To Film Or Not To Film: Effects Of Anti-Shatter Film On Blunt Trauma Lethality From Tempered Glass

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ABSTRACT

A very common approach to retrofitting existing conventional buildings for blast effects is to apply anti-shatter film to all exterior windows. The easiest way of applying film is through “daylight” application, where the film terminates near the edge of the pane of glass and is not attached to the window frame. For annealed glass, this serves to hold fragments together and greatly reduce the risks due to sharp, high-velocity shards of glass. For tempered glass, however, the penetration hazard is already mitigated by the small cubic fragments into which the glass is broken; daylight application of film thus may actually increase lethality by holding the glass sheet together, producing a more massive object that impacts the human and causing more severe blunt trauma.

A recently conducted series of experiments exposed anthropomorphic test dummies to impact from glass sheets, both filmed and unfilmed, at a range of blast environments. The dummies were instrumented to measure head accelerations, from which an estimate of lethality could be obtained. The results show that, at very high levels of impulse, the addition of film to a tempered glass window does not change the outcome: both cases produce a fatality. However, at lower loadings, the results suggest that adding film will increase the lethality by one AIS level. That effect may be even greater at intermediate load levels where test data is currently unavailable.

INTRODUCTION

One of the most hazardous results of an explosive event on nearby buildings is the generation of high-velocity glass debris. While seldom the cause of fatalities, glass fragments are responsible for a large proportion of the injuries sustained by occupants of buildings subjected to blast effects.

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One of the most common ways of mitigating the risk associated with glass is to apply anti-shatter film (ASF) to the interior of the glass pane. The film, generally made of mylar or other plastic materials and available in a variety of thicknesses from 4 to 15 mil, bonds directly to the glass surface and serves to hold together the glass fragments upon breakage. Thus, instead of generating a large number of shards, the majority of the glass mass is projected as a single sheet, albeit containing many cracked and broken pieces. The strength and flexibility of the film are the key to holding this sheet together while it travels through the room.

Perhaps the single most common way of applying ASF to a window is through what is termed “daylight” application. The film extends nearly to the edge of the glass and terminates just a fraction of an inch before the window frame; a small strip of “daylight” is thus left along the frame. Because of this particular edge condition, the film does not add appreciably to the strength of the window, and its primary purpose becomes that of preventing the generation of a large number of glass shards.

However, while holding the shards together is certainly beneficial from the point of view of reducing the risk of penetration injuries, it may be counterproductive in terms of blunt trauma. When a human is hit by a cloud of small fragments, the blunt trauma is limited by the mass of individual fragments which impact the person. By holding these fragments into a single sheet, the film creates a single more massive fragment which may increase the risk of blunt trauma injuries. Particularly in the case of thermally tempered glass (TTG) whose fragmentation pattern tends to be more benign than annealed glass (AG) from the perspective of penetration, the addition of film as part of a retrofit project may actually end up increasing the overall risk of injury rather than reducing it.

OVERVIEW OF TEST SERIES

A series of recent tests provides some valuable data on the effect of daylight film application on the resulting blunt trauma lethality to humans. The tests were part of the DIVINE BUFFALO series performed at Kirtland Air Force Base in New Mexico [1, 2, 3]. Tests 21 (DB 21) and 24 (DB 24) fielded 3 and 4 cubicles, respectively, deployed radially around the charge. Each cubicle contained a single anthropomorphic test dummy (ATD) exposed to debris from a window on the front face of the cubicle. Photographs of a typical cubicle exterior and interior are shown in Figure 1.

Figure 1. Typical cubicle appearance, exterior and interior.

Of the seven total experiments thus conducted, two involved retrofit measures (high-backed chairs, shielding by a computer monitor) such that those results cannot be used for our present investigation of film effects on blunt trauma. Of the remaining five experiments, two used unfilmed glass while three were daylight filmed glass. The film in all cases was 8 mil thick and applied on the interior. The glazing in all cases was nominal ¼” thick TTG (actual thickness 0.22 inches), and the window size was 4 foot square.

The ATDs used were Hybrid II models, instrumented with accelerometers in the head to measure motion in all three directions. These acceleration records were used subsequently to estimate the level of injury sustained. The ATDs were positioned in a fashion that might be typical for an office environment: seated, opposite and near the window, and facing away from the window. A table (bolted to the floor) was provided in front of each ATD to limit the total rigid body displacement after impact of the glass.

Note that the only injury mechanism being evaluated by these ATDs is blunt trauma to the head. Penetration injuries, or blunt trauma in other body parts, requires more intensive instrumentation and was beyond the scope of these tests.

A summary of the relevant parameters for the five cubicles under consideration is presented in Table 1, as well as the positive phase peak pressure and total scaled impulse measured using gages directly on the front face of each cubicle. The loads are significantly greater than the strength of the glazing, and so all the windows failed and were projected into the cubicle with varying magnitudes of velocity.

Table 1. Summary of test parameters and measured loads.

Test / Cubicle	Window size, Glass type	Retrofit	Peak Reflected Pressure (psi)	Scaled Positive Reflected Impulse (psi-ms/lb$^{1/3}$)
DB 21 / 1	4' sq., ¼" TTG	Filmed (daylight)	45	18.4
DB 21 / 3	4' sq., ¼" TTG	Filmed (daylight)	16	9.2
DB 21 / 4	4' sq., ¼" TTG	Filmed (daylight)	6	4.4
DB 24 / 3	4' sq., ¼" TTG	Unfilmed	50	18.6
DB 24 / 4	4' sq., ¼" TTG	Unfilmed	11	4.4

TEST RESULTS

As a representation of the typical ATD response, Figure 2 presents a series of snapshots captured by the high-speed (500 frame per second) camera in DB 21 / 3, which used filmed glass. In the first view at earliest time, we observe the sheet of glass having already left the window frame and approaching the ATD; the film is holding virtually all the fragments in a single sheet. Once the sheet impacts the head, some of the fragments become debonded from the film, particularly those which ricochet back off the ATD's head and back. As a result of the impact and the eccentricity of resistance applied to the sheet, the glass begins to rotate and eventually turns and passes over the ATD's head.

Posttest photographs (Figure 3) show the ATD leaning forward, while the sheet of glass has made a significant impression in the foam on the back wall of the cubicle, at about the same height as its original elevation, indicating a more or less horizontal trajectory. Weighing the sheet of filmed glass showed that it retained some 62% of its original mass; thus, 38% of the mass is strewn about the cubicle in the form of small, nearly cubic fragments. Some of that mass was dislodged during the glass impact against the back wall, or as it fell to the ground, so that the actual mass retention during the glass/ATD interaction is significantly higher, perhaps on the order of 80-90% or so.

Results from filmed glass tests with either higher (DB 21 / 1) or lower (DB 21 / 4) loads produced generically similar responses, albeit with higher or lower levels of motion in the ATD. Results without film were also quite similar, although in those tests all of the glazing mass was converted to small fragments. Figure 4 shows the pattern of imprints made in the back wall by these fragments, as well as showing some of the typical fragments found lying on the table or the floor after the test.

Figure 5 shows some of the glass debris recovered from DB 24 / 4, where the loads were more benign. These fragments, which were extracted from the foam on the back wall, show that at least at these lower load levels, the simple cubic fragment is not the only type. These fragments were 1–2 inches in length with distinct sharp points and edges which would enhance their cutting potential.

(a) t=20 ms.

(b) t=28 ms.

(c) t=34 ms.

(d) t=49 ms.

(e) t=75 ms.

(f) t=109 ms.

Figure 2. Snapshots from film of ATD response in DB 21 / 3.

(a) Posttest position of ATD.

(b) Glass debris on floor near back of cubicle. *(c) Indentation in foam produced by glass impact.*

Figure 3. Posttest views of DB 21 / 3.

A simple, qualitative measure of the cutting effect of these unfilmed fragments can be deduced by considering the posttest condition of the chamois cloth with which these two ATD heads were covered (Figure 6). At the higher load (DB 24 / 3), the chamois is very badly cut, almost shredded; at the lower load (DB 24 / 4), there are very few cuts. The potential for penetration injuries is thus significant at the higher load level, which is what the film is intended to abate. But what about the resulting blunt trauma? Is filmed glass as lethal from that point of view as unfilmed?

Figure 4. Unfilmed glass debris imprints and closeup from DB 24 / 3.

Figure 5. Unfilmed glass debris captured in foam from DB 24 / 4 (graphic scale @ 1”).

Figure 6. Tears in chamois over ATD heads from unfilmed TTG fragments in DB 24 / 3 and DB 24 / 4.

EFFECT OF FILM ON GLASS DEBRIS VELOCITY

The first, most direct effect of the blast is to launch the glass debris, and its lethality is directly related to its velocity. The experimental data on glass velocity was obtained using images from the high-speed film. By comparing to initial images taken from the same camera using a fiducial grid, the position of the glass at various points in time can be determined, from which a velocity history can be deduced. Typical records, like the one shown in Figure 7, show a peak value followed by a slight drop to a residual value. Figure 7 also shows the excellent comparison between the velocity history obtained from the film and that obtained from an accelerometer mounted to the window, contributing to the confidence with which this data can be treated. The post-peak decay is not due to air drag or friction, as there simply isn't enough time for this to occur. Instead, it seems to be related more to the post-break dynamics of the sheet, which still possesses some membrane strength due to the film. These records are based on the position of a single point on the window, hence they do not precisely represent the motion of the window's center of mass.

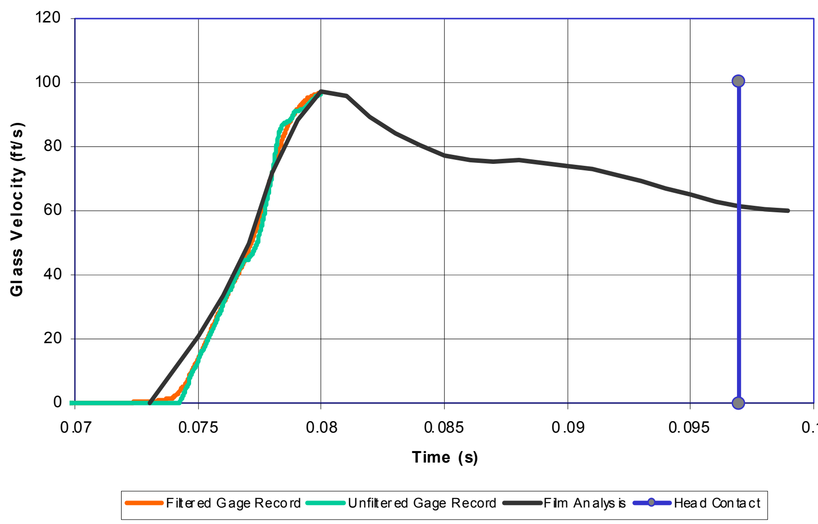

Figure 7. Glass velocity history for DB 21 / 3.

Taking the two key magnitudes, the peak velocity and the residual at the time of impact against the ATD) from histories such as the one shown above, and plotting them against the impulse applied to the window, produces the graph shown in Figure 8. Also plotted in this figure is the straight line that represents the value of velocity that would be expected if the strength of the glass were completely neglected, and the law of conservation of momentum (i.e., $I = mv$) were applied.

Several noteworthy observations can be made on the basis of this comparison. First, we note that the difference in velocity between filmed and unfilmed glass, at the two load levels where comparison is possible, is rather slight. The unfilmed glass has a consistently higher velocity than filmed glass, but that conclusion is somewhat tempered by the fact that, in digitizing the position of the unfilmed fragments, the leading edge of the cloud was utilized. Thus, the position of the centroid of the cloud would lag behind a little and have a slightly lower velocity. But overall, we can say that unfilmed glass debris moves at a velocity at least as great as filmed glass, and probably somewhat more (especially at low loads).

We can also see that as the loading is increased, the difference between the peak and the residual values diminishes. And the data for the intermediate load level (which corresponds to DB 21 / 3) seems suspect, since it lies so far below the I/m relationship. Aside from this point, however, I/m seems to do a credible job of predicting all the velocities, except for the residual velocity from filmed glass at low impulses. At low loads, the strength of the glass will become increasingly significant, and we would expect such a deviation in that regime.

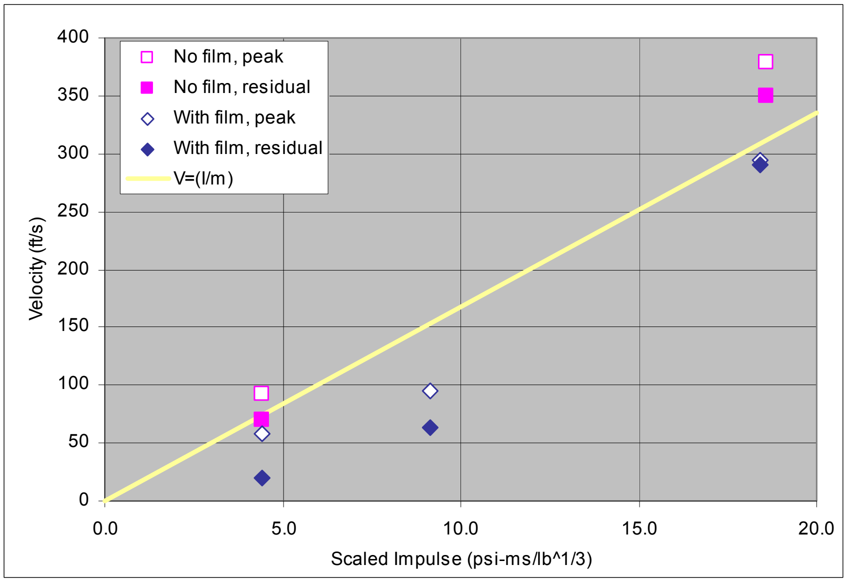

Figure 8. Film effect on glass debris velocity.

BLUNT TRAUMA INJURY ESTIMATION METHODOLOGY

We turn now to the injuries sustained by the ATDs. To be useful as a means of predicting levels of injury, responses measured in the test must be correlated to accepted criteria of injury. While such measures of response have not yet been developed for blast scenarios, a number of metrics and criteria are widely used and available from the automotive safety industry.

To assess blunt trauma injuries for the ATDs in this test series, the acceleration histories measured by the three gages in the head of each ATD are processed to produce a single history of the resultant acceleration, which is then processed using an SAE CFC 1000 filter with a cutoff of 1660 Hz. The resulting history may be processed to obtain the Head Injury Criterion (HIC), which is the most widely used criterion for head and brain injuries [4]. The HIC is calculated using the following equation:

$$HIC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)\, dt \right]^{2.5} (t_2 - t_1)$$

In the above expression, a is the resultant acceleration expressed in g's and t_1 and t_2 are two arbitrary points in time. Various intervals of time are tested and the interval producing the maximum HIC value is selected. Federal Motor Vehicle Safety Standards (FMVSS) define the procedures used to measure and calculate the HIC.

The calculated HIC value for each ATD can then be compared to criteria to generate an injury level, generally characterized by the Abbreviated Injury Scale (AIS). The AIS is a numerical scale developed by the Association for the Advancement of Automotive Medicine and the American Medical Association [5, 6]. In the more than 20 years it has been in existence, it has become the most widely used injury rating system in this country and internationally. The scale covers all body parts, and hundreds of publications are written each year using it.

The relationship between HIC and AIS (for head injuries) is shown in Table 2. In general, a HIC of 1,000 indicates a high probability of moderate brain injury and is to be avoided. Values above 1,500 correspond to a high probability of severe brain injury. Typically, AIS levels of 3 or greater are considered to be serious injuries, while an AIS of 6 is required for a fatality.

Table 2. Correlation between HIC and AIS.

AIS	Severity	Type of Injury	HIC
0	None	None	—
1	Minor	Superficial	< 250
2	Moderate	Recoverable	< 750
3	Serious	Possibly recoverable	< 1,250
4	Severe	Not fully recoverable without care	< 1,750
5	Critical	Not fully recoverable even with care	< 2,500
6	Maximum	Fatal	> 2,500

EFFECT OF FILM ON BLUNT TRAUMA

The most direct way of comparing the results of the five experiments is to plot the HIC and AIS values calculated for each ATD as a function of the scaled impulse to which each was exposed. In this way, differences in human injury can be directly correlated to variations in the loading as well as in the glass conditions (filmed or unfilmed). These plots are presented in Figure 9.

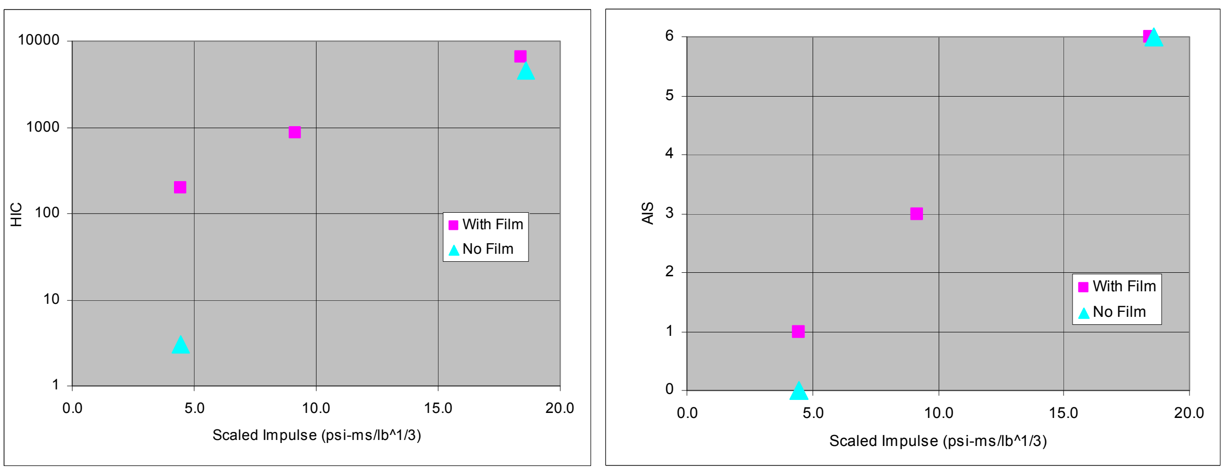

Figure 9. HIC and AIS as a function of load for filmed and unfilmed ¼" TTG.

The graphs show some interesting phenomena. First, considering just the filmed data points, we observe a gradual transition from light injury (AIS=1) to severe injury (AIS=3) to fatality (AIS=6) as the loading is gradually increased. It is also interesting that the relationship between HIC and scaled impulse, for filmed glass, is nearly linear in semi-log space. Unfortunately, because only two unfilmed data points are available, that trend cannot be confirmed for unfilmed glass.

The unfilmed data indicates that at the high load level, a fatality results whether one applies film to the glass or not. The HIC is slightly lower for unfilmed than for filmed (4500 vs. 6600), but not by enough to make a difference, since anything over 2500 is considered a fatality. But at the low loading level, there is a very dramatic difference between the two (200 vs. 3), one of nearly two orders of magnitude. At that slow velocity, then, adding film to the glass does result in a much higher level of head response and acceleration. In terms of injury, the difference is not very great, as the filmed window produces AIS=1 while the unfilmed produces AIS=0. Nevertheless, there is a measurable benefit from a blunt trauma perspective to leaving windows unfilmed.

The truly intriguing potential of this comparison remains unverified, and that is in the middle range of impulses where unfilmed data is not yet available. If we hypothesize that the relationship between HIC and impulse for unfilmed windows is linear, as is observed to be the case for filmed glass, the regime of greatest significance could well be that between 8 and 15 psi-ms/lb$^{1/3}$. Following our hypothesis of a linear relationship to predict the result at the middle test point with I=9.2 psi-ms/lb$^{1/3}$, we would expect (as seen in Figure 10) a HIC for unfilmed glass of around 50, which correlates to an AIS=0. By comparison, the HIC level from the test using filmed glass at that same load level was nearly 1000 and correlated to an AIS=3. Even if the unfilmed glass was slightly worse than this prediction and generated AIS=1, the reduced lethality from a severe injury to a minor one would be very significant indeed. Of course, this hypothesis remains unverified, pending further testing in the near future where the middle loading range can be explored more fully.

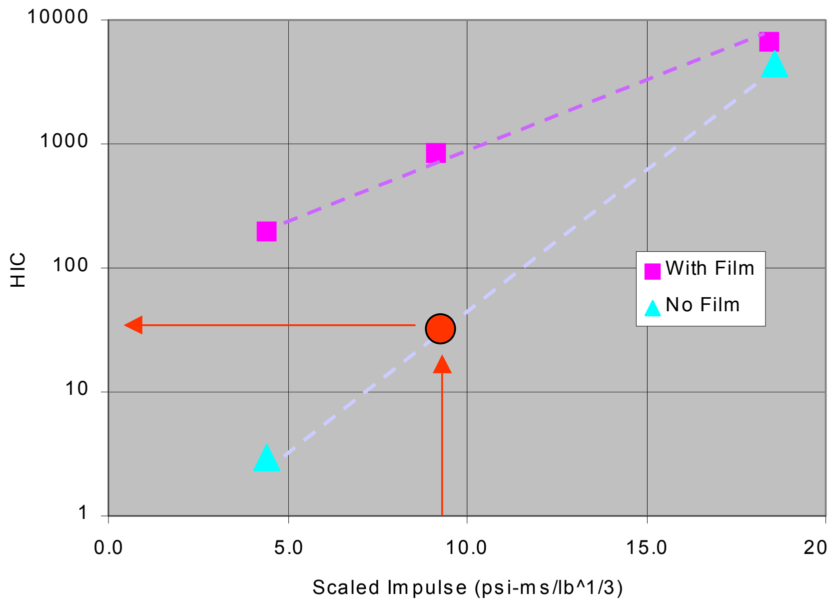

Figure 10. Predicted HIC for unfilmed glass at middle loading range, assuming linear relationships.

CONCLUSIONS

Daylight application of anti-shatter film to windows is an effective way of reducing the penetration injuries resulting from flying glass debris, even for TTG which typically produces more benign shards than AG. At high load levels, both filmed and unfilmed windows produce fatalities due to blunt trauma. However, the film was shown to enhance the propensity for blunt trauma injuries to occupants at the lower end of the loading spectrum, with an increase in AIS from 0 to 1, and an increase in HIC by nearly two orders of magnitude. And we can hypothesize that the deleterious effect of film on blunt trauma will be even more significant (with respect to AIS and injury level) in the middle range of loads.

In light of these results, the wholesale and ubiquitous application of daylight film to windows as a retrofit option should be reconsidered. It will reduce the risk of penetration injuries but may greatly enhance the risk of blunt trauma injuries. The benefits at low loading levels could reverse if the original design threat were exceeded; hence the retrofit design needs to consider the range of threats and the likelihood of an event above the maximum level. Also, serious consideration should be given to anchoring the film to the window frame, which would at least reduce the velocity of filmed glass and potentially offset the increased risk of blunt trauma injury.

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REFERENCES

1. Bogosian, D. D. et al., "Analysis of Data from Cubicle Experiments in DIVINE BUFFALO 21," Karagozian & Case TR-01-20, August 2001.

2. Bogosian, D. D. et al., "Analysis of Data from Cubicle Experiments in DIVINE BUFFALO 24," Karagozian & Case [in preparation].

3. Sheffield, C. et al., "DIVINE BUFFALO 21–24 Cubicle Test Results Report," Defense Threat Reduction Agency, Kirtland AFB, NM, ARA-LR-2.20-002, December 2001.

4. Backaitis, S. H., "The Head Injury Criterion," Head and Neck Injury Criteria, A Consensus Workshop, published by U.S. Department of Transportation, NHTSA, 1981.

5. Pike, J. A., "Injury Scaling," Automotive Safety, Anatomy, Injury, Testing and Regulation, Published by Society of Automotive Engineers, Inc., 1990.

6. "Abbreviated Injury Scale, 1990 Revision," Association for the Advancement of Automotive Medicine, Des Moines, Iowa, 1990.