

# Performance of building cladding in urban environments under extreme winds

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**ABSTRACT:** When tropical storms, hurricanes, typhoons and other extreme wind events make landfall in or around urban areas, the results are often devastating and costly. Structural assessments of high-rise construction in these regions, as well as other areas impacted by extreme wind events, generally reveal satisfactory global structural performance under dynamic wind loading. However, extensive damage to cladding, especially glass, was observed in each case. The goal of this paper is to discuss the urban dilemma designers are presently facing; an overview of cladding damage from Hurricane Alicia, Hurricane Andrew, Typhoon York, and several urban area tornadoes; cladding damage mechanisms including wind pressures exceeding design values, missile impact from wind borne debris, and performance of glass; and strategies to mitigate damage from these sources.

**KEYWORDS:** hurricane, typhoon, tornado, cladding, wind field, wind borne debris

## 1 INTRODUCTION

When tropical storms, hurricanes, typhoons and other extreme wind events make landfall in and around urban areas, the results are often devastating and costly. For instance, Hurricane Andrew was estimated to have inflicted over \$30 billion of damage, making it the most costly and destructive natural disaster in United States' history, when it violently attacked southern Florida on August 24, 1992 [1]. Hurricane Alicia, which affected the Houston-Galveston area of Texas on August 18, 1983, also ranks high on America's list of costly hurricanes with over \$1.5 billion in damage [2]. When Typhoon York struck Hong Kong in 1999, it was considered the worst storm of the area in 16 years since Typhoon Ellen in 1983 [3]. Tornadoes have also caused damage in urban areas such as Nashville, Tennessee, Dallas/Fort Worth, Texas, Miami, Florida and Salt Lake City, Utah. Structural assessments of taller buildings in these regions, as well as other areas impacted by extreme wind events, generally reveal satisfactory global structural performance under dynamic wind loading. However, extensive damage to cladding, especially glass, was observed in each case. The goal of this paper is to discuss the urban dilemma designers are presently facing; an overview of cladding damage from Hurricane Alicia, Hurricane Andrew, Typhoon York, and several urban area tornadoes; cladding damage mechanisms including wind pressures exceeding design values, missile impact from wind borne debris, and performance of glass; and strategies to mitigate damage from these sources.

## 2 URBAN DILEMMA

Urban areas are constantly expanding in both size and population density. New structures, many of them taller buildings to accommodate increased density requirements, are being built in these areas. Current architectural trends are resulting in fully glazed buildings. These exteriors, which

reflect light and images of the surrounding environment, are aesthetically considered very pleasing. However, the compatibility of glass cladding with the main structural system of the building and its environment, especially high wind events, becomes a pertinent question. Cladding often faces the menace of ubiquitous debris which is often propelled into brittle cladding systems and in some cases excessive stress induced by building racking deformations. The direct costs of cladding failure which include the cost of replacing damaged elements is often dwarfed by indirect costs such as business downtime and damage to interior contents. All of these issues suggest a growing urban dilemma to which research and design communities must lend more consideration.

### 3 OVERVIEW OF DAMAGE

The second author was responsible for collecting information regarding the structural aspects of the damage caused by Hurricane Alicia in the Houston-Galveston area [2]. Observations of building cladding, especially in the central business district (CBD) of Houston, showed that glass cladding experienced the most damage of all cladding materials including brick, travertine, granite, aluminum, and pre-cast concrete. Figure 1a shows a portion of Houston's central business district where a large amount of glass damage occurred. Wind speeds in this area did not exceed code values as seen in Figure 1b [4]. Structurally, all of the high-rise buildings performed extremely well. Damage to these buildings was limited to glass cladding and the streets in this area were littered with glass pieces, sheet metal sidings, and other rooftop accessories. The most seriously damaged areas of the 71-story, glass-clad Allied Bank Building were concentrated on the southeast and southwest faces, up to approximately the 40<sup>th</sup> floor (Fig. 2a). Approximately 3000 glass panes were replaced. Broken panes that remained intact after the storm exhibited fractures consistent with those caused by small missiles.

The 51-story InterFirst Tower suffered severe damage to approximately 650 glass panels located on the northeast and southeast faces (Fig. 2a). In addition, after Hurricane Alicia, workers knocked out the remaining glass from damaged windows and allowed it to fall to the street below

Ironically, this facilitated additional damage to the windows long after the hurricane had left the

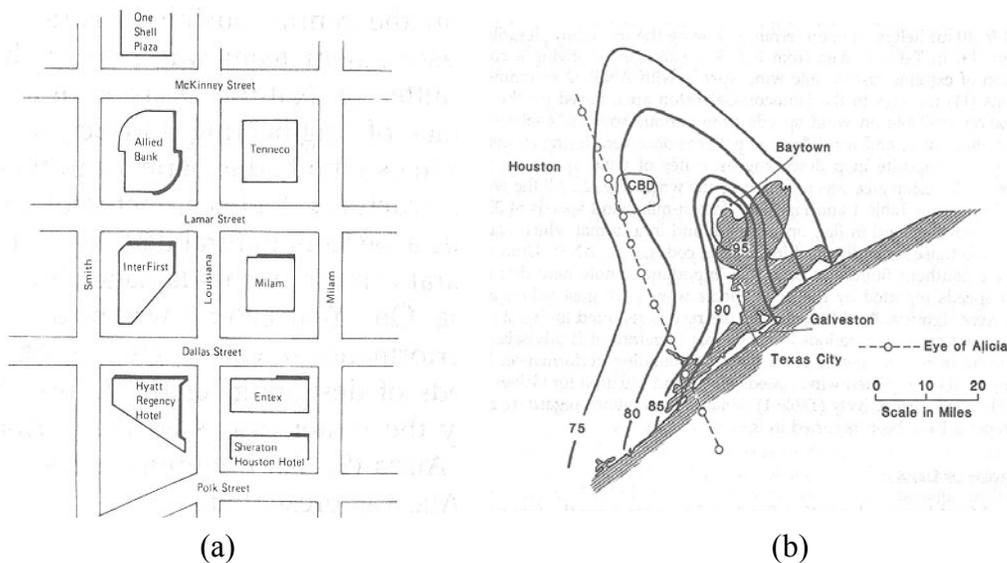


Figure 1. a) Central business district of Houston. Excessive cladding damage in bold. b) Wind speed contours in Houston-Galveston area. Values are fastest mile (mph) at 33 ft (10 m) height [2,4].

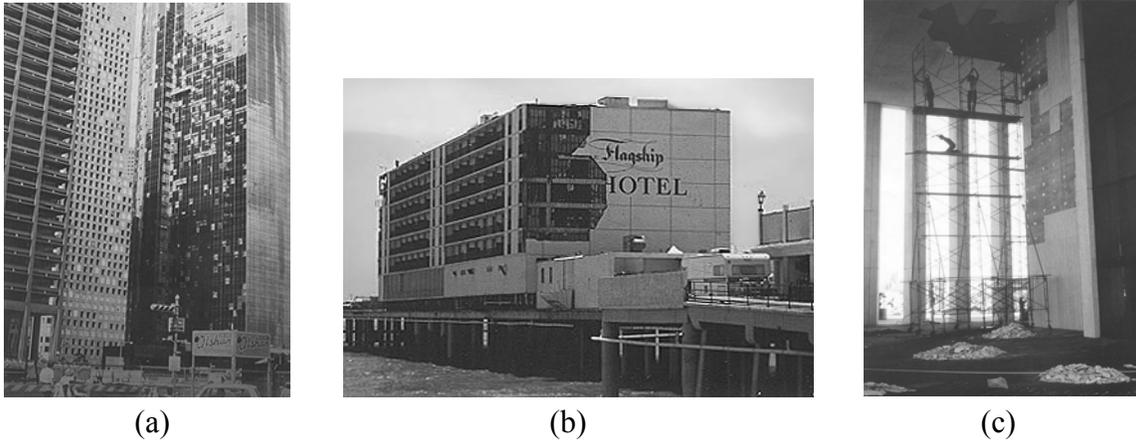


Figure 2. a) Allied Bank and InterFirst Tower b) Flagship Hotel c) Lobby of the American National Insurance Building

area. The Flagship Hotel exhibited extensive damage to large non-glass cladding panels (Fig. 2b). The American National Insurance Building, located behind the seawall in Galveston suffered glass damage as well as damage to stone cladding in its recessed lobby. Large granite panels were dislodged from their seatings and ceiling tiles were damaged (Fig 2c).

Hurricane Andrew devastated southern Florida in 1992 and caused a tremendous amount of damage. In Figure 3a, the peak fastest mile wind speed over open terrain was estimated at 60 m/s (134 mph) and is considered to be an upper bound value [5]. The annexed structure in Figure 3b was damaged as a result of a weak structural system. The high-rise residential structure in Figure 3c lost exterior walls facilitating additional damage to interior contents.

On September 16, 1999, Typhoon York wreaked havoc in Hong Kong causing an abundance of damage to prominent buildings on the island. The wind direction changed from northeast to southwest over the course of the storm. Central Plaza, then Hong Kong's tallest building, lost many glass panels (Figs. 4a & 4b). Nearby, the Great Eagle Center and Harbor Center buildings were missing pieces of flashing on the upper regions of both buildings which may have possibly caused more damage to surrounding buildings in the area. The convention center exhibited damage to panels on the underside of the roof. Figure 4c shows a close up view of glass damage to the exterior of the Immigration building.

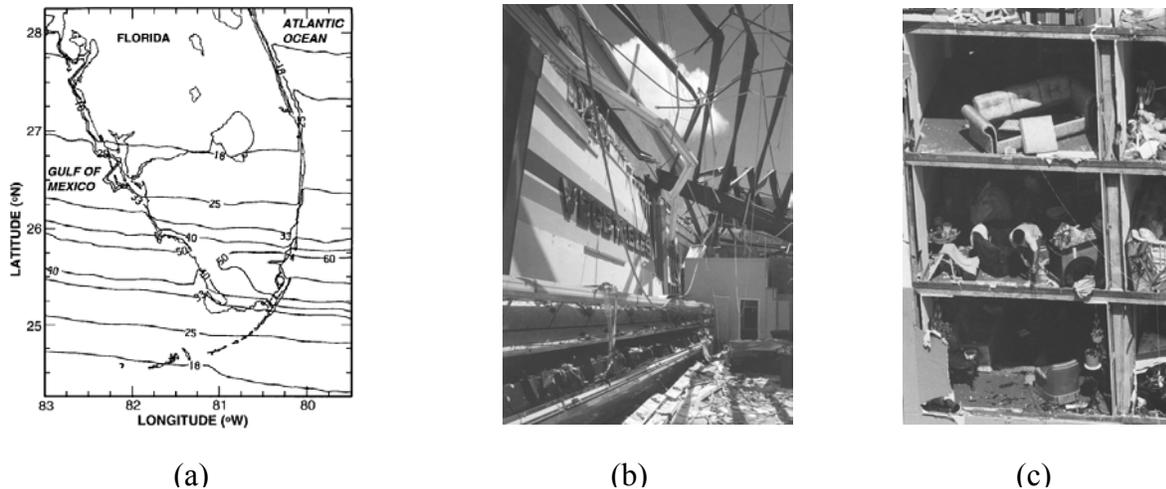


Figure 3. a) Fastest mile wind speeds for Hurricane Andrew (m/s) over open terrain [5]. b) Building damage caused by neighboring structure. c) Residential high-rise structure damage after Hurricane Andrew.

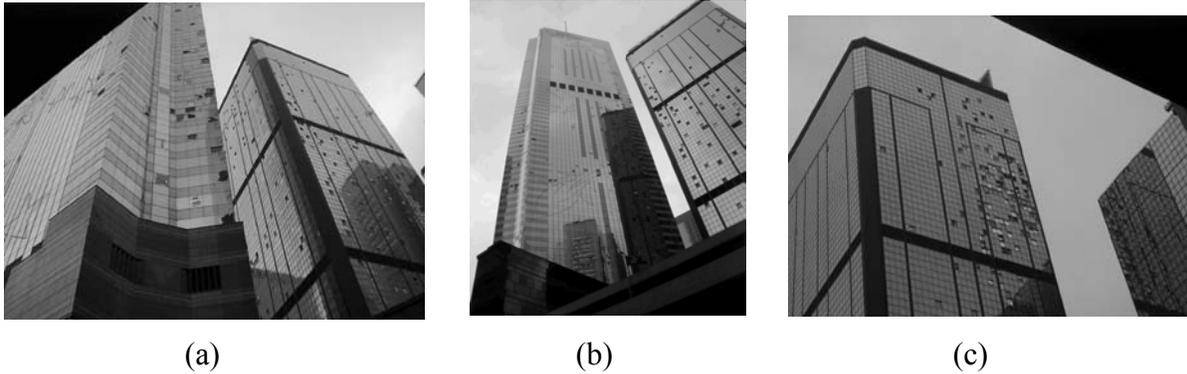


Figure 4. a) Damage to Central Plaza and Immigration buildings. b) Close up view of glass damage to Central Plaza. c) Close up view of damage to the Immigration building.

Tornadoes, in addition to hurricanes and typhoons, can also have a major impact on urban areas. Although it was previously thought that urban areas were virtually immune to tornado threats, perhaps due to heat island effects, recent incidents in Nashville, Tennessee, the Dallas/Fort Worth area of Texas, Salt Lake City, Utah, and Miami, Florida have led to heightened awareness of such occurrences. Figure 5a shows a dramatic photograph taken of the tornado that swept through the outskirts of downtown Miami, FL on May 12, 1997 causing glass damage to numerous buildings. When a tornado weaved its way through downtown Fort Worth, TX on March 28, 2000, virtually all of the exterior windows of the Bank One building were damaged by winds and wind borne debris (Fig. 5b) as well as the Cash America building. Figure 5c shows building damage and accumulation of debris from the tornado that struck Nashville, TN on April 16, 1998.

#### 4 CLADDING DAMAGE MECHANISMS

Analysis of glass breakage and failures of other cladding components in extreme wind events can be attributed to the following mechanisms [2,6]: wind pressures exceeding design values, missile impact from wind borne debris, and performance of glass.

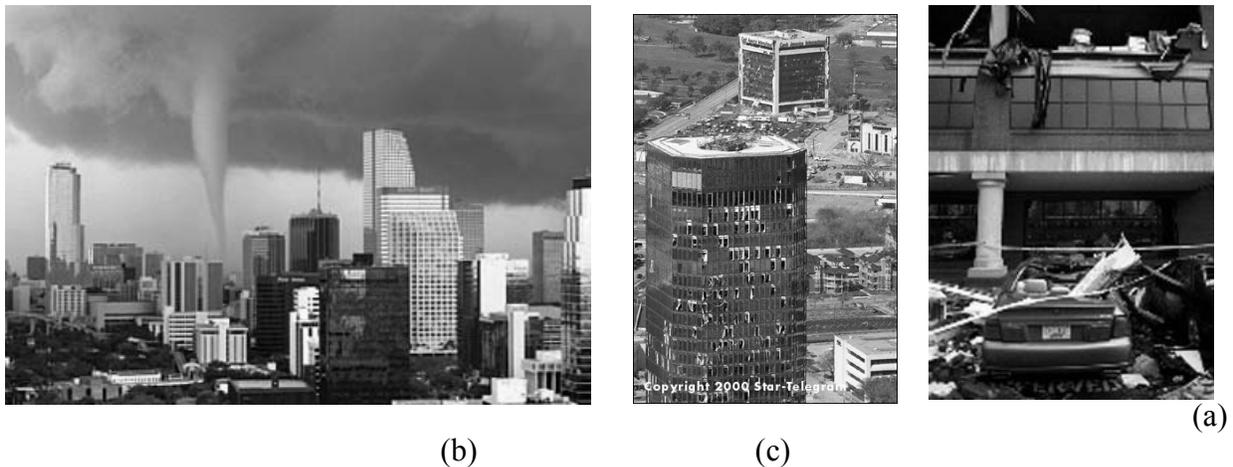


Figure 5. a) Downtown Miami, Florida. (Reproduced from [www.usatoday.com/weather/wtmiami.htm](http://www.usatoday.com/weather/wtmiami.htm) AP Photo/The Miami Herald) b) Bank One building in Fort Worth, TX. (Reproduced from [www.star-telegram.com/specials/00storms](http://www.star-telegram.com/specials/00storms)) c) Building Damage and debris in Nashville, TN. (Reproduced from [www.drytech.com/tornado.htm](http://www.drytech.com/tornado.htm))

#### 4.1 Wind pressures exceeding design values

Wind speeds in excess of design wind speeds, i.e. locally (channelization due to close proximity of structures) or regionally, lead to surface pressures that may exceed design values. This may have a negative impact on cladding performance and subsequently lead to failure. Nevertheless, extensive cladding damage has been observed in regions where wind speeds were known to be less than design values.

As seen in Figure 1b, fastest mile wind speeds at 33ft (10m) were estimated at 80 mph (36 m/s) in and around the central business district of Houston during Hurricane Alicia [4]. ANSI-82 indicated a fastest mile design wind speed of 90 mph (40 m/s) in this area [4,7]. The Hong Kong observatory obtained information on the wind field for Typhoon York from numerous anemometer stations in the Hong Kong area. Wind speeds for various averaged durations are listed in Table 1 [3,8]. The data from Waglan Islands, with topographical correction, possibly provides the best information regarding typhoon wind speeds over open water given its isolated location while Central Plaza [3] and Di Wang Tower [8] data provide information on wind speeds approximately 380 m above sea level. The mean hourly wind speeds recorded at Central Plaza and Di Wang did not exceed the value specified by a practice note issued by the Hong Kong Building Department indicating a mean hourly wind speed of 64 m/s (143 mph) for a 50 year return period at a gradient height of 300m [8]. During Hurricane Alicia and Typhoon York, design wind speeds were not exceeded yet damage to building cladding remained excessive and costly.

During Hurricane Andrew peak fastest mile wind speeds were estimated at 134 mph (60 m/s) in the Miami area while ASCE 7-88 designated a fastest mile design wind speed of 110 mph (49 m/s) in this region[5,9]. These speeds were not widespread and a majority of the region was subjected to fastest mile wind speeds in the range of 90-112 mph (40-50 m/s) [5]. Although design wind speeds appeared to have been exceeded at times during the passage of Hurricane Andrew in 1992, the current code, ASCE 7-02, designates a 3-s gust equivalent to a fastest mile wind speed of 122 mph (55 m/s), slightly less than Andrew's peak but greater than the predominant wind speeds observed in southern Florida [10].

An additional contributory factor to underestimation of wind pressures is an overall lack of our ability to accurately model hurricane wind fields. Hurricane and typhoon wind fields are assumed to be similar to extratropical winds in the absence of sufficient data. This assumption comes in part due to a lack of information suggesting that the wind field departs significantly from extratropical winds. Other shortcomings in modeling the wind field are caused by lack of information on the turbulence structure, ubiquitous convective cells, and hurricane spawned tornadoes, duration of sustained winds. These combined with the switching aerodynamic nature of pressure fluctuations, and the ability of winds to lift and transport wind borne debris, add to the uncertainty and destructive potential of these storms.

Station	1-min	10-min	Hourly	1-min peak gust
Waglan Island	51.8 (116)	45.7 (102)	42.3 (95)	64.9 (145)
Central Plaza	45 (100)	39.5 (88)	37.2 (83)	54.8 (123)
Di Wang	----	35.6 (80)	32.9 (74)	----

Table 1 Wind speeds in m/s (mph) recorded at anemometer stations in Hong Kong [3,8].

#### 4.2 Missile impact from wind borne debris

This mechanism plays a significant role in damaging glass cladding when substantial wind borne debris is present [11,12]. After Hurricane Alicia, a group of glass distributors determined that more than 80% of glass breakage was caused by wind borne debris in their report to the Con-

struction Industry Council of the City of Houston [2,13]. Sources of debris include roof gravel, construction debris, broken glass, and insufficiently secured roof-top appurtenances. The most vulnerable areas of buildings are those at plaza level, where street level debris is concentrated, and those at or below the levels of neighboring roofs bearing potential wind borne missiles. For example, in Hurricane Alicia, a huge percentage of the glass damage to both the InterFirst and Allied Towers (Figs. 2a & 2b) occurred below the height of the Tenneco building. Upon later inspection, a large amount of gravel had been blown from Tenneco's roof. This phenomenon is further substantiated by the prevailing wind direction, the location of the Tenneco building, and the damaged faces of the InterFirst and Allied Towers (Fig. 1a). Another source of debris is the broken glass created during a storm. Glass from broken windows fell to street level after being blown about by violent winds, initiating a domino effect which in turn caused more damage to the windows below.

Sheet metal siding may also damage or shatter glass panes during a wind storm. A twisted piece of sheet metal tore loose from a building and came to rest after wrapping around a telephone pole during the tornado that hit Nashville, TN. Most pieces of sheet metal found amongst post-hurricane or tornado debris failed due to poor fastenings as a result of large wind pressures. Because penthouses and other rooftop appurtenances are subjected to complex flow fields in which wind speeds may exceed design values, appropriate engineering attention should be given to these rooftop structures. Pressure tap measurements would yield substantial information as to the types of loading rooftop structures experience during extreme wind events.

Figure 6a demonstrates the variety and amount of debris that can be present during an extreme wind event. This debris cloud created during the tornado that struck Salt Lake City, UT contains everything from small particulate matter to large strips of sheet metal siding. The photograph is a dramatic representation of the amount of wind borne debris that may be present during a storm and the amount of cladding damage that may result.

A majority of the evidence supporting wind borne missiles as a high contributor to cladding damage is substantiated by damaged windows that remain intact after a wind event. Close observation often reveals large areas of pits, nicks, and scratches indicative of wind borne debris impact, and sometimes even large holes are discovered. Although some abraded windows remain completely intact, they are eventually replaced since it is very likely that their decreased glass strength would lead to poor performance in future storms.



(a)



(b)

Figure 6. a) Debris cloud during tornado in Salt Lake City, UT. (Photo by David Hsieh (Reuters) Reproduced from [hpcsun.unl.edu.nebraska/SLCtornado.html](http://hpcsun.unl.edu.nebraska/SLCtornado.html)) b) Broken windows due to poor performance of glass as observed at the John Hancock building, Boston, MA.

### 4.3 *Performance of glass*

Another possible source of glass damage extends from poor glass performance under dynamic stresses induced by the external pressure, structural movement, or improper installation. A classic example is the John Hancock building in Boston where purportedly, improper glass design and installation led to the failure of a large number of glass panels (Fig. 6b). As a result, every glass panel was eventually replaced and for a short time the building was nicknamed the plywood palace. The major contributors to the complexity of structural glass behavior to wind loads are its brittle failure mechanism, variable breaking strength, load duration, strength degradation, and spatiotemporal fluctuations in wind pressures. These complexities create difficulty in accurately determining a failure cause as that from inadequate strength. However, this does not eliminate inadequate glass strength as a possible source of damage.

## 5 CONCLUSIONS AND RECOMMENDATIONS

Glass and other components of the cladding system performed poorly during Hurricanes Alicia and Andrew, Typhoon York, and the tornadoes in the Memphis and Dallas/Fort Worth areas.

Failure of non-glass cladding primarily resulted from poor connections to the main structural system due to improper design or strength degradation caused by corrosion, rather than the force of the wind itself. The following observations were made in each case:

- 1 In areas where wind speeds did not exceed code-recommended values, cladding components should have performed adequately.
- 2 Underestimations of surface pressures, variations in internal building pressures, local channelization, and improper modeling of wind fields may have individually or collectively contributed to some glass damage.
- 3 There are many difficulties in concluding that glass failures were due to inadequate glass strength or performance, but it does not eliminate poor performance of glass as a possible source of damage.

Based on a majority of the evidence, missile impact from wind borne debris was the primary cause of glass damage. ASCE 7-02 Minimum Design Loads for Building and Other Structures addresses issues regarding wind borne debris more completely than previous versions of the standard [10]. For instance, it defines “wind borne debris regions” to make designers aware of the possibilities of missile impact leading to a breach of the building envelope and subsequent increase in internal pressurization. The standard recognizes debris sources such as loose aggregate roofs on adjacent buildings within 1500 feet of new construction. In such areas, new buildings will be required to have protected glazing or be considered open at a height of 30 feet above the debris source to street level. If a new building is to have a loose aggregate roof, then it must also be considered a debris source. The previous edition of the standard, ASCE 7-98, only required protected glazing or assumed openings for the lower 60 feet of a building [14].

In an effort to reduce future incidences of widespread cladding damage in areas of high-rise developments, the following recommendations are proposed for areas subject to extreme wind events:

- 1 Prohibit loose gravel on rooftops. Use mechanical fasteners for large paving blocks or develop alternate roofing materials.
- 2 Ensure integrity of rooftop appurtenances and appendages under worst case wind conditions.

- 3 Institute measures to control debris at construction sites.
- 4 Give proper engineering attention to penthouses, especially fasteners.
- 5 Enhance construction quality through regular inspections.

A common theme in extreme wind events is that an overall lack of extreme wind resistant provisions is most responsible for all the damage incurred, rather than simply the severity of the actual storms. Cladding damage, especially glass damage, is not only costly but also threatens pedestrian safety, increases damage to interior contents, and lengthens business downtime. Current levels of cladding damage and associated losses are unacceptable. Implementing the above recommendations and compliance with specifications in ASCE 7-02 will help in improving cladding performance in future extreme wind events.

## 6 ACKNOWLEDGEMENTS

This study was in part supported by the National Science Foundation grant CMS-00-85109. The authors are thankful to Drs. G. Chiu and B. Lee for providing pictures of damage from Typhoon York.

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