approached 10 for the building shown in Fig. 4.

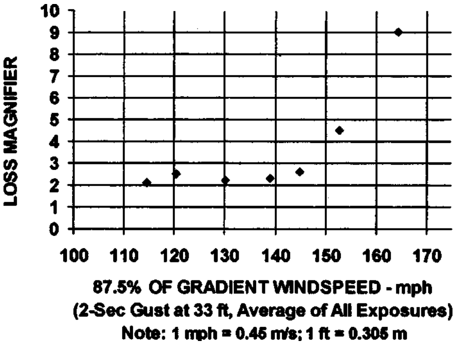

Fig. 2. Total insured loss increases rapidly when building envelope is compromised [adapted from Sparks et al. (1994)]

Fig. 3. Roof gravel blow-off caused window glass damage in Houston, Tex.

Minor (1994) traces the history of the development of debris impact considerations in the design of buildings. The Australians adopted debris impact provisions in building standards for tropical cyclone regions as early as 1975 and in their national wind load standard in 1989. Initial work with windborne debris in the United States related to tornado-resistant design for emergency shelters and nuclear facilities. Large objects such as timbers and automobiles were found to fly and tumble near the ground, whereas small objects such as shingles and roof gravel were determined to fly at greater heights. This technology was applied to

Fig. 4. Roof gravel broke fully tempered glass on building in Cutler Ridge, Fla.

Table 1. Glass Breakage Velocities from 2 gm Roof Gravel.

Wind speed for significant amounts of 2 gm roof gravel to leave roofs without parapets (from Kind and Wardlaw 1976)	Speed of 2 gm roof gravel after accelerating over 100 ft in 100 mi/h wind (from Minor et al. 1978)	Mean minimum break velocity of ¼ in glass from impact of 2 gm roof gravel (from Minor et al. 1978)		
		Annealed glass (AN)	Heat-strengthened glass (HS)	Fully tempered glass (FT)
100 mi/h	70 ft/s	23 ft/s	36 ft/s	64 ft/s

Note: 1 gm=0.0044 lb; 1 ft=0.305 m; 1 mi/h=1.6 km/h; 1 ft/s=0.305 m/s.

the behavior of windborne debris in hurricanes. Dade and Broward counties in south Florida were the first governmental entities to enact provisions for windborne debris in a U.S. building code (SFBC 1993, 1994).

Designing for Postimpact Behavior Is Imperative

Windstorm damage experiences and subsequent assessments have revealed that intrinsic strength alone does not measure the ability of cladding to perform in windstorms. Window glass in particular, but also some types of wall and roof cladding, may be strong enough for windstorm-exerted wind pressures but are not able to preserve the integrity of the building envelope when impacted by windborne debris. This observation prompts the conclusion that postimpact behavior is as important as preimpact strength insofar as preservation of the building envelope is concerned (Minor 1997). This observation also served as a basis for the protocol for testing hurricane-resistant cladding products wherein debris impacts are followed by cycles of pressure representing hurricane wind gusts (ASTM 2002a, 2002b).

Buildings clad in glass have proved to be particularly susceptible to damage instigated by windborne debris. Commonly, the glass is broken through impact from flying roof gravel or other debris, and broken glass particles exit the window opening. The detrimental effects of internal pressure coupled with wind and water entering the building follow. Tests have proven that even fully tempered glass will break under these types of impact. In fact, it has been shown that if the gravel is flying as the result of wind action, it is usually traveling at sufficient speed to break the three basic types of window glass: annealed, heat-strengthened and fully tempered (Table 1). Tempered glass, in particular, has a poor performance record as a cladding element in windstorms (Behr and Minor 1994). Its highly valued safety-glass property, which causes it to break into millions of nonlacerative particles, is detrimental to the objective of preserving the building envelope.

Certain types of wall and roof cladding also may prove unacceptable in windborne debris environments for the same reason. External insulation and finish systems (EIFS) do not perform well after being impacted by windborne debris. Windborne debris may penetrate the relatively soft insulation layer, and the insulation layer can be pulled from supporting studs (Fig. 5). Asbestos cement siding and vinyl siding may fracture under debris impacts because of intrinsic brittleness. Roofing systems that employ clay or concrete tiles may fail because of a lack of connections or limited connections to underlying sheathing or because of debris impacts.

Building officials have recognized the limitations of certain commonly employed building components in windstorm environments. Following Hurricane Andrew in 1992, building codes were altered to require the use of impact-resistant cladding components and opening protective devices (shutters) in hurricane-prone regions. The national standard for defining wind loads on buildings *ASCE 7-02* (ASCE 2003), the *International Building Code* (ICC 2003a), and the *International Residential Code* (ICC 2003b) contain design requirements for windborne debris impacts in hurricanes prone regions. ASTM Standards *E 1886* and *E 1996* outline test protocols and specifications for testing windborne-debris-resistant products (ASTM 2002a, 2002b). The test protocol is designed to represent conditions that are likely to occur in a hurricane: debris impact followed by cycles of pressure created by direction-changing hurricane wind gusts (Table 2).

It has been ten years since the appearance of building code provisions that require components of the building envelope to survive impacts from windborne debris and the following cyclic pressures. During this time period, the window, door, wall, and roofing industries have produced many innovative products that meet these requirements. Hundreds of code-compliant products

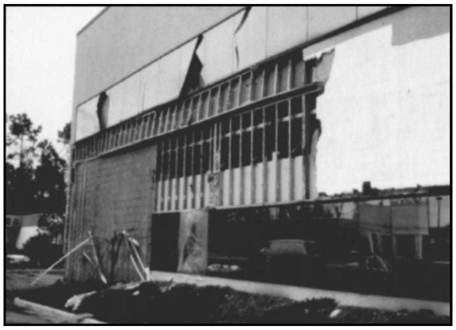

Fig. 5. EIFS system experienced missile penetration and loss of insulation

Table 2. Test Protocol for Building-Envelope Products in Windborne Debris Regions

1. Impact with large or small missile followed by…			
2. Inward-Acting Pressures ($+P_{max}$)		3. Outward-Acting Pressures ($-P_{max}$)	
Range	Number of cycles	Range	Number of cycles
$0.2\ P_{max}/0.5\ P_{max}$	3,500	$0.3\ P_{max}/1.0\ P_{max}$	50
$0.0\ P_{max}/0.6\ P_{max}$	300	$0.5\ P_{max}/0.8\ P_{max}$	1,050
$0.5\ P_{max}/0.8\ P_{max}$	600	$0.0\ P_{max}/0.6\ P_{max}$	50
$0.3\ P_{max}/1.0\ P_{max}$	100	$0.2\ P_{max}/0.5\ P_{max}$	3,350

Note: ($+P_{max}$) and ($-P_{max}$) are design pressures determined from applicable building code.

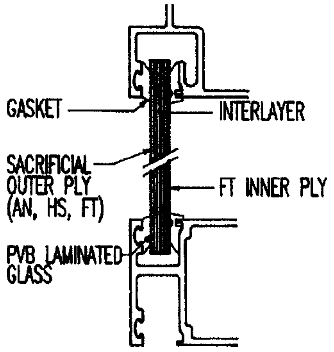

Fig. 6. The sacrificial ply concept allows use of conventional window frames

can be reviewed on-line at www.miamidade.gov/buildingcode/ (link to product control) and www.tdi.state.tx.us (link to windstorm, then to product evaluation index). Two innovative window products are illustrated in Figs. 6 and 7. Fig. 6 is called the sacrificial ply concept because the laminated-glass plies and polyvinyl butyral (PVB) interlayer are designed to "sacrifice" the outer glass ply to breakage from the specified small missile. Broken glass particles from the outer glass ply are retained by the PVB, and enough strength is designed into the unbroken inner glass ply to carry the required design wind pressures, acting alone (Kaiser et al. 2000). This concept is economical because conventional window framing may be employed (special framing and supplemental anchorage of the glass to the window frame are not required). Fig. 7 achieves anchorage of a laminated glass lite, both plies of which may break from impacts from large or small missiles, through extension of part of the interlayer into the window frame for anchorage. The extended interlayer component is polyethylene terephthalate (PET), which, unlike PVB, is stable in the presence of air. Other building-envelope products that can meet windborne debris impact standards include silicone-anchored PVB laminated glass, glass with anchored inner-surface PET films, windows formed from polycarbonate sheets, metallic wall and roof panels, and plastic skylights.

Conclusion

Years of field investigations and research into performance of the building envelope in windstorms disclose that a major change in the philosophy of building design is warranted. The building envelope should be given status equal to the principal structural frame in terms of design attention. Further, windborne debris should be addressed, where appropriate, in the design process. Finally, postimpact performance of building-envelope components should be given status equal to considerations of prefailure strength if the integrity of the building envelope is to be preserved during windstorms.

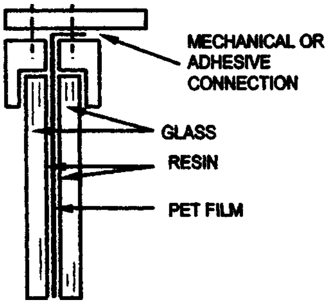

Fig. 7. Innovative window glass concept anchors glass to frame with polyethylene terephthalate (PET) interlayer.

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