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EVALUATION OF FILM COATED WINDOW GLASS SUBJECTED TO THE EFFECTS OF WINDSTORMS

Ronald B. Shankland Jr.

Introduction

The harm incurred by structures, equipment, and people due to window unit failure during a windstorm is drastically reduced if the glass remains in the frame until the storm has subsided.

There are basically two types of window glass used in curtain wall cladding systems: heat treated and annealed. Heat treated glass is tempered during its manufacture so that it retains residual surface stresses in the range of 3500 psi to 10,000 psi, or more. Annealed glass is cooled very slowly under controlled conditions in order to remove undesired internal stresses (Reznik, 1987). Also known as float glass, annealed glass is manufactured by floating molten glass on a bed of molten tin and then allowing it to cool very slowly (Minor, 1990a). Annealed glass is generally less expensive and easier to cut to size than heat treated glass. It is the basic type of glass used in architectural glazing (Minor, 1990a).

These two basic types of glass can be used as a single layer (monolithic) or combined (laminated or layered). Previous research (Behr *et al.*, 1985; Reznik *et al.*, 1987; Vallabhan *et al.*, 1987; and Pantelides *et al.*, 1991) has shown that laminated glass performs well in windstorm situations, especially if the glass is held in the frame with a silicone sealant.

In order to improve resistance against fallout after breakage, it has been proposed that a surface film (usually polyester) be applied to monolithic annealed glass. An economical way to make new window glass safer, it may also be a relatively inexpensive way to retrofit existing windows.

Background and Previous Research

Architectural glass has been receiving much scrutiny over the past two decades. Prior to this period, window glass was not given much attention during the design phase of a building project. The architect was primarily concerned with the aesthetics of glass treatment and selection of glass was a relatively simple procedure as noted by Minor (1990a). The architect would simply determine the thickness of the "plate" glass for a given opening size by referring to a single chart. This chart had been developed by glass manufacturers over 25 years ago. Many building codes still adhere to these principles, although they may have been slightly modified.

Past failures of glass in such high-rise buildings as the John Hancock building in Boston and the Sears Tower in Chicago have highlighted the need for a more in-depth analysis. In particular, these failures have drawn attention to a vital detail concerning the failure of glass cladding – what happens to the glass when the window breaks? In a ground floor office this can be inconvenient and somewhat dangerous, but when large glass shards plummet to street level from many tens of stories above, the danger is immediately apparent (Minor, 1990b). In addition, modern office buildings contain equipment and furnishings such as computers, copiers, and telephone systems, that are expensive and sensitive to adverse environmental conditions (Harris, 1978).

The energy crisis of the 1970's caused additional changes in the materials and techniques available for architectural glazing (Minor, 1990a). Tinted, coated, and insulating glass appeared on the market as alternatives for standard "plate" glass. These new types of glass provide increased energy savings through their reflective and insulating properties. Also, laminated glass was made available to improve safety and is now seeing widespread popularity in the building industry.

It was determined through previous research (Beason, 1974; McDonald, 1976; Minor, 1976) that much of the glass breakage occurring during windstorms was attributable to two primary factors: uniform lateral pressure and missile impacts.

The term "uniform" may be misleading because it implies a steady-state loading condition. In truth, lateral loading of window glass can fluctuate both in magnitude and direction. The aerodynamics involved with a structure, or series of structures, in a windstorm can be extremely complicated. Understanding of this phenomena is being improved by the use of wind tunnel testing to determine wind pressures at various locations on the building (Minor, 1990b). Glass on the windward side of the building may experience strong pressures while the glass at the corners and on the leeward side may experience strong negative pressures, i.e., suction. As wind direction and velocity changes, so does the loading configuration on the glass. A single window may experience many cycles of positive and negative pressure in varying intensity due to gusts and turbulence. Minor (1976) noted that window breakage did not occur solely during extreme windstorms (i.e., tornadoes and hurricanes), but that many failures occurred when maximum recorded windspeed velocities were at or below the design velocity.

Missile impacts also effect glass breakage. Extreme wind conditions, such as those in effect during a tornado, may carry objects as large and heavy as automobiles, trees, lumber, and bricks. Wind velocities of a more moderate nature, however, can carry smaller objects which may also be hazardous to window glass. Minor (1976) discussed the propensity of roofing gravel being injected into the windstream through one of three mechanisms: explosive injection, ramp injection, and aerodynamic injection.

Explosive injection occurs when a roofing system fails due to a large pressure differential between the interior and exterior of a building and the gravel is injected into the windstream. Ramp injection occurs when roofing gravel, moving laterally due to horizontal wind pressures, strikes a protuberance. The gravel particle then incurs a vertical component to its velocity and is injected into, and carried by, the windstream. The Bernoulli Effect is primarily responsible for aerodynamic injection. Rapidly moving air above a layer of gravel has a lower pressure than the stagnant air below. If this pressure difference exceeds the weight of the gravel particle, it will be lifted into the windstream and carried away.

Once airborne, it becomes a question of whether or not the wind can sustain the gravel as missiles. Minor (1976) showed that it was indeed possible and that gravel could attain sufficient impact velocities to damage or break window glass.

Objectives

The purpose of this research was to determine the effectiveness of surface applied film on monolithic, annealed window glass for preventing excessive loss of glass particles after small missile damage and windstorm induced stresses. In addition, the missile damage characteristics of the "tin side" and the "air side" of the glass was explored. The "tin side" of the glass is the surface of annealed float glass that had been in contact with the molten tin during its manufacture. The other side of the glass pane is known as the "air side".

Research Plan

The research plan was designed to test twelve specimens of 58 by 96 by 3/8 inch annealed glass lights with a 0.004 inch (4 mil) thick polyester film applied to one surface. The film tested in this research was product number CL-400-X, manufactured by Madico, Inc. The advertised properties of the film include: 85% visible light and 0 to 4% ultraviolet light transmission, single-ply, 25,000 psi tensile strength, 100 pounds per inch width break strength, acrylic pressure sensitive adhesive, and 4 to 5 pounds per inch peel strength.

Two sets of parameters were evaluated. Three identical specimens were tested for each combination of the two parameters.

The first parameter to be evaluated was the film coverage. In all cases, the film was applied only to the surface that would be facing the interior of the building. This surface would not receive missile impacts. One set of six windows was fully covered with the film and the other set had the film trimmed back one-half inch all the way around the perimeter. If an existing window were to be replaced with a new window, it is possible that the new window could be completely covered with film. On the other hand, if an existing window were to receive an in-situ film application, it could only be applied up to the edge of the gasket holding the glass in the frame.

The second parameter to be evaluated was missile velocity. A 2.03 gm steel ball bearing was used as the missile. One half of the window specimens were impacted by missiles travelling at the lowest velocity capable of causing observable damage. This is known as the Minimum Damage Threshold Velocity (MDTV). Threshold damage is the lower limit of damage which can be seen at arm's length in good light. Generally it was a very small nick in the surface of the glass which would otherwise be barely noticeable. Minor (1990a) points out that as a rough general rule, any surface imperfection that is visible at arm's length reduces the strength of the glass at this point by half. Also, we took note of the differences, if any, in the velocities required to cause minimum damage between the "tin" side and the "air" side of the glass. The other six windows were impacted by missiles at a velocity of 80 miles per hour (117 fps). This velocity was chosen because it represents the average velocity of roofing gravel missiles being carried by a 100 year mean recurrence interval windspeed in most areas of the country.

All of the specimens in this test series were dry-glazed, that is, they were held in the frame by neoprene gaskets as commonly used in curtain wall glazing systems.

The numbering system employed to identify these specimens was based upon the above-listed conditions:

F = Surface Applied Film
D = Dry Glazed
DT = Minimum Damage Threshold Velocity
HV = High Velocity
T = Trimmed Film
F = Full Film Coverage

A numeric suffix identifies individual specimens. For example, F-D-DT-F-2 identifies the second specimen of the series which was dry glazed, impacted at MDTV, with full film coverage.

The following specimens were tested:

	Full Coverage	Trimmed Coverage
Minimum Damage Threshold Velocity	F-D-DT-F-1 F-D-DT-F-2 F-D-DT-F-3	F-D-DT-T-1 F-D-DT-T-2 F-D-DT-T-3
High Velocity	F-D-HV-F-1 F-D-HV-F-2 F-D-HV-F-3	F-D-HV-T-1 F-D-HV-T-2 F-D-HV-T-3

Test Equipment

The procedures followed and equipment used in this test closely parallel those used by Pantelides, Horst, and Minor (1991) for their work on "Evaluating Post-Breakage Behavior of Architectural Glazing in Windstorms". The glass testing facility at the University of Missouri-Rolla consists of a specimen holding table with pressure/vacuum chamber, two 500 gallon pressure/vacuum holding tanks, air cannon and alignment system, and control and data acquisition station.

The specimen holding table and chamber allowed the glass pane to be dry-glazed into a standard aluminum curtain wall frame and then be subjected to missile impacts and pressure/vacuum cycles. The chamber was instrumented with a liquid water manometer for measuring both the pressure and the vacuum applied to the specimen.

The pressure/vacuum holding tanks permitted relatively large volumes of air to be moved into or out of the pressure/vacuum chamber on the specimen table. This process was controlled for the most part by manually-operated valves; however, one window was partially cycled by a computer that monitored pressure transducers and controlled the valves. When manually operated, the valve operator would watch the manometer during pressure or vacuum application.

The air cannon was used to accelerate the 2.03 gm missiles to the required velocities. Cannon operation was managed from the control and data acquisition station. The operator was able to load and fire the cannon by remote control from this station and was also able to read and record the data relating to the muzzle velocity of the missile. Positioning the cannon was accomplished with the aid of guide tracks mounted on the floor and ceiling and a vertical standard mounted on wheels between the tracks. The cannon was affixed to the standard. Both the tracks and the standard were measured and marked to enable precise and repeatable alignment of the cannon.

Muzzle velocities were obtained through the use of a digital timer that measured the time required for the missile to travel 12 inches between two light beams in the cannon barrel. Velocities in feet per second were calculated by taking the reciprocal of this reading.

Other equipment included an ultraviolet lamp to detect traces of tin on the "tin side" of the glass, a dial gauge and mounting bar for measuring out-of-plane deflections of the pane, and an electronic balance for weighing the amount of glass ejected from the window.

Test Procedure

The film was applied to all glass specimens by technicians at Taylor Glass Company in Rolla, Missouri. They picked up the glass from the testing facility and took it to their workshop where they applied the film in accordance with the manufacturer's specifications. An applicator solution, provided by Madico, was employed as a slip agent to neutralize the pressure sensitive adhesive during application. After the specified curing time, Taylor Glass Company returned the finished specimens to the glass testing facility.

The pressure/vacuum chamber was prepared for testing by affixing a plastic shroud to the inside of the chamber and sealing its perimeter with duct tape. The purpose for the shroud was to enable testing to continue even if the window partially failed and remained in the frame. The shroud would seal small holes and tears in the film, as well as breaches in the gasket system, and allow pressure to be maintained against the window. This step was necessary because of an inability to provide the volume of air commonly associated with actual windstorms. Use of a plastic shroud is permitted in accordance with ASTM 1233-88, paragraph 10.1.1, as long as the shroud does not impart any additional strength to the specimen. Similarly, a shroud was placed on the outside of the window when breaches occurred during the vacuum phase of the test.

Observations were made with the aid of ultraviolet lamp to determine if the "tin side" or the "air side" of the glass would be receiving the missile impacts. The window was then cleaned with a glass cleaning solution and mounted in the frame using standard dry-glazing techniques. Particular attention was paid to ensure that all specimens, especially the trimmed film specimens, were properly centered in the frame. The film side of the pane was on the inside of the chamber. Note that the inside of the chamber corresponds to the inside of a building, thus, a vacuum applied in the chamber would correspond to a pressure applied to the outside the building. Pressure applied in the chamber would correspond to an outward acting pressure ("negative" pressure or suction) on the building.

The window was then subjected to missile impacts with the air cannon. Previous experience with observed field damage indicated that a window typically encounters approximately five impacts per square foot during a windstorm (Pantelides *et al.*, 1991). Consequently, a semi-random pattern of 190 impact locations was used. For the minimum damage threshold velocity, each location was impacted with a very low velocity missile and then the velocity was increased in very small increments until detectable damage occurred. For high velocity missile impacts, the velocity was adjusted as close to 80 mph as possible before actually impacting the window. Then the window was impacted with small adjustments being made to the cannon's air pressure to maintain the desired missile velocity. The glass dislodged by high velocity missile impacts was collected and weighed.

The next step was to subject the missile damaged windows to windstorm loadings. The pressure/vacuum cycles intended to simulate the loading conditions experienced during a windstorm were previously established by Pantelides *et al.* (1991). The vacuum sequence consists of 12 low vacuum cycles (33.8 psf) followed by one medium vacuum cycle (45 psf). This was repeated for a total of 5 times and then one high vacuum cycle was applied (56.3 psf). Each load was held for a duration of three seconds. The pressure sequence followed with the same pattern of low, medium, and high pressure cycles, but the magnitudes were 133% of the vacuum values (i.e., 45 psf, 60 psf, and 75 psf). These two sets of cycles were to be repeated eight times. The out-of-plane deflections were measured, if possible, for the last three loadings at the end of a sequence. Dislodged glass particles were collected and weighed at various times throughout the vacuum/pressure cycle sequence.

Failure of the window system occurred due to one of two events: either it became impossible to maintain loading due to excessive leaks or the window glass fell out of the frame. At this point the remaining loose glass was collected and weighed. The failed window was then disposed of after careful inspection for any abnormalities.

Results

Listed below is a brief group summary and then notes specific to each of the twelve windows tested in this research. Following the individual notes is a general summary of results.

Specimen	Vacuum	Pressure	Failure Mode
F-D-DT-T-1	60L, 5M, 1H	4L	Film Tear, Gasket
F-D-DT-T-2	60L, 5M, 1H	1L	Gasket
F-D-DT-T-3	60L, 5M, 1H	2L	Gasket
F-D-HV-T-1	24L, 2M,		Corner delam, Gasket
F-D-HV-T-2	50L, 4M,		Gasket
F-D-HV-T-3	36L, 3M,		Corner delam, Gasket
F-D-DT-F-1	60L, 5M, 1H	12L,1M	Gasket
F-D-DT-F-2	60L, 5M, 1H	1L	Gasket
F-D-DT-F-3	60L, 5M, 1H	1L	Gasket
F-D-HV-F-1	48L, 4M,		Gasket
F-D-HV-F-2	20L, 1M,		Corner delam, Gasket
F-D-HV-F-3	36L, 3M,		Film tear, Gasket

F-D-DT-T-1: Average Minimum Damage Threshold Velocity (AMDTV) was 18.4 fps, "tin side" was impacted, Low Vacuum #60 (LV60) had a 0.450" inward deflection, Medium Vacuum #5 (MV5) had a 0.525" inward deflection, High Vacuum #1 (HV1) had a 0.600" inward deflection. After first low pressure loading there was extensive cracking from the center to the corners and some delamination along the larger cracks. Cracking seemed to have originated near the center of the pane. Edge damage which occurred during installation appeared to have no effect. A horizontal tear in the film near the middle of the pane one inch wide and nearly the width of the opening made it difficult to maintain full pressure. Gasket came out during the last pressure cycle causing the end of the test.

F-D-DT-T-2: AMDTV 19.4 fps, "tin" or "air" side not known, LV60 0.400", MV5 0.540", HV1 0.630". Full plate response cracking occurred on Low Pressure #1 (LP1). Gasket failed on Low Pressure #2 (LP2) and the window fell out of the frame onto the floor. About two feet of glass broke off into the frame.

F-D-DT-T-3: AMDTV 17.0 fps, "tin side", LV60 0.430", MV5 0.540", HV1 0.650". Gasket failure after LP2.

F-D-HV-T-1: Average missile velocity 116.3 fps. "Tin side". About 70% of missile damage was crushed cone and 30% was crushed cone with 1" local radial cracking. Crushed cone diameters averaged 2 inches with a 1/4" ring of film delamination around the cone. Low vacuum #1 (LV1), extensive full plate response cracking, glass is cracked into block about 65 sq in., some 1/8" wide delamination of film at the cracks, one inch permanent deflection (PD). LV12, 1-5/8" PD. MV1, 1-7/8" PD. MV2, about 72 sq in. of upper right corner film is delaminated. Unable to maintain vacuum. Applied a plastic shroud to seal the leak. LV25, failure. Top half of the window came out of the frame and was stopped only by the specimen table and chamber. Film was not torn; however, it was delaminated, especially in the corners.

F-D-HV-T-2: Average missile velocity 116.4 fps. "Tin side". About 50% of missile damage was crushed cone and 50% was crushed cone with 1" local radial cracking. Crushed cone diameters averaged 2 inches. LV1, cracked into blocks about 72 sq in., 1/2" PD, some 1/8" wide delamination along cracks. LV12, wedge gasket popped out from 12" to 20" along the top edge from left corner. LV24, gasket popping out from 18" to 30" from bottom on right side. MV4, 2-1/2" PD, gasket or small delamination is leaking, applied shroud to seal against further leakage. LV50, failure. Glass came out of rabbet along left half of top and top 2/3 of left side. Window is still in the frame. Applied pressure to blow failed window out of frame. The window was angled 30 to 40 degrees about right edge before it fell out of the frame. The exposed film due to delamination was not as sticky as it was on other specimens.

F-D-HV-T-3: Average missile velocity 116.9 fps. "Tin side". About 50% of missile damage was crushed cone and 50% was crushed cone with local radial cracking. Crushed cone diameters averaged 2 inches with a 1/4" ring of film delamination around the cone. MV1, corners show serious evidence of delamination, film is about to pull away from upper right corner. MV2, 2-7/8" PD. MV3, upper left corner has pulled away, top wedge gasket coming out, 1-5/8" by 2-3/4" piece of glass falls from upper left corner. LV37, failure. Upper left corner half way down left side and half of the top wedge pulled out. Film did not tear: corner pulled away.

F-D-DT-F-1: AMDTV 14.0 fps, "air side", LV60 0.4", MV5 0.5", HV1 0.6". Explosive full plate response cracking originating near the center of the window during Medium Pressure #1 (MP1). The light cracked into several pieces. Failure occurred when the glass fell out of the frame due primarily to gasket failure. The exposed delaminated film was not very tacky. The film did not tear. Full pane film coverage and a full month of curing appeared to have made no difference.

F-D-DT-F-2: AMDTV 20.6 fps, "air side", LV60 0.456", MV5 0.544", HV1 0.640". All low vacuum loads were controlled by the computer, medium and high vacuums and the low pressure load were manually controlled. In general, the computer overshot the required loads by several psf. It does not appear that this made a difference in the failure mode. Failure occurred due to the gasket coming out of the frame. It peeled out along the top and then down the sides. Explosive full plate response cracking occurred just prior to gasket failure. The shroud pushed the window out of the frame, top first. Very little film delamination. Most of the delamination happened in the upper right and left corners, but this may have occurred due to falling on the floor.

F-D-DT-F-3: AMDTV 19.3 fps, "tin side", LV60 0.421", MV5 0.540", HV1 0.624". Top and left wedge gaskets peeled from upper left corner as window swung out as if hinged on the right. Glass then folded down upon itself. All four wedge gaskets and the right side preset gaskets were pulled out. Definitely gasket failure. There was explosive full plate response cracking just prior to failure. The shroud pushed the light out of the frame, top left corner first. Very little delamination. No tearing of the film. The film that was delaminated was somewhat sticky.

F-D-HV-F-1: Average missile velocity 116.2 fps. "Tin side". About 50% of the damage was a crushed cone and the other 50% was crushed cone with local radial cracking. Average diameter of the crushed cones was 2 inches. LV1, cracking started in middle of pane. LV4, 3/4" permanent deflection (PD). LV8, 7/8" PD. LV10, Bottom wedge gasket starting to pull out in middle of frame. LV12, deflected 0.870" during loading. MV1, 1- 7/8" PD. LV17, delamination begins in upper left and right corners. LV22, bottom wedge gasket almost all the way out. MV2, 2-1/8" PD. LV35, delamination starting in lower left corner, no tears in the film yet, very little leakage through areas of delamination, even in the corners. MV3, 2-1/2" PD. MV4, failure. Upper left corner pulled in, then the upper right corner, then the wedge gasket peeled out of both sides down to 2/3 of the window height. Then the upper wedge gasket failed and the glass pulled into the frame all the way across the top. Unable to maintain further pressure.

F-D-HV-F-2: Average missile velocity 116.2 fps. "Tin side". Average diameter of crushed cone was 2 inches. About 50% crushed cone and 50% crushed cone with local radial cracking. This specimen appears to have been poorly laminated. There are several spots where insects, hair, dust, and dirt are trapped under the film. The worst places are in two areas: the first is in the upper right corner (8" high by 12" wide) and the other is about 12" wide and extends from 2 feet below the top to about 5 feet below the top. In these areas the film is about 50% delaminated due to improper quality control during the application process. These imperfections were observed prior to missile impacts. LV1 cracked into pieces that are about 64 sq in. LV2, 1/4" wide delamination along cracks. LV3, upper right corner starting to delaminate. LV12, deflected 1.610". MV1, deflected 2.490", permanent deflection is 2-1/2". LV19, upper right corner failed, sealed the breech with plastic to continue. LV20, failure started in upper right corner. 80% of top and right side is out of the frame. This was a gasket failure; however, it was definitely enhanced by the poor film application in the upper right corner.

F-D-HV-F-3: Average missile velocity 116.1 fps. "Air side". Almost all missile damage is two-inch diameter crushed cone with local radial cracking. LV1, full plate response cracking into pieces about 65 sq in., delamination along cracks, 1/4" wide. LV11, 1-1/2" PD. LV12, deflected 1.575". MV1, over 1.8" deflection, gauge ran out of travel. MV2, tear in film in upper right corner, 1-1/2" long. MV3, failure started in upper right corner, wedge gasket peeled out of right side and along top.

General Summary

The weight of glass particles dislodged during missile impacts and load cycling is, for the most part, insignificant when compared to the weight of the entire pane. The amount of glass dislodged when the window fails is significant. In addition to the hazard of an entire pane of windstorm damaged glass falling out of its frame, several large chunks of glass were dislodged as the window failed and either fell into the chamber or fell out onto the floor. It is difficult to estimate how much of this glass would have remained attached to the film it the failed pane had not contacted the floor.

Gasket pullout was, by far, the leading cause of window failure. It may prove worthwhile to investigate the possibility of alternate glazing systems for installing monolithic annealed glass with surface applied film, such as silicone sealant adhesive.

There appeared to be a propensity for gasket pullout to initiate in the upper corners of the frame. This is probably because the weight of the glass assists in resisting movement at the bottom of the pane. Tearing of the film was a deciding factor in only two of the twelve windows tested. In order of increasing influence on total window failure, the factors that are of most concern are 1) gasket failure, 2) delamination, and 3) tearing of the film. Gasket failure is inherent with this type of glazing system and resistance to tearing is a property of the film itself. Delamination tendencies could possibly be reduced if proper application of the film were adhered to more stringently.

Conclusions

Several valuable conclusions pertaining to the performance of film coated, annealed, monolithic, dry-glazed, curtain wall windows can be drawn from the results of this research:

1) Surface applied film of the type and configuration tested is not an effective means for retaining window glass in a curtain wall system that has been damaged by missile impacts and cyclic windstorm loading effects.

2) There is no significant difference between the performance of windows that have full film coverage and those that have trimmed film coverage.

3) Windows that have received minimum damage from airborne missiles may survive slightly longer than those that have received high velocity missile impacts; however, neither of these windows can be expected to survive a 100 year mean recurrence interval windstorm.

4) There is no statistically significant difference between the missile velocity required to cause minimum damage to the "air side" versus the "tin side" of monolithic annealed float glass.

5) The amount of glass lost from the window prior to total failure is trifling when compared to the weight of the pane and would not pose a significant hazard to life or property.

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