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ANALYSIS OF MULTIPLE-IMPACT BALLISTIC PERFORMANCE OF A TEMPERED GLASS LAMINATE WITH A STRIKE FACE FILM

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14. ABSTRACT
Multiple high velocity impacts are of particular concern to bullet resistant glass systems incorporating commercial tempered or heat strengthened glass as exterior or strike faces. Initial impact by a single projectile typically produces a quasi-symmetrical crater exhibiting the typical mirror, mist, and hackle regions with radial cracks propagating across the entire strike face. These radial cracks effectively reduce system survivability during subsequent impacts. Should an impact from a second projectile occur on the damaged glass, loosely constrained fragments would be forced in a direction away from the strike face resulting in less resistance to projectile penetration. Since a greater amount of material is ejected from the strike face, the second crater is often significantly larger than the first and exhibits extreme geometrical variation. The sequence of multiple impacts could be deduced from the size and geometry of the existing craters as these characteristics are relatively dependent on the radial crack pathways from the previous impacts. If the glass fragments were constrained in the strike face, it may be possible to increase the extent to which they interact with the projectile, each other, and the remaining material in lateral directions, further facilitating energy dissipation while reducing crater size. One proposed solution explored the simple application of a window film to the strike face with the purpose of increasing penetration resistance by way of limiting material loss. A three-dimensional laser scanner and analytical software were employed to capture a point cloud of each crater and facilitated dimensional analysis and comparison. Digital quantification of crater characteristics supported the findings that utilizing a film to confine fragments on the strike face effectively decreased the average crater size and improved the material performance during subsequent ballistic impacts in protective glass systems.

15. SUBJECT TERMS
glass, ballistic impact, crater, spall, film

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Key words: glass, ballistic impact, crater, spall, film

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TABLE OF CONTENTS

DISTRIBUTION A – Approved for public release; distribution unlimited. AFCEC-201407; 6 February 2014

LIST OF FIGURES

DISTRIBUTION A – Approved for public release; distribution unlimited. AFCEC-201407; 6 February 2014

LIST OF TABLES

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1. SUMMARY

Multiple high velocity impacts are of particular concern to bullet resistant glass systems incorporating commercial tempered or heat strengthened glass as exterior or strike faces. Initial impact by a single projectile typically produces a quasi-symmetrical crater exhibiting the typical mirror, mist, and hackle regions with radial cracks propagating across the entire strike face. These radial cracks effectively reduce system survivability during subsequent impacts. Should an impact from a second projectile occur on the damaged glass, loosely constrained fragments would be forced in a direction away from the strike face resulting in less resistance to projectile penetration. Since a greater amount of material is ejected from the strike face, the second crater is often significantly larger than the first and exhibits extreme geometrical variation. The sequence of multiple impacts could be deduced from the size and geometry of the existing craters as these characteristics are relatively dependent on the radial crack pathways from the previous impacts. If the glass fragments were constrained in the strike face, it may be possible to increase the extent to which they interact with the projectile, each other, and the remaining material in lateral directions, further facilitating energy dissipation while reducing crater size. One proposed solution explored the simple application of a window film to the strike face with the purpose of increasing penetration resistance by way of limiting material loss. A three-dimensional laser scanner and analytical software were employed to capture a point cloud of each crater and facilitated dimensional analysis and comparison. Digital quantification of crater characteristics supported the findings that utilizing a film to confine fragments on the strike face effectively decreased the average crater size and improved the material performance during subsequent ballistic impacts in protective glass systems.

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2. INTRODUCTION

2.1. Background

The desire to use low-cost glass laminates for large structures requiring various levels of blast and ballistic protection has increased significantly in recent years. When the threat level is not extremely high and budget concerns preclude the use of high performance materials for glazings, tempered glass laminates are widely available and can also be custom manufactured by numerous entities around the world. The tempered glass is typically used in conjunction with polymer interlayers to enhance impact resistance, thermal properties, and provide an improvement in safety should the window(s) shatter. Tempered glass provides ballistic resistance through compressive strength and energy absorption as the glass fractures as well as causing erosion in the penetrating projectile. Figure 1 shows a typical impact to a tempered glass laminate by a small arms rifle projectile.

Figure 1. Typical Response of a Tempered Glass Laminate to a Single High Velocity Impact by a Small Arms Rifle Projectile

Figure 1 shows that comminution of glass has occurred and spall was ejected from the strike face resulting in the formation of a crater. Radial and circumferential cracks also formed throughout the strike face as a result of the impact. However, the contributions of these mechanisms to defeating a projectile are mainly realized during the first impact as subsequent impacts find the glass shattered and unable to absorb the same amounts of energy as during the first impact. The radial and circumferential cracks have created loose fragments on the strike face and a subsequent impact could easily displace material not only at the point of impact, but also across a large area of the strike face as seen in Figure 2.

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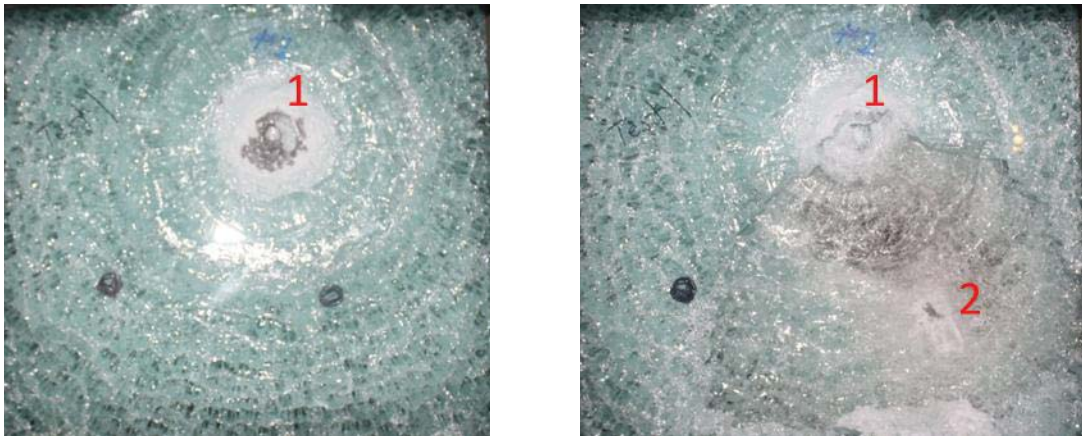

Figure 2. Common Response of Tempered Glass to Multiple-Impact Events

This second impact has essentially removed the glass strike face from the target and a third impact would likely penetrate deeper or exit the target with a greater velocity than the first two impacts.

The hypothesis of this research was based on the assumption that if the glass and loose fragments, or spall, could be constrained during the initial impact event and subsequent impact events—even if it was fractured—it would provide more resistance by forcing the glass to interact with itself as well as the projectile instead of being ejected from the strike face in all directions. Many options were considered for constraining the strike face spall, such as adding a thin polymer layer like polycarbonate, to the strike face. Ultimately a decision was made to examine the effect a strike face film would have on ballistic resistance. A typical film was chosen from many types currently used on the back face of windows as a cost effective way to prevent spall from entering a building (causing injury to occupants or damaging assets). A film could easily be retrofitted to the strike face of existing tempered glass windows, and such films could be removed and replaced for a fraction of the cost of a thicker polymer layer.

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3. METHODS, ASSUMPTIONS, AND PROCEDURES

3.1. Test Samples

In order to study the potential benefits of confining strike face spall, two simple laminated glass designs were tested. Each design incorporated a 0.18 in thick polymer interlayer between two layers of 0.5 in tempered silica based "soda lime" glass. A 0.08 in shatter resistant film was applied to the back face of both designs; however Design B also had the same film on the strike face accounting for the only difference between the two designs. The design configurations are shown in Figure 3.

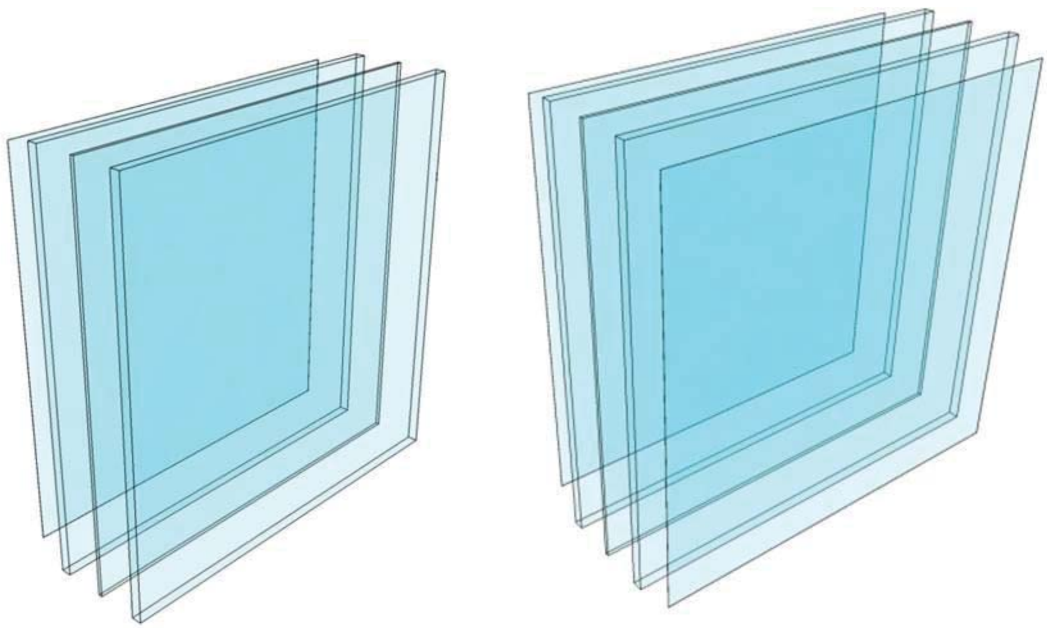

Figure 3. Design A (left) without Strike Face Film and Design B (right) with Strike Face Film

Six samples of each design were acquired for a total of twelve samples. Sample dimensions were 20 in × 20 in to accommodate three impacts at equidistant locations on an 8-in diameter circle.

These designs were chosen to represent widely available, non-proprietary tempered glass laminates for ballistic resistance applications, although sample thickness in this particular case was much lower than what would be expected in the field in order to allow complete penetrations which would facilitate the documentation of a strike face film performance metric based on residual velocities.

3.2. Threat

The threat projectile for this research effort was a small arms rifle bullet with an ogive. The bullet had a lead core and full metal jacket. Additional details of the projectile may not be disclosed at this time due to ongoing research for potentially sensitive applications.

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3.3. Test Setup

Ballistic testing was conducted at the Air Force Civil Engineer Center (AFCEC) Ballistic Test Facility at Tyndall AFB, FL. A universal receiver powder gun was used to fire the threat projectiles. Data collection was focused on four areas: strike velocity (to ensure consistency from one test to the next), exit velocity, mass of spall ejected from the strike face, and crater analysis. Each sample was rigidly mounted to the test frame by clamping an aluminum plate in four corners, as shown in Figure 4. The plate and frame effectively provided a 1-in bite on each sample.

Figure 4. Rear View of the Test Frame

3.3.1. Velocity Measurement

Impact velocities were kept as constant as possible for all samples throughout testing. The distance from the muzzle of the barrel to the target strike face was 33 ft (10 m) and four Oehler Model 57 photoelectric infrared velocity screens recorded two initial velocities at distances of 6 ft and 8 ft to confirm acceptable velocity while two Oehler Model 57 screens measured an exit velocity at a distance of 6 ft behind the sample (Figure 5). In order to simplify analysis, the readings at 6 ft from the front and back of the sample were taken as the “impact velocity” and “exit velocity”, respectively.

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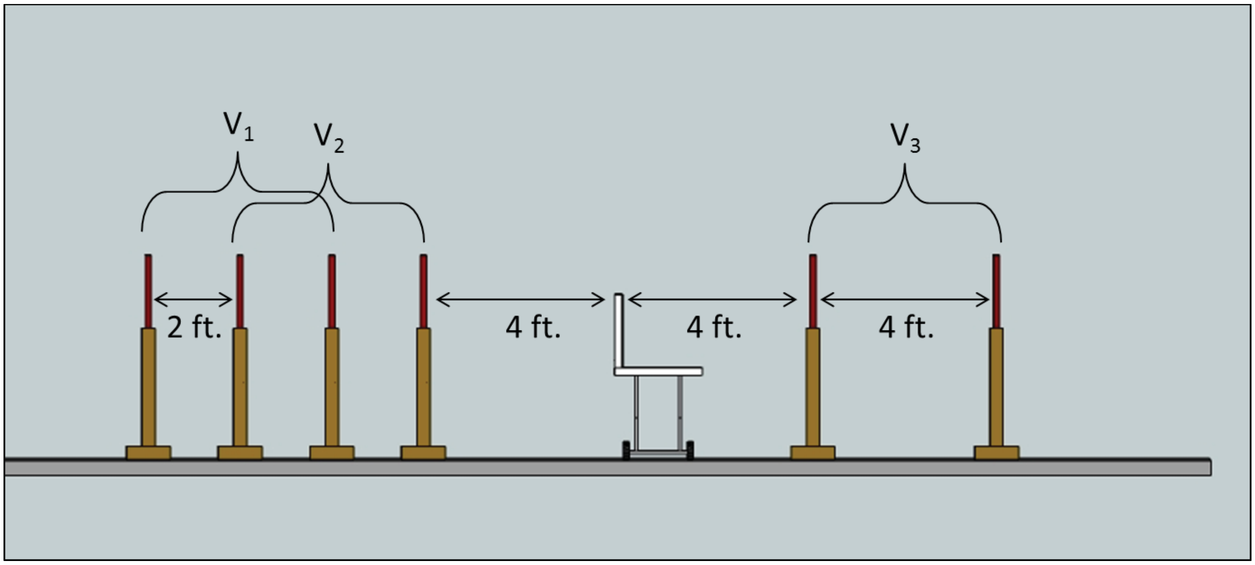

Figure 5. Velocity Measurement Specifications

3.3.2. Strike Face Spall Collection

In order to facilitate simple and efficient strike face spall collection, a 20 in × 20 in × 20-in box with two open ends opposite each other was constructed with ¾-in plywood and attached to the front of the test frame with a ratchet strap. One open side of the box was butted up against the target frame with a foam gasket while the opposite open side was covered with a doubled 0.003-in thick trash bag (0.006 in total thickness) and secured with tape to allow the projectile to pass through unhindered, but prevent the escape of any strike face spall ejected during the impact event (Figure 6).

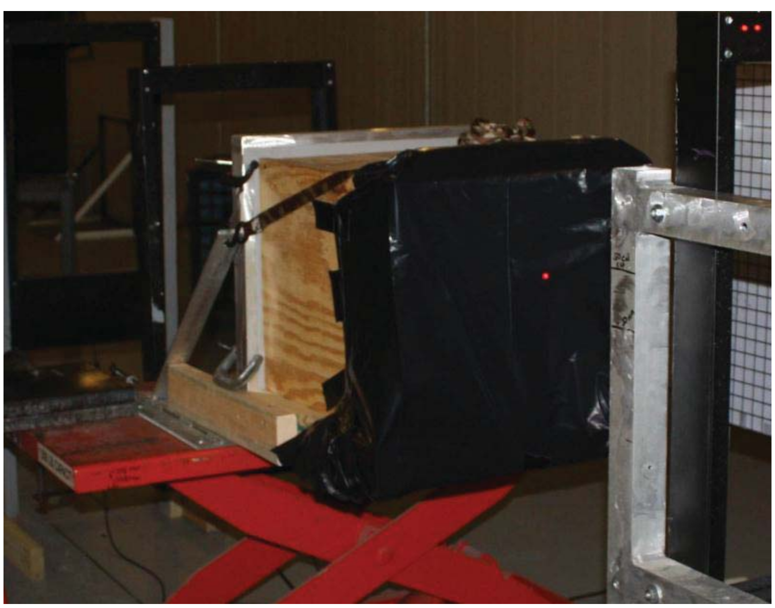
Figure 6. The Spall Collection Box Attached to the Target Frame

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3.3.3. Crater Analysis

After the spall generated from each impact was collected and weighed, the crater created by the impact was spray painted matte black to allow for effective laser scanning. A FARO FUSION® 3-D laser scanner with fixed base and rotating/extendable arm was oriented to the test frame and used to create a point cloud of each crater (Figure 7).

Figure 7. Laptop, FARO FUSION® Arm, and Sample Mounted in Fixture

The point cloud was the input into Geomagic Qualify®, a software program that facilitated the creation of a solid model from the point cloud (Figure 8). The software was used to remove outlier points and the number of points scanned was uniformly reduced to facilitate a faster solid model generation. Once a solid model was created, analysis was able to be performed to obtain cross-sections of the craters and topographical images as well as data such as crater volume, area, and depth.

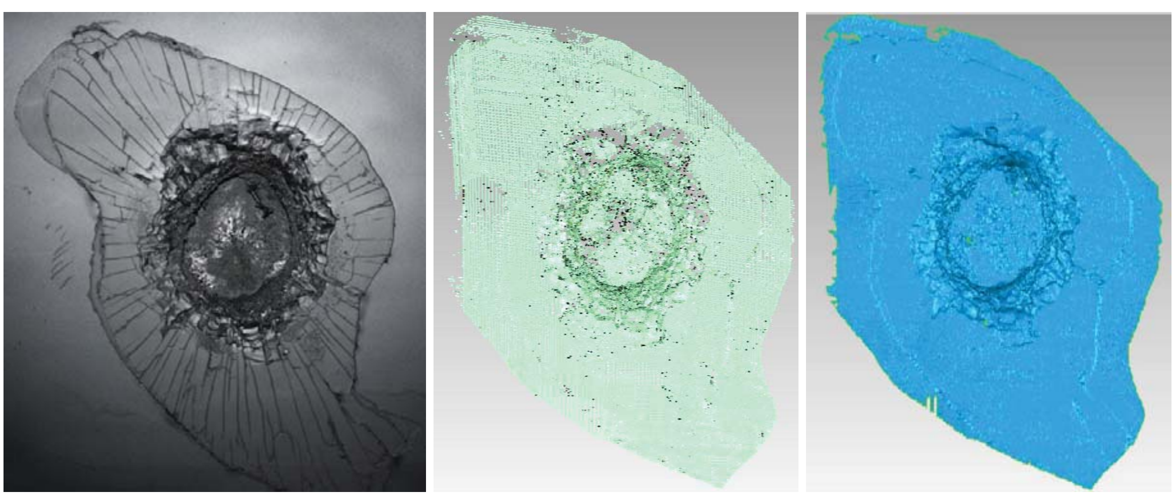

Figure 8. A Photo of the Crater (left), Point Cloud of the Crater (center), and Solid Model of the Crater (right)

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3.3.4. Test Procedure

All samples were impacted three times at the nominal impact velocity. The undamaged sample was first fixed in the test frame, painted black, and scanned with the laser to obtain a digital replica of the undamaged laminate. The three impact locations were marked on the strike face and the laser attached to the universal receiver was aimed at the first point of impact. The box was then attached to the front of the test frame and the trash bag secured to the box. After each impact, the spall was swept out and weighed. Loose spall was also carefully swept from the strike face crater on samples that did not have film over the strike face. For samples with a strike face film, the film was carefully cut away around the crater and the loose fragments confined by the film were weighed separately from the initial spall in the box. The process for collecting spall from a sample is shown in Figure 9. The crater was then painted black and scanned with the laser. A tested and scanned sample can be seen in Figure 10.

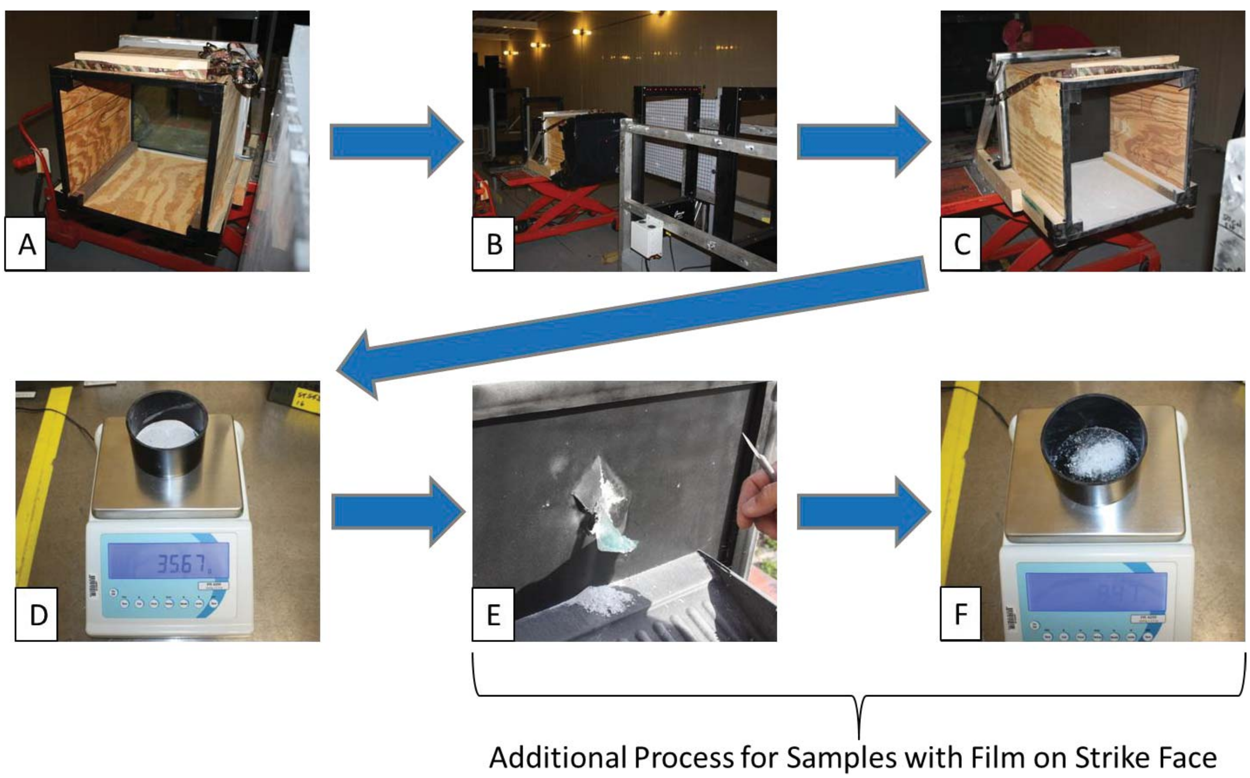

Figure 9. The Spall Collection Process: (A) Attaching the Box to the Front of the Frame, (B) Impacting the Sample with Trash Bag in Place, (C) Initial Spall Contained in the Box, (D) Weighing the Initial Spall, (E) Removing Additional Fragments Containe

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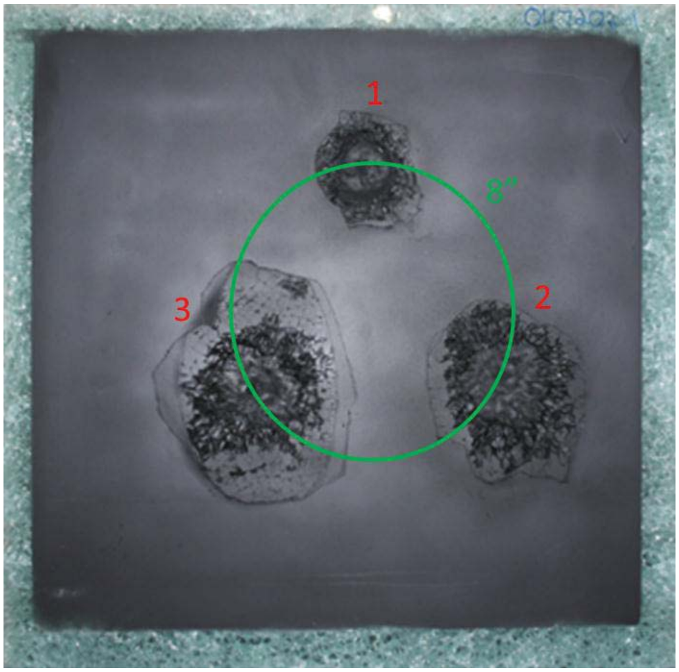

Figure 10. A Tested and Painted Sample with a Strike Face Film Showing the Three Impact Locations

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4. RESULTS AND DISCUSSION

4.1. Velocity Reduction

Over 25 velocity measurements were compiled and analyzed to provide direct comparison among the three impacts on each sample. Performance was based on the percent reduction of velocity from the nominal impact velocity, as seen in Table 1. All tests resulted in complete penetrations of the samples with less than 10 faulty exit velocity readings due to spall from the back face traveling through the velocity screens at the same time as the projectile.

Table 1. Exit Velocity as a Reduction of Impact Velocity

Shot	No Film on Strike Face	Film on Strike Face
1	85.4% reduction	90.4% reduction
2	34.6% reduction	38.2% reduction
3	32.8% reduction	39.2% reduction

It is apparent that the presence of film on the strike face provided a slight performance increase over those samples that had no film on the strike face. By taking an arbitrary impact velocity—say 3,000 ft/s, which falls around common velocities produced by small arms rifle threats—the sample without film on the strike face would produce an exit velocity of 438 ft/s on the first impact for this specific threat while a sample with film on the strike face would produce a velocity of 288 ft/s on the first impact, which is roughly 34 percent lower. While this is quite a large variation for the first impact, the second and third impacts are much less significant at 5 percent and 10 percent lower for the samples with a strike face film, respectively. These variations can be seen in Figure 11.

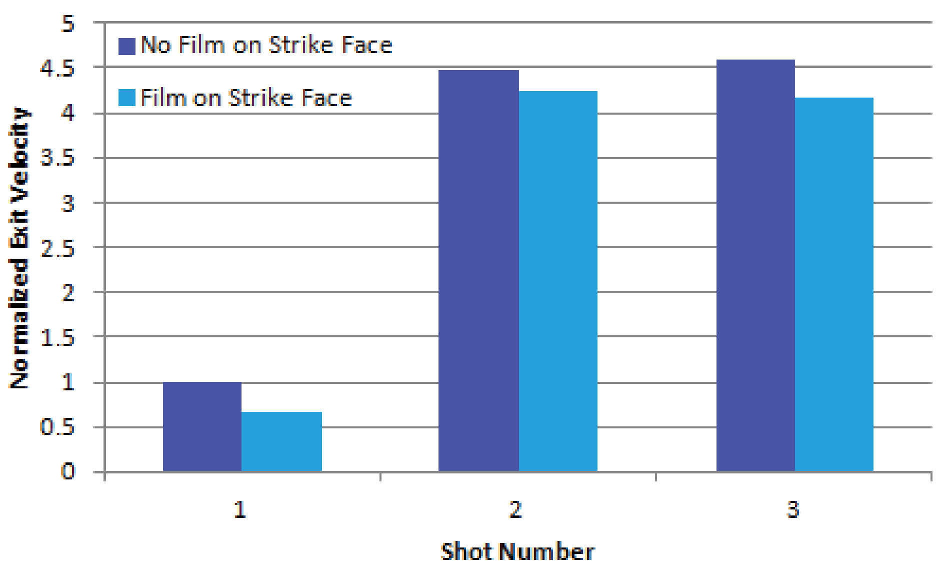

Figure 11. Exit Velocity Normalized with Respect to First Shot Exit Velocity on Filmless Sample

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4.2. Analysis of Strike Face Spall

The spall created by impacts on both samples was very fine, however there were fewer large fragments collected from samples with film on the strike face indicating a slightly higher degree of comminution during those impact events. The amount of spall collected from the first through third impacts (in this case the initial spall could also be considered the total spall) progressively increased on the samples without a strike face film, as expected. For samples with a strike face film, the initial spall collected from each impact was much lower than that collected from the filmless samples and although it increased through subsequent impacts, it was at a much lower rate than that of the filmless samples. Figure 12 shows the average initial and average total amounts of spall collected from both designs.

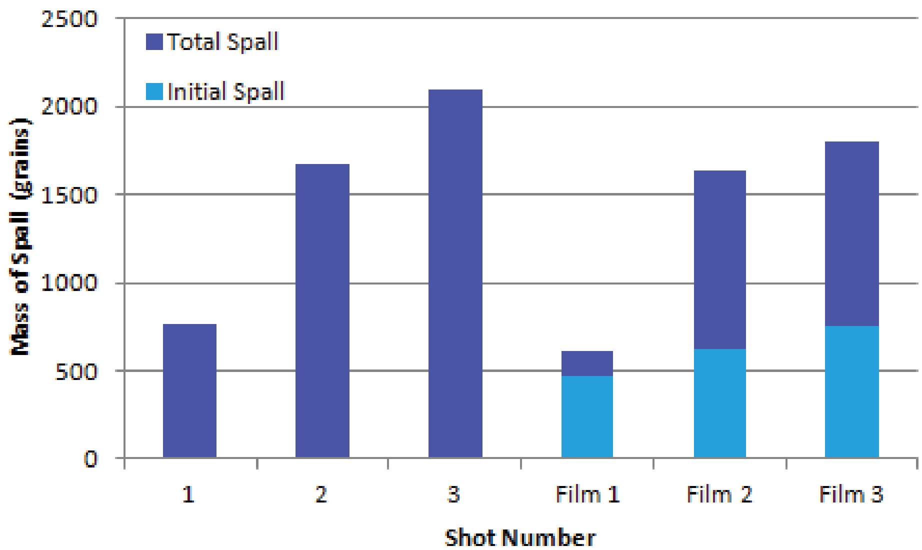

Figure 12. Average Mass of Spall Recovered from Each Impact for Samples with and without Film

Note that the average amount of spall generated by the third impact on the samples with strike face film was roughly the same as the first impact initial spall on a filmless sample. This was attributed to the film confining the loose glass fragments. Once the film was cut away (Figure 13), these loose fragments were collected and added to the respective initial masses which resulted in the total spall collected for the strike face film samples more closely relating to spall collected from the filmless samples.

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Figure 13. Photos of the Strike Face before the Film was Cut Away (left) and after the Film was Removed and Loose Fragments Collected (right)

4.3. Crater Analysis

Analysis of the craters was conducted solely through the 3-D digital crater replicas created by the laser scanner. Topographical analysis was conducted initially to compare the geometries between laminate designs and study any other distinguishable characteristics of the craters. As shown in Figure 14, the craters created in filmless samples tended to have a more conical shape while the craters created in samples with film on the strike face had a more cylindrical shape with steep edges. It was hypothesized that the film constrained the glass and forced it to interact with itself and the projectile as it penetrated through the sample. This resulted in the glass having no other direction to travel except the direction that the projectile entered, thus ejecting spall straight away from the strike face rather than in a 30 to 45 degree cone as was observed in the filmless sample. The orange and red areas depict the front face of the polymer interlayer and the location of penetration is actually visible as a darker spot in the left image.

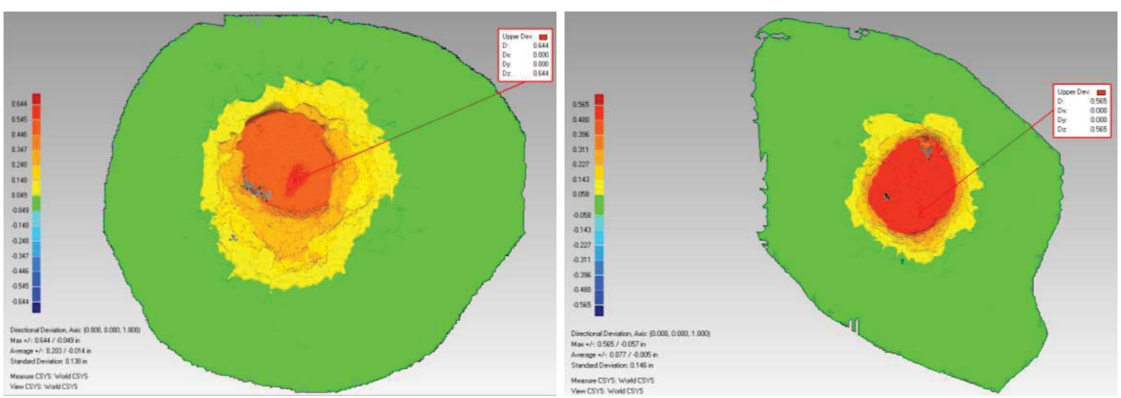

Figure 14. Topographical Representations of the First Impact on a Sample without Film (left) and a Sample with Film (right). Green Represents the Surface and Red Represents the Bottom of the Crater

A more detailed look at the geometry of the craters was achieved using a cross-sectional tool in the software, which had the capability to generate a cross-section through any plane and at any angle through the crater. Figure 15 shows the two corresponding cross sections of the images in

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Figure 14. Notice the characteristics of the edges on the crater created in the sample with a strike face film. The flat portion on the bottom is the front face of the polymer interlayer and corresponds with the red area in Figure 14.

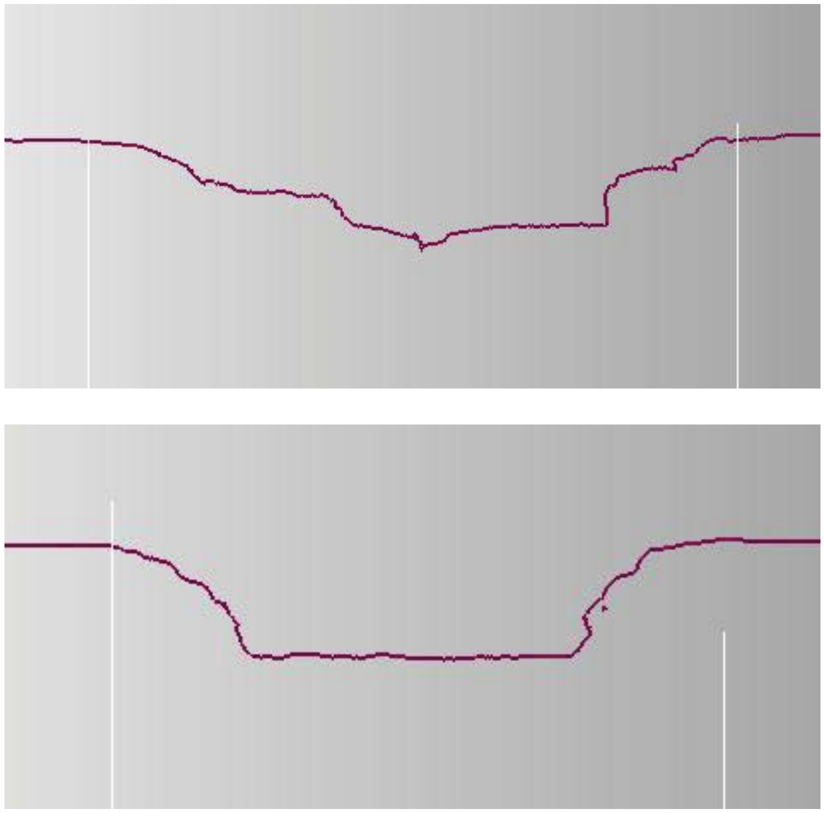

Figure 15. Cross-Section of the Resulting Crater without Film on the Strike Face (top) and with Film on the Strike Face (bottom)

Measurement of volume was taken by creating a co-planar layer on the strike face surface and utilizing the software to determine the volume contained between that layer and the bottom of the crater. Figure 16 shows this process where the bright red areas represent material above the plane and the dark red areas are below the plane where the volume was measured. Note that crater volume in samples with film on the strike face was measured after the film was cut away and loose fragments removed.

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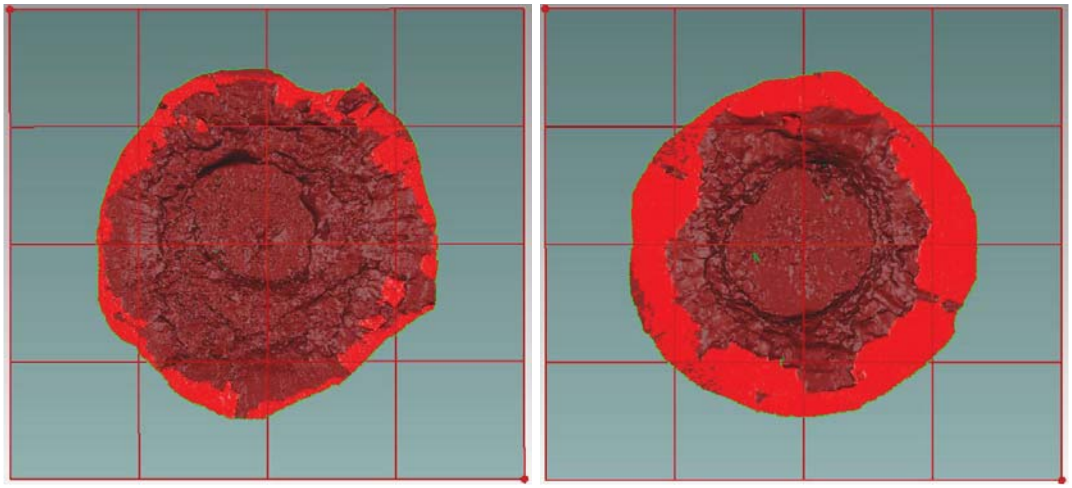

Figure 16. Volume Measurement of the First Impact on a Sample without Film (left) and a Sample with Film (right)

The results of volume analysis were consistent with the total spall collected for both laminate designs, however the small discrepancies could be attributed to glass fragments being ejected from areas away from the craters and subsequently the locations where the missing volume was measured. Table 2 shows a comparison of the two designs where the samples with film lost 24 percent less volume on average during the first impact, while the second and third impacts showed negligible differences between the two designs as well as each other.

Table 2. Average Volume of Craters (in^3)

Shot #	No Film on Strike Face	Film on Strike Face
1	1.818	1.383
2	2.670	2.778
3	2.611	2.603

The areas of the craters were of considerable importance as they would most likely influence material response to subsequent impacts depending on the proximity to the previous point of impact. The area of each crater was measured in plane with the strike face of each sample, in effect providing the area of the largest portion of the crater "cone".

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Table 3 presents the average areas of the craters. Results are similar to those inferred from the volume measurements where the first impact on samples with film resulted in 40 percent lower area than in samples without film. There was an indiscernible difference between the second and third impacts for each laminate design.

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Table 3. Average Area of Craters (in^2)

Shot #	No Film on Strike Face	Film on Strike Face
1	10.155	5.946
2	11.233	11.663
3	11.288	11.538

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5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

An effort to determine the ballistic performance improvements offered to tempered glass laminates by thin strike face films was conducted in a small arms ballistic facility. Two laminate designs were tested with the presence of a strike face film constituting the only difference between designs. The designs were selected to ensure complete penetrations so exit velocities could be recorded for comparison of ballistic performance. Spall ejected from the strike face of the samples was collected for analysis and the resulting craters were scanned with the 3-D laser to facilitate analysis of crater characteristics to determine any relation to the ballistic performance of the laminates. It was found that the application of a film on the strike face of a tempered glass laminate most notably improved ballistic performance for the first impact sustained by the laminate. However, the hypothesis that film would improve multiple impact performance compared to samples without film was weakly supported by 5 percent and 10 percent improvements in ballistic performance for the second and third impacts, respectively. It was expected that if the glass could be constrained with the film it would be forced to interact more with itself and the projectile, thus reducing the penetration capability of the projectile. This was generally confirmed during spall collection and analysis as a significant amount of spall was collected upon the removal of the film, however the accompanying velocity reduction was minimal for the second and third impacts. The volume and area measurements of the second and third impact craters were essentially unaffected by the presence of a film, but the first impact craters were significantly smaller and ejected less material in samples that had a strike face film, further supporting the larger velocity reduction findings.

5.2. Recommendations

Additional testing with subsequent points of impact closer to existing craters on laminates with a strike face film would be of great interest to determine if any performance variance exists when compared to the work conducted in this report. Also, testing against fragment simulating projectiles to determine effectiveness in a blast debris or cased munition near miss scenario would provide a different set of data which would facilitate the comparison of film performance against different projectile geometries.

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LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

3-D	3-dimensional
AFCEC	Air Force Civil Engineer Center
ft	foot
ft/s	feet/second
in	inch
s	second

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