WAVE PROPAGATION AND IMPACT DAMAGE IN TRANSPARENT LAMINATES

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Conventional transparent armor consists of glass laminates with polymer interlayer and backing. Numerous empirical investigations have shown that the type of materials, the ratio of materials, and the thickness of the interlayer do play a role in the effectiveness of the laminate. In order to examine the wave and damage propagation through laminated structures, a high-speed photographic study has been conducted. The specimens were impacted in a so-called edge-on impact arrangement and damage propagation was observed by means of a Cranz-Schardin camera. Two types of glass were considered, Borofloat™ glass and Starphire® ultra-clear float glass. The influence of interlayer thickness on wave and damage propagation was examined.

INTRODUCTION

Operation Iraqi Freedom and the experience of the International Security Assistance Force (ISAF) in Afghanistan have clearly demonstrated the criticality of transparent armor in many army systems. As the threats have escalated and become more varied, the challenges for rapidly developing optimized threat specific transparent armor packages have become extremely complex. In order to accelerate the development of validated design and predictive performance models, the Army Research Laboratory, the U.S. Army Tank Automotive Research Development and Engineering Center have entered into a collaboration with The Ernst-Mach Institute (EMI) of Efringen-Kirchen, Germany. The fully instrumented Edge-on Impact facility at EMI, modified for dynamic photoelasticity, is being used to quantify stress wave propagation, damage nucleation and propagation during high velocity impacts. Summarized in this paper are a selection of results on monolithic and laminated borosilicate glass and soda-lime glass of type Starphire™. Crack, damage and stress wave velocities have been determined directly. In addition, the stress wave and damage retardation by various thickness bonding interfaces has been measured. These results are a critical tool to corroborate and refine existing materials and transparent armor package models by providing insight and critical data into the role of different materials and interfaces that can eventually guide materials and laminate design.

EXPERIMENTAL SET-UP

An Edge-on Impact (EOI) test method coupled with a high speed Cranz-Schardin camera, with frame rates up to 10^7 fps, has been developed at the Fraunhofer-Institute for High-Speed Dynamics, EMI, to visualize damage propagation and dynamic fracture in structural ceramics. Similar to the previous work on the transparent polycrystalline ceramic, AlON [1], and fused silica [2], two different optical configurations were employed. A regular transmitted light shadowgraph set-up was used to observe wave and damage propagation and a modified configuration, where the specimens were placed between crossed polarizers and the photo-elastic effect was utilized to visualize the stress waves. Pairs of impact tests at approximately equivalent velocities were carried out in transmitted plane (shadowgraphs) and crossed polarized light. Figure 1 shows a schematic of the Edge-on Impact test with the added crossed polarizers; Figure 2 illustrates an exploded view of the impactor/sample interaction.

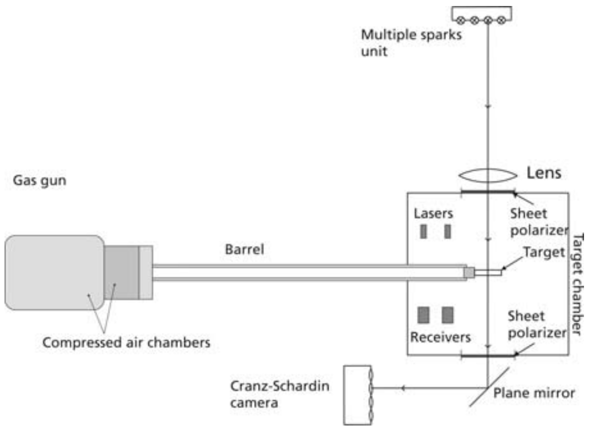


Fig. 1: EOI Test Set-up with Cranz-Schardin camera

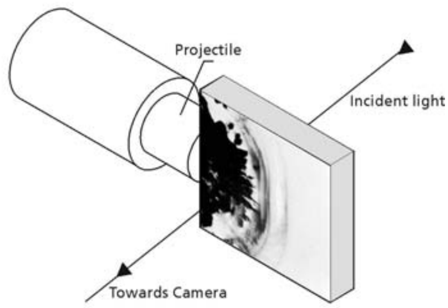


Fig. 2: Close-up view of test sample set-up for shadowgraphs

Both steel solid cylinder and spherical impactors have been used at velocities from 350- 450 m/s on 100x100x10 mm plates. Once the baseline glass materials were tested and analyzed, multi-component glass laminates were produced and tested at ≈ 400 m/s. The data collected from the EOI test consists of a series of 20 photographs as a function of time, typically at 0.25 - 2 μs intervals. Pairs of impact tests at approximately equivalent velocities are carried out in plane and crossed polarized light to correlate the dynamic fracture with the associated stress fields. Detailed graphs are then created plotting crack, damage and compression and shear stress wave velocities.

BASELINE RESULTS

Experiments performed in plane light show the evolution of damage and material failure, while the photoelastic visualization illustrates the stress wave propagation as a function of time. Figure 3 shows a selection of two shadowgraphs (top) and corresponding crossed polarizers photographs (bottom) of a baseline test with Starphire glass, impacted by a spherical steel projectile of 16 mm diameter at 440 m/s. The shadowgraphs show a crack front growing from the impacted edge of the specimen. Only one crack center can be observed close to the upper edge of the specimen. The crossed polarizers photographs illustrate the propagation of the longitudinal and the transversal stress waves. Release waves due to reflections at the upper and lower edge can also be recognized. Note that damage appears dark on the shadowgraphs and the zones with stress birefringence are exhibited as bright zones in the crossed polarizers photographs.

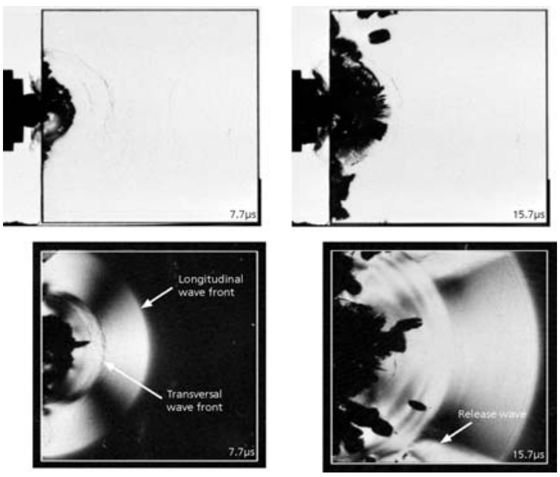


Fig.3: Selection of two shadowgraphs (top) and crossed pol. photographs (bottom) from impact on Starphire glass with steel sphere at 440 m/s

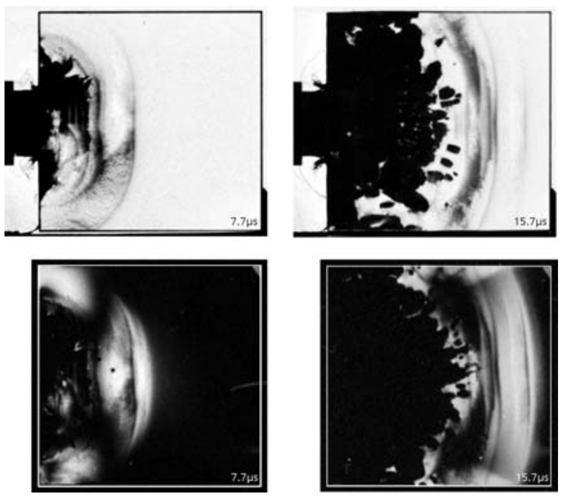


Fig.4: Selection of two shadowgraphs (top) and crossed pol. photographs (bottom) from impact on Starphire glass with steel cylinder at 390 m/s

Figure 4 shows a selection of two shadowgraphs along with the corresponding crossed polarizers photographs of the baseline tests with the cylindrical projectile. A coherent damage zone is growing from the impacted edge, preceded by a zone with separated crack centers, initiated by the stress waves. It can be recognized that the stress wave front appears more advanced and exhibits a different curvature in the crossed polarizers view. This seeming discrepancy can be explained by the different sensitivities that the different optical techniques employed exhibit with respect to the stress level that can be visualized. In a shadowgraph image the light intensity depends on the second spatial derivative $\partial^2 n/\partial x^2$ of the refractive index, whereas in the crossed polarizers set-up the intensity of the transmitted light depends on the photo-elastic properties of the material. Therefore, it is possible that the first visible wave front in the shadowgraph configuration appears at a different position than the forefront of the stress wave, visible in the crossed polarizers set-up. Both techniques can visualize different parts of the same stress wave.

The high-speed photographs from baseline tests with the steel sphere and cylinder on Borofloat glass are presented in Figures 5 and 6.

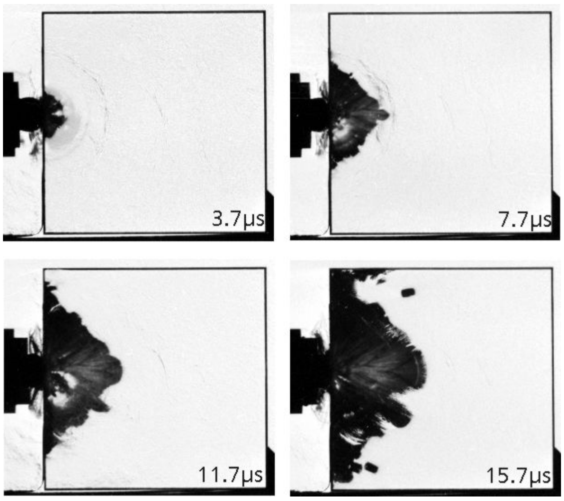


Fig.5: Selection of four shadowgraphs from impact on Borofloat glass with steel sphere at 430 m/s

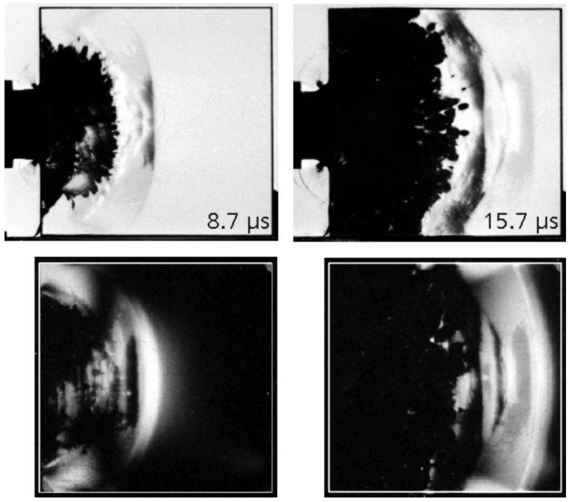


Fig.6: Selection of two shadowgraphs (top) and crossed pol. photographs (bottom) from impact on Borofloat glass with steel cylinder at 390 m/s

Crack and damage patterns very similar to those observed with soda-lime glass can be recognized. However, the crack and damage velocities determined from the position-time analysis of the high-speed photographs were higher than with Starphire glass. Table 1 and 2 summarize the crack velocity, damage velocity and wave propagation data of the baseline tests with Starphire and Borofloat glass, respectively.

Table 1: Measured wave, crack and damage velocities with Starphire soda-lime glass

Impactor	Optical Set-up	Long. Wave Velocity c_L [m/s]	Trans. Wave Velocity c_T [m/s]	Crack Velocity v_{Cr} [m/s]	Damage Velocity v_D [m/s]
Sphere	Shadowgraph	---	---	1580	1580
Sphere	Crossed Pol.	5763	3518	---	---
Cylinder	Shadowgraph	5761	---	---	3270
Cylinder	Crossed Pol.	5779	---	---	---

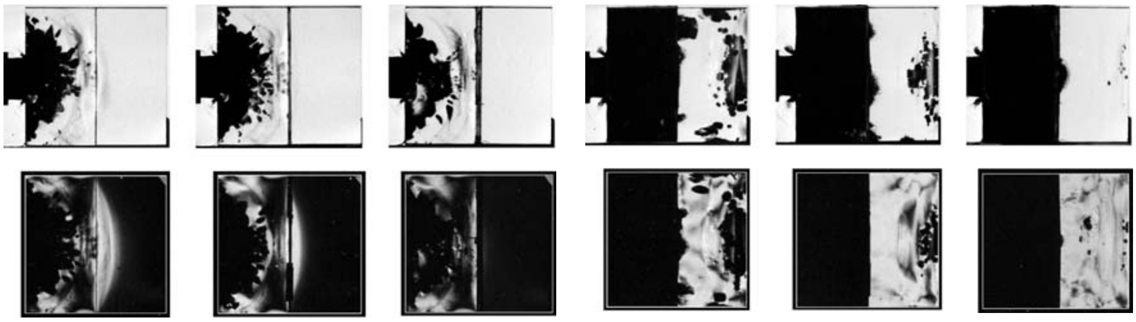
Table 2: Measured wave, crack and damage velocities with Borofloat glass

Impactor	Optical Set-up	Long. Wave Velocity c_L [m/s]	Trans. Wave Velocity c_T [m/s]	Crack Velocity v_{Cr} [m/s]	Damage Velocity v_D [m/s]
Sphere	Shadowgraph	5462	---	2034	2034
Cylinder	Shadowgraph	5531	---	---	4150
Cylinder	Crossed Pol.	5635	---	---	---

STARPHIRE GLASS LAMINATES

The influence of a polyurethane (PU) bonding layer on wave and damage propagation was examined with cylindrical projectiles only. Four pairs of tests with specimens consisting of two parts of the dimensions 50 mm x 100 mm x 9.5 mm were conducted in order to examine the influence of interlayer thickness. Starphire specimens with bonding layers of thickness 0.64 mm, 1.27 mm, 2.54 mm and 5.08 mm were examined. The influence of two PU interlayers (2.54 mm) was also tested with specimens that were built of three parts of the dimensions 30 mm x 100 mm x 9.5 mm. Figure 7 illustrates a comparison of wave propagation and damage in Starphire specimens with bonding layers of thickness 0.64 mm, 2.54 mm and 5.08 mm. The impact velocity was 380 ± 5 m/s in all tests. The upper line of pictures shows the shadowgraphs, while the corresponding crossed polarizers photographs are presented in the lower line of pictures, respectively. Figure 7a illustrates the specimens at 10.7 µs and Figure 7b at 23.7 µs after projectile impact. The shadowgraphs at 10.7 µs show that the first glass layer (left part of specimen) is damaged through the coherent fracture front growing from the impacted edge and through the nucleation of crack centers, initiated by the longitudinal stress waves. At that time, no damage can be recognized in the second glass layer (right part of specimen). The crossed polarizers photographs demonstrate, that the first longitudinal stress pulse has not yet crossed the thickest glue interlayer (right), whereas the stress wave is clearly visible in the right half of the specimens with the thinner glue interlayer.

0.64 mm 2.54 mm 5.08 mm 0.64 mm 2.54 mm 5.08 mm



a) 10.7 µs b) 23.7 µs

Fig.7: Starphire laminates with interlayer of different thickness impacted by steel cylinder at 380 m/s

After 23.7 µs (Figure 7b) the compressive stress pulse has already been reflected as a tensile wave at the rear edge of the specimens in all three cases. The shadowgraphs illustrate that damage in the second glass layer is mainly due to the tensile wave and starts from the rear edge of the specimen. In the case of the thickest glue interlayer only little damage was observed in the second glass layer.

The effect of two bonding layers of 2.54 mm thickness is demonstrated in Figure 8 which shows a selection of four shadowgraphs and corresponding crossed polarizers photographs in the time interval from 6 – 25 µs after impact of a steel cylinder at about 400 m/s. The first layer of glass was completely damaged within the first 15 µs. Damage could be recognized in the second layer after 16 µs, when the first crack centers became visible which were initiated by the reflection of the compression wave at the interface between the second glass and the second bonding layer. No damage was observed in the third glass layer during the time interval of observation. The wave propagation in the specimens was analyzed and the path-time history for the case with the two 2.54 mm bonding layers is presented in Figure 10. When the waves hit an interlayer one part is reflected while the other part is transmitted into the next glass layer. Due to the low acoustic impedance of the interlayer compared to the glass, the amplitude of the stress pulses is attenuated considerably. The low wave velocity in the interlayers effected a time delay of ≈ 0.7 µs at each bonding layer compared to the unperturbed propagation through the glass.

The delay times measured in all tests were plotted in a delay time versus bonding layer thickness diagram (Figure 9). Linear regression of the data yielded an average delay time of 0.33µs/mm. This is in good agreement with the calculated value based on a longitudinal wave velocity c_L = 5770 m/s for Starphire glass and $c_L \approx$ 2000 m/s for the polyurethane [3].

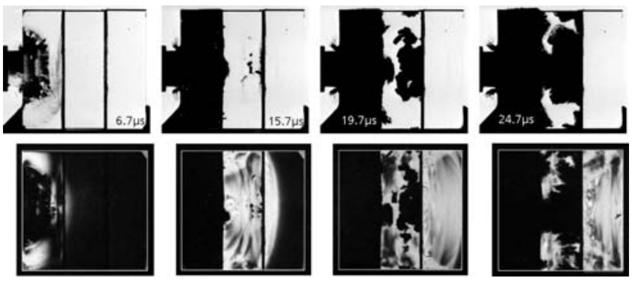


Fig. 8: Selection of four shadowgraphs and corresponding crossed polarizers photographs;
Starphire specimen with two PU bonding layers;
Impact velocity 400 m/s

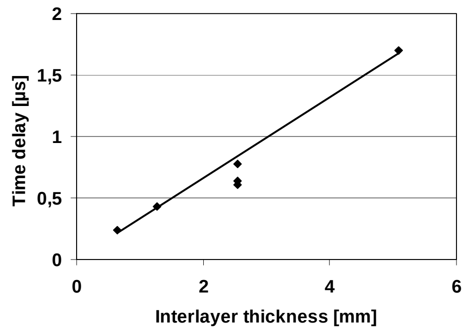


Fig. 9: Interlayer bonding delay time versus bonding layer thickness.

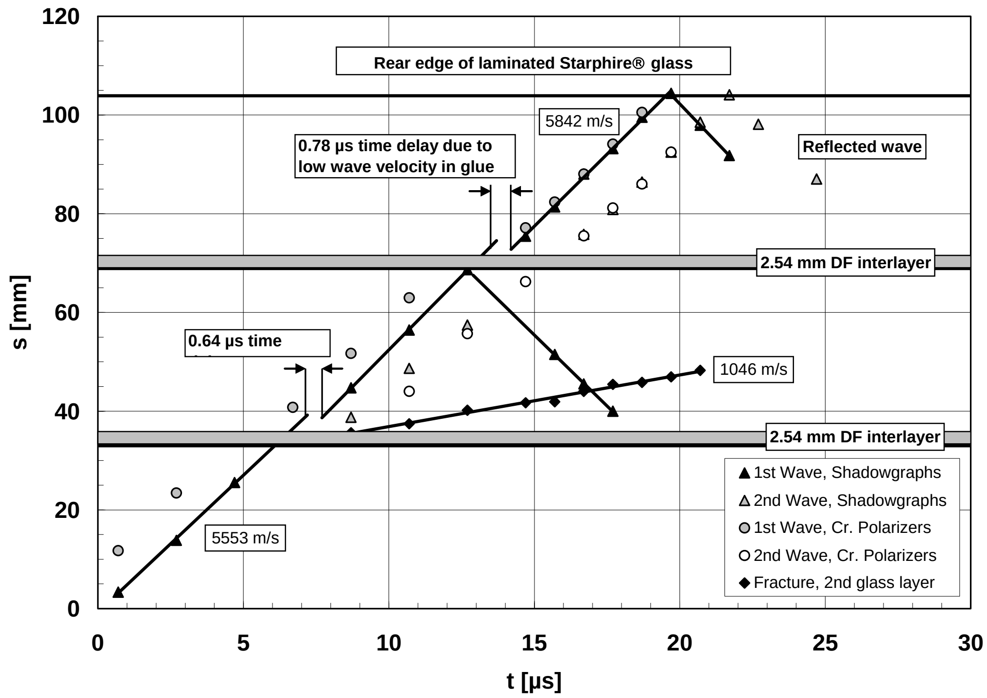


Figure 10: Path-time history of wave propagation in specimens with two 2.54 mm polyurethane (DF) bonding layers

CONCLUSION

The Edge-on Impact test method was applied in order to visualize wave and damage propagation in materials for transparent armor. The influence of bonding layer thickness on damage evolution in Starphire glass laminates was examined. The high resolution of the high-speed photographs allowed for the determination of the stress wave time delay during the transition through the bonding layers. It is expected that the capabilities of the experimental method help with the development of damage models and that the combination of experimental and computational modelling results will guide materials and laminates design.

ACKNOWLEDGMENTS

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