Figure 8. Tenacious deposits on glass surface due to rainwater run-off from concrete panels. (RCI 2010, with permission from RCI, Inc.).

Figure 9. Unacceptable cleaning pattern remains after improper polishing operation. (RCI 2010, with permission from RCI, Inc.).

Given the cause of the swirling pattern, attempts were made to mitigate the pattern using an optical-grade polish. While recommended surface restoration techniques vary among the major glass manufacturers and fabricators, many of them include polishing with cerium oxide. As a laboratory trial, a proprietary blend of cerium oxide polish was applied with a hard felt pad mounted on a variable speed drill. Localized results on the spandrel panel sample indicated that the fine scratches of the swirling pattern were essentially removed.

Based on these promising laboratory trials, field mock-ups were performed utilizing commercial-grade, closed-wheel automated equipment that recirculates a thin slurry of a blended cerium oxide polishing compound in potable water. Ten polishing trials were performed to evaluate the number and pattern of polishing passes necessary to achieve conditions acceptable to building management. After the first several trials with multiple polishing passes in each direction, the exterior glass surfaces were significantly improved compared to their original conditions when viewed in sunlight. However, when viewed in critical light (i.e., viewed at very small angles relative to reflected sunlight), the remaining faint crisscross pattern and residual scratches were judged to be unacceptable by building management. Only a combination of multiple linear and circular polishing passes resulted in a nearly blemish-free surface under critical sunlight conditions (Figure 10). A separate edge polishing unit was used to address the outer one inch of affected surface area that could not be reached with the shrouded closed-wheel unit.

Periods of direct sunlight provided the best conditions for viewing glass surfaces from the exterior and interior of the building. When polishing trials were conducted in the shade or during overcast periods, the presence of the swirling patterns and the progress of the polishing efforts were evaluated using a 250-watt portable work light (halogen bulb) held close to exterior glass surface.

This case study and others (not included herein) reveal that angel hair scratches are more likely the result of inappropriate cleaning operations rather than a storm event. Based on past experience, rubs and other surface blemishes with a relatively prominent points of impact, such as crushes, digs or scratches, have a greater likelihood of occurrence from a storm event.

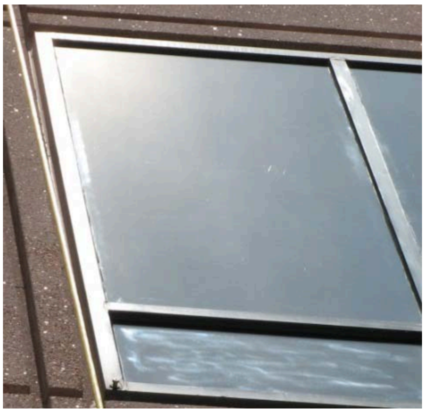


Figure 10. Upper window unit after remedial polishing, resulting in a nearly blemish-free surface. (RCI 2010, with permission from RCI, Inc.).

Western Region Hotel

The facade of this hotel, situated in a hurricane-prone region, includes exposed concrete elements and sliding glass door assemblies. As a result of exterior restoration work, which involved painting, concrete repairs and sliding door replacement, the exterior glass surfaces of the new sliding doors became scratched. The affected lites of glass were all fully tempered. Reportedly, no specific glass protection measures had been taken during the restoration work and various subcontractors had performed cleaning of the glass following their respective work operations.

The glass frequently exhibited many closely spaced parallel linear scratches as shown in Figure 11. Some scratches were longer than 3 inches. While the scratch pattern was typically random, near obstructions (e.g., balcony railings) the scratches were generally oriented in the same direction. By experimenting with the type of scraper (Figure 12) reportedly used to remove concrete patching debris from the glass, the authors were able to replicate the documented scratches.

All noted scratches were similar in appearance; therefore, it could be concluded that they were generally the result of inappropriate cleaning operations rather than previous storm damage. Some particles were noted to be adhered to the exterior heat-treated glass surfaces (as noted in the "Industry Debate" section above). By experimenting with trial cleaning of these surfaces, it was determined that adhered particles did not play a significant role in the development of the subject scratches.

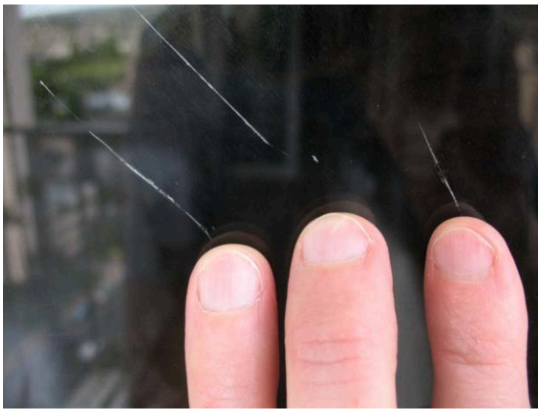


Figure 11. Multiple linear scratches documented on sliding glass doors. (RCI 2010, with permission from RCI, Inc.).

Figure 12. Tile scraper reportedly used to remove concrete patching debris from glass. (RCI 2010, with permission from RCI, Inc.).

Western Region Residential Towers

Two recently completed residential towers containing sliding glass doors and punched window assemblies had documented glass surface damage in the form of scratches and point blemishes. As shown in Figure 13, both deeper scratches as well as fine angel hair scratches were noted on the interior (No. 4) and exterior (No. 1) IGU surfaces. Point blemishes (Figure 14) were also present on both surfaces. As noted above, the occurrence of relatively uniform angel hair scratches from storm debris are less likely than other blemishes with a relatively prominent point of impact. Based on laboratory analysis, the dark-colored point blemishes had a morphology consistent with molten iron. As a result, this damage was not likely caused by a storm event.

Figure 13. Combination of linear scratches and angel hair scratches observed in direct sunlight. (RCI 2010, with permission from RCI, Inc.).

Figure 14. Dark-colored point blemishes. (RCI 2010, with permission from RCI, Inc.).

CONCLUSIONS

From the six case histories presented above, the following guidelines are suggested for the investigation and remediation of surface-damaged glass following a high wind event:

- The ASTM C 1036 test methods for blemish detection, or an adaptation thereof, can be utilized to determine an acceptable level of surface damage.
- It may be necessary to evaluate the structural integrity of glass lites following storm events if aesthetic criteria other than those in ASTM C 1036 are utilized.
- It is necessary to distinguish between damage likely resulting from storm events or other causes based on physical evidence, field tests, and supporting data.
- In some cases, it is cost-effective to repair surface-damaged glass using specialized polishing techniques; however, mock-ups are recommended to confirm aesthetic acceptance.
- Laboratory studies are often helpful in determining magnitude and identifying characteristics of surface blemishes, including embedded debris.
- Do not assume that hurricane-resistant glass products guard against significant surface damage and the need for future glass replacement.

Furthermore, since the improper handling and construction clean-up of glass units can also result in unacceptable aesthetic conditions and possibly structural damage, the authors offer the following guidelines for new construction or remedial work:

- Ensure that glass surfaces are protected, preferably in a manner suitable to the new glass manufacturer if applicable, until the project is complete.
- Prior to commencing work, require the contractor to submit glass cleanup procedures for architect/engineer approval; include procedures for all types of anticipated debris and glass damage.
- Consider performing a benchmark glass condition assessment prior to commencing any facade work.
- Contractor should notify the architect/engineer of record of any scratches or debris on glass prior to commencing cleanup.
- Consider including required new glass surface quality in specifications; in addition, cite which standard or project-specific protocol will be utilized to evaluate glass surface condition prior to final completion.
- Consider potential glass staining conditions and attempt to eliminate in the design phase.

REFERENCES

American Society for Testing and Materials (ASTM). (2001). *ASTM C 1036-01 Standard Specification for Flat Glass.*

American Society for Testing and Materials (ASTM). (2006). *ASTM C 1036-06 Standard Specification for Flat Glass.*

American Society for Testing and Materials (ASTM). (2011). *ASTM C 1036-11$^{\varepsilon 1}$ Standard Specification for Flat Glass.*

American Society for Testing and Materials (ASTM). (2009). *ASTM E 1300-09a Standard Practice for Determining Load Resistance of Glass in Buildings.*

CEN. (2004). *EN 572-2:2004 Glass in building - Basic soda lime silicate glass products - Part 2: Float glass.*

General Services Administration (GSA). (1977). *Federal Specification DD-G-451d* Glass*, Float or Plate, Figured (Flat, for Glazing, Mirrors and Other Uses.*

Glass Association of North America (GANA). (2008). *GANA TD 02-0402 Heat-Treated Glass Surfaces Are Different.*

Glass Association of North America. (2000). *GANA 01-0300 Proper Procedures for Cleaning Architectural Glass Products.*

Haldimann, Matthias (2006). "Fracture Strength of Structural Glass Elements–Analytical and numerical modeling, testing and design." Ecole Polytechnique Fédérale de Lausanne. EPFL Thesis 3671.

International Window Cleaning Association (IWCA). (2004). *IWCA Tempered Glass Informational Bulletin - Scrapers & Fabricating Debris*. http://www.iwca.org

Anatomy of Glass Damage in Urban Areas during Hurricanes

K. Butler[1], A. Kareem[2]

[1]AIR Worldwide, 131 Dartmouth St., Boston, MA 02116; email: kbutler@air-worldwide.com
[2]Professor, Department of Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame, IN 46556; email: kareem@nd.edu

ABSTRACT

Glass damage and failures of cladding components during extreme wind events can be attributed to a variety of different mechanisms, including extreme wind pressures, missile impacts from debris, and structural performance of glass within its support system. Wind speeds in excess of design values, either during the storm or through the channelization of the winds due to the close proximity of other structures, can lead to surface pressures similarly beyond design. However, extensive cladding damage has been observed in regions where wind speeds experienced were known to be below the design values. This research provides insight into the performance of the JP Morgan Chase Tower and the adjacent parking/office structure, in the downtown Houston area in the aftermath of Hurricane Ike. It is shown through both computational fluid dynamics (CFD) and wind tunnel analyses that slight variations in wind direction led to increased development of vortical flow between the high-rise and adjacent structure, as well as increases in the observed pressure loads on the exterior surface. The combined effects of elevated pressures and the existence of vortical flows possibly initiated damage and then propagated further damage from airborne debris. Similar mechanisms of debris damage were witnessed during Hurricane Alicia (1983), which also impacted Houston.

INTRODUCTION

Analysis of glass breakage and failures of cladding components in extreme wind events demonstrates that damage can be attributed to some of the following mechanisms: wind pressures exceeding design values, missile impact from wind borne debris and the structural performance of glass within its own support system. The failure of cladding, particularly during tropical storms, has been well documented, with the major cause typically identified as roof gravel or other windborne debris (i.e. Kareem 1985, 1986; Minor and Behr 1993). In Houston, TX., for instance, surveys of extensive glass damage from Hurricane Alicia revealed that over 80% could be attributed to windborne debris (Minor 1984). Sources of the debris included roof gravel, broken glass, and insufficiently secured roof-top appurtenances (Kareem 1985, 1986).

Wind speeds in excess of design wind speeds, either during the storm or through the channelization of winds due to the close proximity of other structures, could also lead to damage through surface pressures in excess of corresponding design values. However, it is possible to observe cladding damage in regions where the wind speeds experienced were known to be below the design values. During Hurricane Alicia, the fastest mile wind speeds at 33 ft were estimated to be 80 mph, below the design wind speed of 90 mph as outlined in ANSI-82 (Kareem 1985, 1986). Additionally, internal pressure fluctuations could also be attributed to cladding failure, particularly if the windward wall experienced a breach in which the opening exposed the remaining side and leeward walls to higher pressures.

Hurricane Katrina, a category 3 hurricane at landfall, had a significant impact on both urban and suburban areas of New Orleans, LA. In the aftermath, field reconnaissance surveys were performed to assess the level of damage to glass and cladding on a number of tall buildings in the central business district of New Orleans (Bashor and Kareem 2006). Considerable evidence showed that wind-borne debris from rooftops contributed to the glass and cladding damage of nearby buildings. While many codes and standards, such as ASCE7-05, provide some design recommendations that account for both the possibility of flying debris and eliminating sources of flying debris, the effectiveness of these standards continues to be evaluated.

Similar to hurricanes, tornadoes could also have major impacts on suburban developments and on smaller urban areas, though their effects may be highly localized. It was previously hypothesized that urban environments were not favorable to the development of tornadoes, where tornadic systems were thought to be dampened by the aerodynamics of building clusters and the attendant heat island effects. However, severe storms in and around Atlanta, GA in 2008 showed that tornado-producing systems may not be disturbed by the urban environmental effects, especially in cases where the urban development sprawls over a large region with open spaces rather than dense developments like New York City. The extremely localized winds in tornadoes cause significant damage to low-rise structures, through cladding damage from aerodynamic pressure loading and from debris impacts. Though many of these areas are contained within the hurricane wind speed design regions of the United States, tornadoes possess unique vortical wind fields that have the ability to transport larger debris items, which may pose a hazard beyond the scope of the current design parameters.

The Houston-Galveston area of coastal Texas has been subjected to numerous hurricane impacts, prompting various building and cladding performance studies. On August 18, 1983, Hurricane Alicia battered the Houston-Galveston area of Texas causing an estimated $1.5 billion in damage and destruction (Kareem 1985, 1986). While the structural systems of the buildings in these areas performed as expected during the storm, the cladding and glazing on some structures did not fare as well (Williams and Kareem 2003). Hurricane Alicia left the streets of downtown Houston littered with the glass shards from the broken windows of office buildings and high-rises (Kareem 1985). More recently, Hurricane Ike in 2008 impacted the Houston-Galveston corridor, causing substantial damage to some of the taller, more prominent buildings in the central business district (CBD). During Hurricane Ike, there were pockets of concentrated damage to glass around the CBD of Houston. Within the CBD, the JP Morgan Chase Tower and the adjacent structure to the south-east, in particular, sustained a rather unusual pattern of cladding and glass damage on their adjacent surfaces. Understanding the unique nature of the damage pattern was the focus of this study.

BACKGROUND

According to the available information as recorded by the weather instrumentation at Houston's George Bush Intercontinental Airport and the NOAA H*Wind Project surface wind analysis (National Oceanic and Atmospheric Administration 2008), the eye of Hurricane Ike approached and bypassed the downtown Houston area between 2:30am and 5:30am (local time), on September 13, 2008. At that time, Hurricane Ike was a category 2 storm. The winds were identified to be predominantly blowing from a north-to-northwest direction, having one minute sustained wind speeds of 70mph (approximately 85mph in terms of 3 second gust), well below the 107mph (exposure C) 50-year design hurricane wind speeds for the region (based upon ASCE 7-05). The winds for 20-year return period design are approximately 97mph. Therefore, winds during Hurricane Ike were probably below even a 20-year return period event. An approximate time line of the surface wind speeds for the Houston CBD is shown in Figure 1.

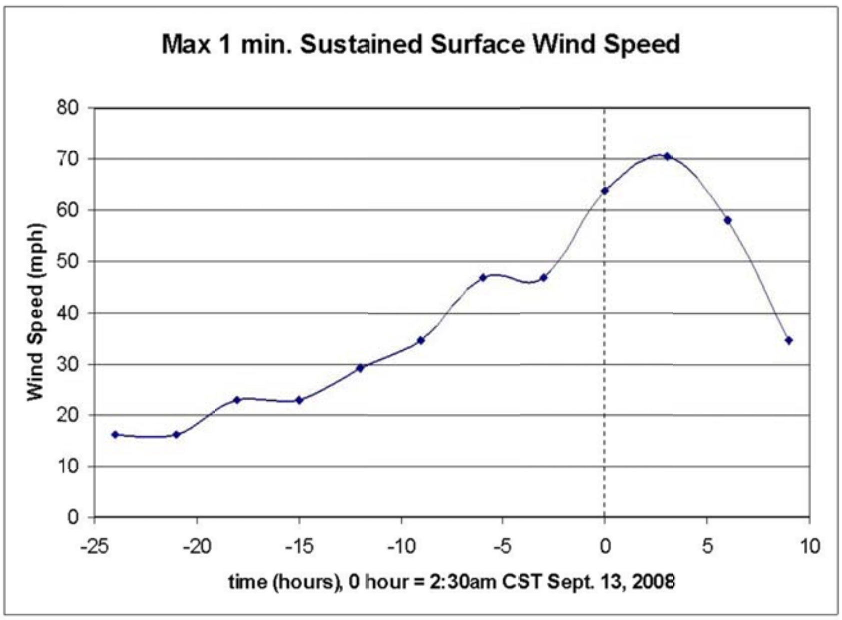
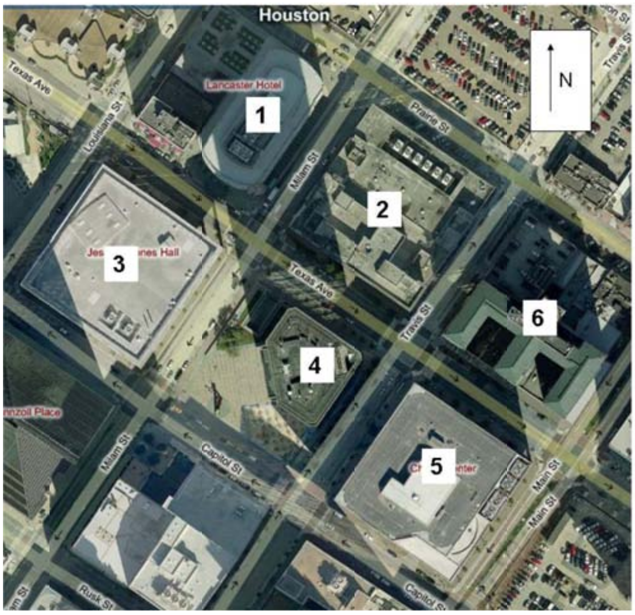


Figure 1: Time history of surface wind speeds acquired from NOAA H*Wind.

The JP Morgan Chase Tower is situated in the CBD of Houston, TX. The building is roughly prismatic in shape with a truncated corner facing northwest, giving the structure five surfaces. The layout of the buildings in the immediate vicinity of the JP Morgan Chase Tower (JPMCT) is shown in Figure 2. The JPMCT was built in 1982 along with the Chase Center, a complementary building that houses other offices and parking facilities, located on the opposite side of Travis Street. Field observations following Hurricane Ike revealed that the damage to the JPMCT was primarily focused on the lower third of its face adjacent to Travis Street and the

Chase Center. As Figure 3 shows, the damage to the JPMCT was greatest amongst the floors up to approximately the same elevation as the Chase Center, with most of this area losing all of its windows and coverings. Most, if not all, of the glass and glazing on the Travis Street face of the Chase Center was similarly damaged in the storm.



1 – Calpine Center (*2003*), **138m**

2 – Houston Chronicle (*1923*), **50m**

3 – Jesse Jones Hall (*1966*), **~30m**

4 – JP Morgan Chase Tower (*1982*), **305m**

5 – JP Morgan Chase Center (*1982*), **73m**

6 – Post Rice Lofts

Figure 2. Layout of structures within Houston CBD.

Figure 3. Damage to the JPMCT from Hurricane Ike (2008).

Local TV affiliate station KTRK-TV captured the existence of rotating flow structures between the JPMCT and Chase Center during Hurricane Ike. The camera crew recorded the extent of the vortex as it formed between the Chase Center and

JPMCT. Residents on the 10th floor of an adjacent building witnessed the damage and swirling winds at the intersection of Texas Ave. and Travis St. Eyewitnesses also reported seeing transient formations of tornado-like vortices at the corner of Texas and Travis. These formations were extremely short lived and were estimated to extend from the street level to approximately the 10th story of the JPMCT. Witnesses also reported glass shards being lifted up within the tornado-like flows, as well as that the noise level of glass/cladding being pelted by broken shards and also of shards dragging along the street was overwhelming.

Formal reports compiled by a number of agencies (NatHaz Modeling Laboratory 2008; ABS Consulting 2008; Federal Emergency Management Agency (FEMA) 2009) have provided a synopsis of the damage patterns. In addition, FEMA (2009) also noted that buildings with aggregate-surfaced roofs were located to the south of the JPMCT. However, the wind speed and direction would have been insufficient to mobilize the aggregate-surfaced roofs to generate the damage observed. Rooftop damage to the JPMCT was minimal, while the Chase Center roof membrane covering was compromised during the storm.

EXPERIMENTAL SETUP

The JPMCT is bounded by a series of prismatic shaped buildings, whose arrangement was modeled both in a wind tunnel and utilizing computational fluid dynamics (CFD). The following sections describe the setup and purpose of these experimental settings:

Wind Tunnel

Flow visualization inside a wind tunnel was performed using scaled models of the buildings, identified in Figure 2. The purpose was to visually identify particular flow incidences that would induce the unique flow patterns observed by eyewitnesses between the JPMCT and Chase Center. Observations of the flow patterns between the structures were used to establish the particular flow angles critical for vortex development, and those flow angles were then selected for further study using CFD.

The CFD portion of the study was also coupled with targeted pressure measurements on a scaled model of the JPMCT. Given the limited number of pressure measurement locations available, the CFD experiment (described in the following section) was able to provide information regarding areas of the building's surface where critical surface pressure loading may have occurred. There are 35 measurement locations, mainly located along the east corner of the JPMCT, as well as along the south-east face. Figure 4B shows the arrangement of pressure measurement locations on the scaled model surface.

CFD

While wind tunnel studies offer the most reliable measure of wind pressures and forces on buildings or urban arrangements, advances in CFD simulations are evolving and the offer a multifaceted view of wind effects in a numerical domain.