

# IMPROVED LOW-COST MULTI-HIT TRANSPARENT ARMOR

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## ABSTRACT

Operation Iraqi Freedom has 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. The current industry methodology is to add more glass layers to increase the thickness and thus weight to achieve new protection requirements. ARL began a program to develop a transparent armor using a materials by design approach whereby materials were selected based on the role they play in a ballistic event. The outcome of this approach was a new ARL Multi-Hit Transparent Armor design (patent pending, Patel et al., 2005) based on prior success in ceramic/all-plastic systems, which exploits the synergy of glass and polymers, particularly a rigid poly(methyl methacrylate), PMMA, and has produced a lighter window that can defeat four impacts in a 1 ft<sup>2</sup> panel. The impacts were spaced in two adjacent 120 mm triangles. The weight of this new system offers a 30 percent weight reduction while using materials that are commercially available and are comparable in cost to what is being fielded today. In this paper, the role of materials influence including both glass and polymers on the impact efficiency and overall mode of failure is discussed.

## 1. INTRODUCTION

The state of the art in vehicle transparent armor protection is a glass based laminate. Glass is the current material of choice for advanced threats because of cost, availability, and offers mechanical properties such as stiffness and hardness. Figure 1 is a schematic of a transparent armor design. The conventional approach to increased protection is to add more layers of glass (increase weight), which can increase both threat and multi-hit protection. For small arms threats, a typical glass-based system weighs on the order of 25-35 pounds for 1 ft<sup>2</sup> area (25 – 35 psf). While glass is excellent in ballistic defeat, the drawback is that glass produces behind armor debris (or spall) that can be as deadly as the incoming threat; therefore, soldier survivability is enhanced through a spall-liner (Sands et al., 2004).

Traditionally, ductile polymers are the materials of choice for spall suppression. Hence, current design already includes the combination of polymeric materials with traditional glass to improve soldier protection.

The basis of this study was to determine the effectiveness of using lighter intermediate materials to replace the glass used in conventional designs. The hypothesis was that there is a fixed amount of striking ply material needed to achieve ballistic performance. By replacing glass with polymers, one can achieve 20-30 percent reductions in areal densities while retaining multi-hit capabilities. The methodology used was a “materials-by-design” approach whereby materials are selected based on the perceived role they undertake in a ballistic event. For example, the striking ply has very different function than the materials in the middle of the laminate and the backing layers. By understanding the ballistic event, materials were chosen to improve the performance while reducing the weight. The first part of this large study was to investigate the intermediate material to determine its role in the ballistic event and then to deduce which materials can meet the requirements. PMMA was found to meet many of the requirements so a study was conducted to see the effectiveness of this material.

Poly(methyl methacrylate), PMMA, commonly known as a brittle plastic, exhibits unique viscoelastic behavior and high rate-sensitivity mechanical response. Quasi-static compression measurements revealed that the strain-rate dependence of apparent yield stress of PMMA was more significant than that of polycarbonate (Hsieh et al., 2004). Despite the inherent brittleness, PMMA exhibited ballistic impact performance that scaled with projectile impact rate and with plate thickness. In fact, PMMA and polycarbonate targets of an equivalent thickness of about 12 mm displayed similar performance against the 0.22-caliber fragment-simulating projectile, yet absorbing the energy by different deformation and failure mechanisms (Hsieh et al., 2004). The ductility of PC is attributed to molecular motion associated with main chain molecules (Billmeyer, 1984), and this motion is presumably present even upon exposure to high-rate impact and can therefore afford the efficient dissipation of impact energy. This molecular mechanism is not prevalent in PMMA. Instead, the molecular relaxation of

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| 14. ABSTRACT                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |                                    |                                     |                                         |                                          |                                 |
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PMMA is presumably associated with side chain carbonyl ester groups (Billmeyer, 1984). The molecular mobility of these side chain groups is rather flexible at the ambient temperature; however, these short chain segments become completely frozen once they are exposed to conditions in which the rate of mechanical deformation increases and reaches a threshold value. Thus, such side-chain molecular relaxation that does not contribute to the ductility of PMMA under quasi-static mechanical deformation will instead be sufficient to impart the desired rigidity upon the high-rate impact. These rate-dependent viscoelastic relaxation observations are consistent to the mechanical deformation upon quasi-static compression and split Hopkinson-bar impact measurements (Moy et al., 2003a, 2003b).

## 2. EXPERIMENTAL

### 2.1 Materials

In this study, a borosilicate (Schott Borofloat<sup>TM</sup>) glass was used as striking ply. An alternative to a borosilicate glass is soda-lime silica glass or float glass. Float glass is the most widely used glass due to its low cost and availability and ARL has investigated several systems using soda-lime silica glass based armor. Borosilicate was chosen for this study because it has a lower density 10 percent lower than float glass. The mechanical and physical properties of both Borofloat and PPG Starphire glass are listed in Table 1. The properties measured were density ( $\rho$ ), longitudinal sound velocity ( $V_L$ ), shear sound velocity ( $V_s$ ), elastic modulus ( $E$ ) and shear modulus ( $G$ ).

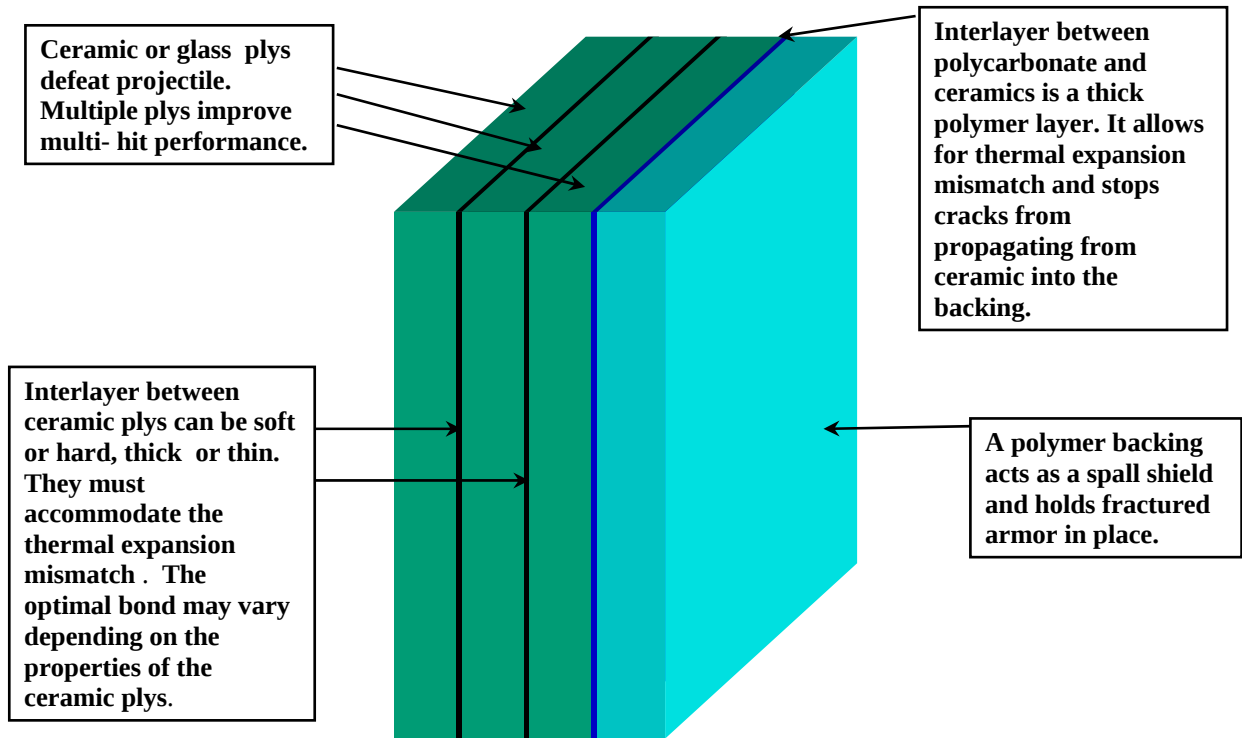


Fig. 1. Schematic of a transparent armor.

In this work, the use of additional polymeric materials in the ballistic laminate design is explored with the emphasis on driving down weight of the ballistic system further and additionally on increasing the fragment and spall protection of the designs. In addition, we have exploited a “materials-by-design” approach as a route to fabricate next generation transparent armor systems and this paper will describe our efforts to demonstrate success in hybrid glass/plastic armor with significant performance benefits.

Table 1. Properties of Schott Borofloat<sup>TM</sup> and PPG Starphire<sup>TM</sup> Glass

| Glass     | $\rho$<br>(g/cm <sup>3</sup> ) | $V_L$<br>(m/s) | $V_s$<br>(m/s) | $E$<br>(GPa) | $G$<br>(GPa) |
|-----------|--------------------------------|----------------|----------------|--------------|--------------|
| Borofloat | 2.23                           | 5552           | 3418           | 62.2         | 26           |
| Starphire | 2.50                           | 5548           | 3416           | 72.3         | 29.3         |

Properties of Borofloat and Starphire measured using ultrasonically (M. Motyka at ARL)

The intermediate materials used to replace glass for this development was PMMA. In this study, cell-cast Plexiglass G<sup>®</sup> PMMA produced by ATOFINA was chosen for use in making glass/plastic laminates for ballistic evaluation based on results from previous ARL studies (Hsieh et al., 2004). Other acrylics are also currently being evaluated.

The interlayer material used in this study was aliphatic polyurethane manufactured by Deerfield. Table 2 lists the physical and mechanical properties of Deerfield 4700 PU (Bayer MaterialScience, 2006).

Table 2. Hardness, density, and tensile properties of Deerfield 4700 PU interlayer (Bayer MaterialScience 2006).

| PU | Hardness<br>(Shore A) | $\rho$<br>(g/cm <sup>3</sup> ) | Tensile<br>Strength<br>(MPa) | Ultimate<br>Elongation<br>(%) |
|----|-----------------------|--------------------------------|------------------------------|-------------------------------|
|    | 78                    | 1.08                           | 37.9                         | 500                           |

Bayer Makrolon AR was the backing polycarbonate material used in this study. The material used was coated to improve the scratch resistance of the polycarbonate.

## 2.2 Fabrication of Laminates

Individual plates were cleaned and arranged to the specified design, then sealed tight in a vacuum bag followed by lamination in an autoclave. The parts were heated to 220 °F for 4 hours and then cooled slowly to room temperature. The laminated parts were subjected to ballistic impact testing for evaluation of multi-hit ballistic performance in the 120 mm triangle spacing.

## 3. Results and Discussion

### 3.1 Failure Mechanisms of PMMA

The choice of polymeric materials is critical for use in the design and integration of transparent glass/plastic and all-plastic based armor systems. PMMA has low tensile elongation, and increasing plate thickness can augment the bending stiffness of PMMA thus result in improved target impact performance. Figure 2 demonstrates the significance of geometry constraint associated with a monolithic 12 mm thick PMMA compared to failure observed in a corresponding layered PMMA composite with equivalent overall target thickness. The composite assembly consisting of eight layers of 1.5 mm thick PMMA plates exhibited significantly inferior ballistic performance against the 0.22-caliber FSP impact than the monolithic 12 mm thick PMMA target. The eight-layer target was stacked and wrapped with tapes but not adhesively bonded in order to

accommodate the post-failure analysis of each individual layers. In addition to a cone-shape fracture pattern, the eight-layer targets displayed crack initiation separately in each individual layers which is distinctly different from a through-thickness-cracks pattern observed in the 12 mm thick PMMA monolith (Figure 2). This experimental observation was similar to the modeling results obtained by Holmquist et al., 2001 from ballistic impact simulation of layered ceramic composites. Their computations revealed that compression-induced deformation was dominant in the one-layer target whereas layering reduces ceramic ballistic performance (Holmquist et al., 2001). They also pointed out that any target, which is dominated by tensile failure, will absorb less energy and be less resistant to penetration, and more material will fail in a corresponding six-layer target of equivalent overall plate thickness.



(a)



(b)

Fig. 2: Ballistic impact tested PMMA targets: (a) monolithic 12 mm thick PMMA plate and (b) eight-layer laminate of 3 mm thick PMMA.

### 3.2 Dynamic Deformation and Hardness of PMMA

Polymers, unlike glass and ceramics, are viscoelastic materials, and exhibit strong rate-sensitivity not only in mechanical deformation but also in failure behaviors. An earlier study revealed that PMMA underwent a drastic

change in the mode of failure from brittle deformation and large-cracks pattern to high intensity but localized cracks formation when the impact velocities were increased well above the ballistic limit (Hsieh et al., 2004). Despite the complexity of stress state at high rates, these observations nevertheless suggested the propensity to suppress crack propagation under these impact loading conditions. Ravi-Chandar et al., 2000 in their studies of dynamic impact behavior of PMMA with preformed notch crack and edge groove also clearly demonstrated that PMMA when tested at high impact velocities exhibited shear mode cracks, in addition to the opening mode cracks, propagated along the groove. Broberg, 1987 pointed out that fracture toughness of PMMA could be significantly enhanced once a high enough confining pressure was applied such that the possibility of mode I (opening mode) crack growth could be completely eliminated and further, if the in-plane compressive stress was sufficiently large then the only available path for crack growth might be along the direction of maximum shear. Broberg, 1987 also experimentally validated this idea by performing biaxial compression measurements under critical loading conditions which in particular favoring a straight mode-II crack growth, and he revealed that the mode II fracture toughness of PMMA was about 2.5 times of mode-I fracture toughness. It is noteworthy that the mode-II fracture toughness of PMMA is close to the  $K_{IC}$  of PC.

PMMA is not as hard as glass, yet its extraordinary response in mechanical strengthening at high rates resulted in a drastic increase in the effective hardness (Hsieh et al., 2004). This can also enhance the dynamic impedance match between the hard face and backing plates, thus leading to improved stress-wave propagation in the glass/plastic composites. Results of ballistic impact measurements shown in Figure 3 clearly indicate that PMMA, when incorporated into a glass/plastic laminate, exhibits better efficiency against the impact of .22-caliber fragment-simulating projectile, compared to the PMMA-containing all-plastic laminates of equivalent areal density (Hsieh et al., 2004).

These unique material characteristics of PMMA suggest that PMMA if designed and incorporated properly can play an important role in the ballistic performance of glass/plastic based armors.

### 3.3 Multi-Polymer Backing Design

First, PMMA was incorporated to replace glass as intermediate layers for making glass-PMMA-PC laminates. This new multi-polymer backing design has significantly reduced fracture after the initial impact compared to considerable damage encountered in the traditional multi-layer glass systems. As a result, a drastic improvement in the multi-hit performance is achieved, particularly with regard to post impact visibility. The new

design is 30% lighter than the conventional multi-hit windows currently in theater for comparable ballistic protection, and producible at an equivalent cost. Finally, the new lightweight solution provides an increased net transparency because of the improved optical clarity of PMMA over low-cost glass often used in ballistic systems.

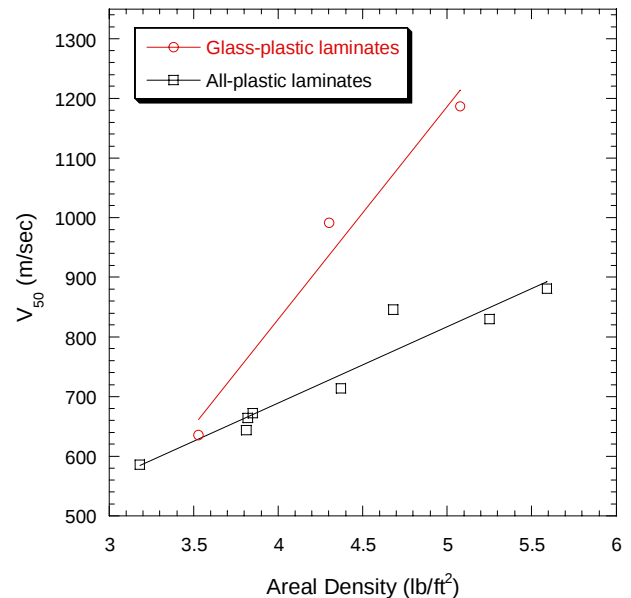


Fig. 3. Comparison of V<sub>50</sub> versus areal density data for the all-plastic laminates and glass-plastic laminates against the .22 caliber FSP impact; solid lines are the linear curve-fit.

Numerous designs were constructed and tested using this design methodology. Initially, there was significant delamination occurring. Several interlayers and surface treatments were investigated to improve the bonding of the laminate. These changes were tested concurrent to significant design changes in the laminate.

The culmination of the investigation was in the excellent multi-hit performance of the transparent armor. Figure 4 displays the success of multi-hit performance for a representative glass/plastic target with multi-polymer backing design when subjected to four successive impacts required within two adjacent 120 mm triangles. This was conducted on over 10 panels with successful results validating the materials by design approach. Once the initial design methodology was validated, a study was conducted to further understand the role of each component of the system. Two design parameters that were studied were the effect of thickness of the spall layer and the effect of thickness of the striking ply. These changes were made in the laminate while holding the overall areal density constant as well as the remaining design constant.



Fig. 4. Multi-hit test result for ARL hybrid glass-plastic transparent armor showing successful threat defeat for four successive impacts.

The choice of spall layer thickness was found to be critical. In several studies, the failure encountered in two different glass/PC designs as shown on Figures 5 and 6 were evaluated. Both targets were made without PMMA had equivalent areal density but a slight difference in the layout of PC spall layers; however, the overall impact strengths were drastically different between these two targets. When spall layers were made from laminates of two 3 mm thick PC plates, the target was capable to defeat the projectile penetration. On the other hand, catastrophic failure occurred in the glass/PC target when a 6 mm thick PC plate was used as spall layer. PC is ductile, yet increasing the plate thickness of PC can result in a change of the state of stress from plane stress to plain strain (Kinloch et al., 1983), thus causing a significant reduction in the degree of plasticity and leading to the brittle mode of failure.

In the second experiment, the thickness and lay-up of the glass were varied. Tests were conducted on one thick plate versus two plates of half the thickness. Once again all other design components were held constant. The results of these experiments indicated an increase by 15 percent in performance when using one thick striking ply over two plates making up the same overall thickness.

The results indicated the sensitivity to small changes of the design. One of the major reasons for this is that as the laminate weight is reduced by 30 percent, each component must perform better for the system to work better. In a traditional lay-up, weight is a risk mitigator and thus the system is not as susceptible to small changes.

This approach requires significant testing to characterize the system. Currently, the effect of accelerated weathering on the ballistic performance is being determined. Other environmental and durability characterizations will also be conducted shortly to ensure that these designs are robust.

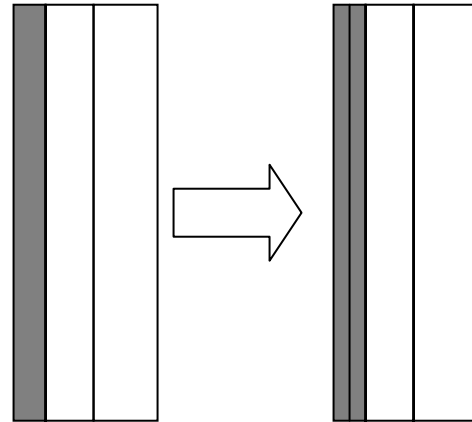


Fig. 5. Illustration of the change from one thick spall layer (shaded) to two thinner spall layers (shaded) to make up the total thickness

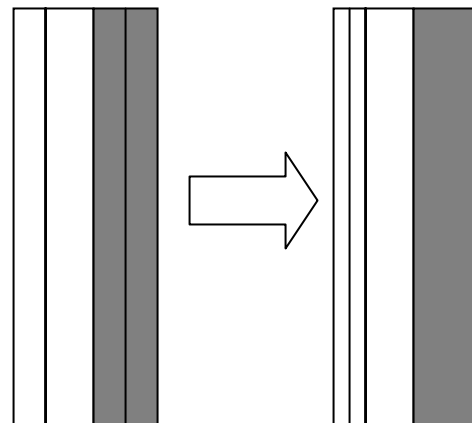


Figure 6: Illustration of the design change from two layers of striking ply (shaded) to one thick striking ply (shaded).

## CONCLUSIONS

A materials by design approach was undertaken at USARL to develop a lighter transparent armor. Using an understanding of the different roles that different segments in a transparent armor require, ARL was able to develop a lighter transparent armor without using commercially available materials. A new ARL Multi-Hit

Transparent Armor design based on prior success in ceramic/all-plastic systems exploits the synergy of glass and polymers, particularly a rigid poly(methyl methacrylate), PMMA, and has produced a lighter window that can defeat four impacts in a 1 ft<sup>2</sup> panel. A parametric study was also conducted to further understand the roles and the response of design elements to the performance of the armor. Design refinements and evaluation of the weathering and durability of these systems is currently ongoing for this program.

### ACKNOWLEDGEMENTS

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# **IMPROVED LOW-COST MULTI-HIT TRANSPARENT ARMOR**

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**U.S. Army Research Laboratory  
Aberdeen Proving Ground, MD**

Distribution A: Approved for public release; distribution is unlimited

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# ***Need for Multi-hit Transparent Armor***



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## *Outline*



- Background
- Transparent Armor Basics
  - Functional Design
  - Current Approach
  - Transparent materials
  - Needs and requirements
  - Testing and evaluation
- ARL Transparent Armor Technologies
- ARL Glass-Plastic

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## ***Overall Program Objectives***

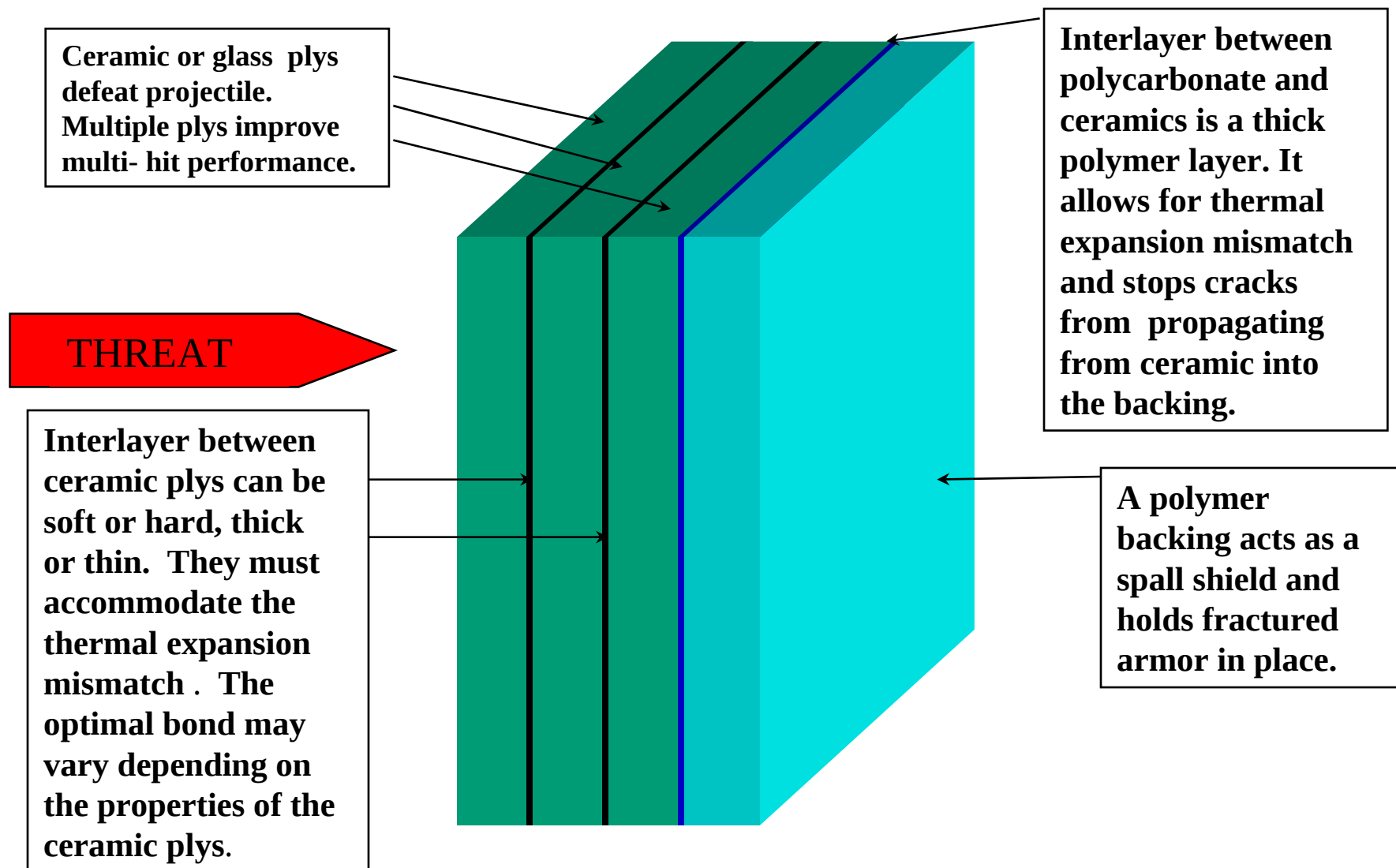
- To reduce the weight and thickness of transparent armor
- Provide equal or better protection against current threats
- Develop durable systems that can survive current and future environments

- Identify technology gaps of current systems
- Develop new materials and processes to address technical hurdles
- Understand materials properties to improve modeling and simulation

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# UNCLASSIFIED *Functional Design of a Transparent Armor System*



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# ***Current Approach for Increasing Performance***



**Increased Protection**

**Weight Reduction**

**Thinner Laminates**

**Affordable**

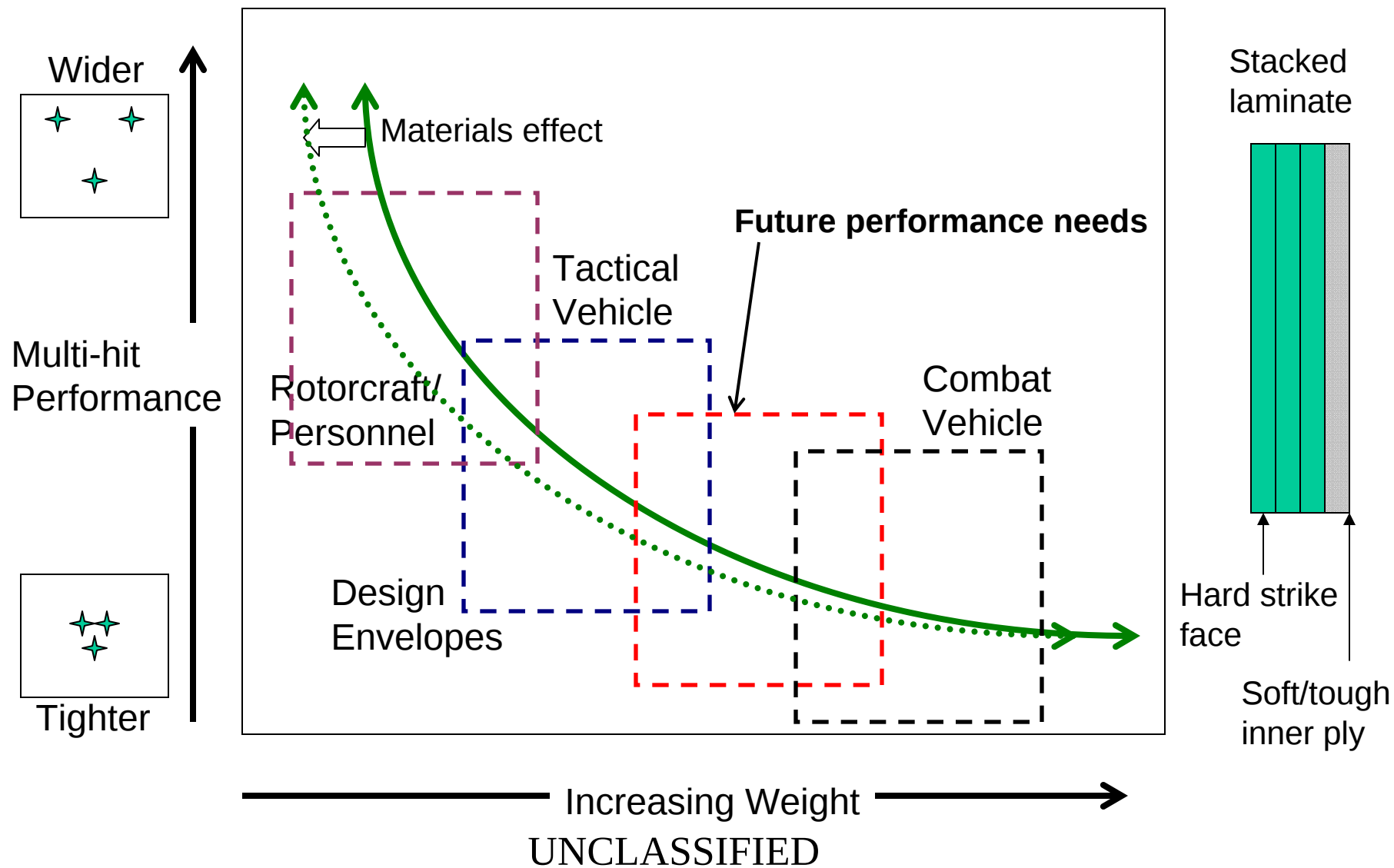
- Increase thickness of armor system
  - Thicker plates
  - Increase number of plys
- Insert new materials
  - Improved polymers
  - Improved glasses
  - Improved ceramics
- Optimize laminate construction
  - Improved interlayers
  - Synergistic approach of material lay-up

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## *Ballistic Multi-hit Versus Transparency Weight*





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## ***Transparent Materials***



- Transparent ceramics
  - Aluminum Oxynitride (ALON)
  - Magnesium Aluminate Spinel (spinel)
  - Single Crystal Aluminum Oxide (sapphire)
- Glasses and Glass-ceramics
  - Soda-lime silica
  - Borosilicate
  - Fused silica
  - TransArm
  - Strengthened Glasses
  - Newly developed glass-ceramics
- Polymers
  - Modified polycarbonates
  - Polyurethane
  - Nano composite polymers
  - Other advanced polymers
- Issues:
  - Cost
  - Sizes available (thickness, area, curvature)

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# ***Testing and Evaluation Materials***



- Need to validate designs against other threats/velocities
- Need to characterize durability
  - Adhesion
  - Moisture sensitivity
  - Thermal cycling
  - Life cycle prediction
- Need to incorporate protection against non-ballistic threats
  - Rocks
  - Dust
  - Moisture
  - Scratching

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***Testing and Evaluation  
Materials***



- Armor Transparent Purchasing Document: ATPD 2352, T. Avery (TARDEC)
  - Provides specifications and requirements for transparent armor
  - Ballistic Testing
  - Optical requirements
  - Environmental durability
  - Manufacturing and quality control

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# *Transparent Armor Solutions*



1. Glass/plastic Ballistic Glass: Multi-component laminate using soda-lime-silica glass and polycarbonate backing
2. ARL Glass Transparent Armor: Utilizes a borosilicate glass hard-face and multi-polymer backing (Pat. Pending)
  - 30 % weight reduction
  - Comparable cost to existing systems
  - 120 multi-hit triangle
3. ARL Ceramic-based Transparent Armor: Utilizes a transparent ceramic hard face such as AlON, Sapphire, Spinel (Pat. Pending)
  - 50 % weight reduction against next level threat
  - 120 mm multi-hit triangle
  - Manufacturing issues
4. All-polymer transparent armor
  - Multi-hit performance
  - Visibility after impact
5. Partitioned windows for Systems 1-3 (Need Feedback)
  - Bond lines acceptable?

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# ***ARL Glass-Plastic***

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## ***ARL Glass-Plastic Transparent Armor***

- Objective: Reduce the weight of transparent armor using commercially available, low cost materials
- Materials by Design Approach
  - Need to understand the role each segment of transparent armor lay-up
  - Select materials based on properties required
  - Test and evaluate
  - Optimize solution

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## ***ARL Glass-Plastic Transparent Armor***

- Studied the role of the different component of the armor
- 1<sup>st</sup> Approach: replace middle glass segment with plastic
- Role of intermediate plys of armor
  - Absorb energy
  - Dissipate amplitude of principal stress
  - Increase footprint of damage zone
- Polymer properties required
  - Transparent
  - Brittle fracture vs. plugging
  - *Exhibit dynamic hardness*
  - Commercially available
  - Thick cross sections
- Initial material tested
  - PMMA in thick cross sections

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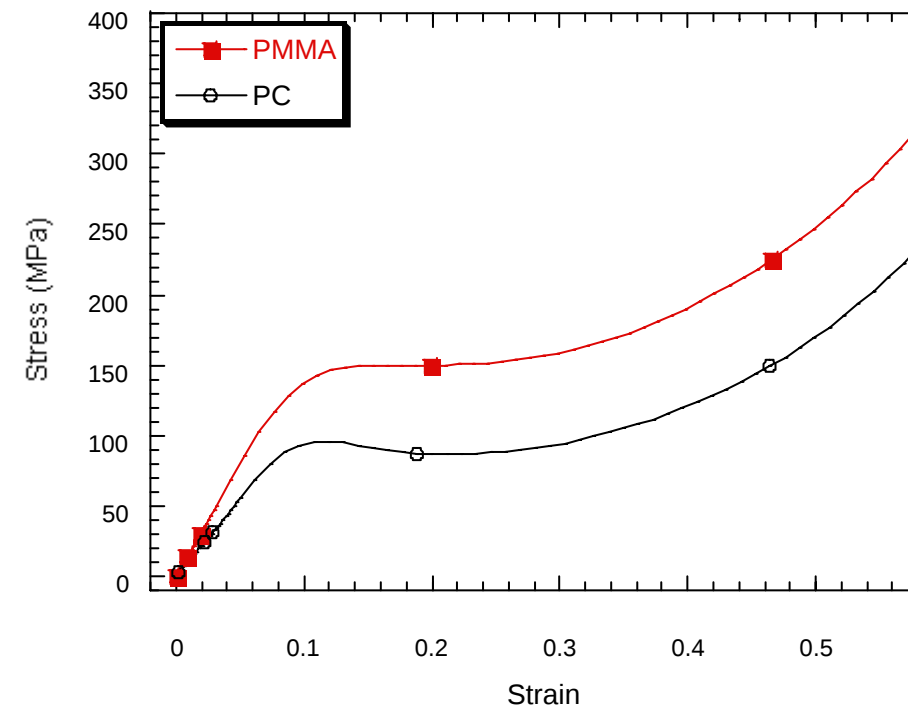
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## *A New Look at the Role of Hard PMMA*



|                               | Lexan PC    | PlexiGlas G PMMA |
|-------------------------------|-------------|------------------|
| <b>Tensile Modulus (MPa)</b>  | <b>2208</b> | <b>3102</b>      |
| <b>Tensile elongation (%)</b> | <b>100</b>  | <b>5</b>         |

### Quasi-static Compression



PC



PMMA

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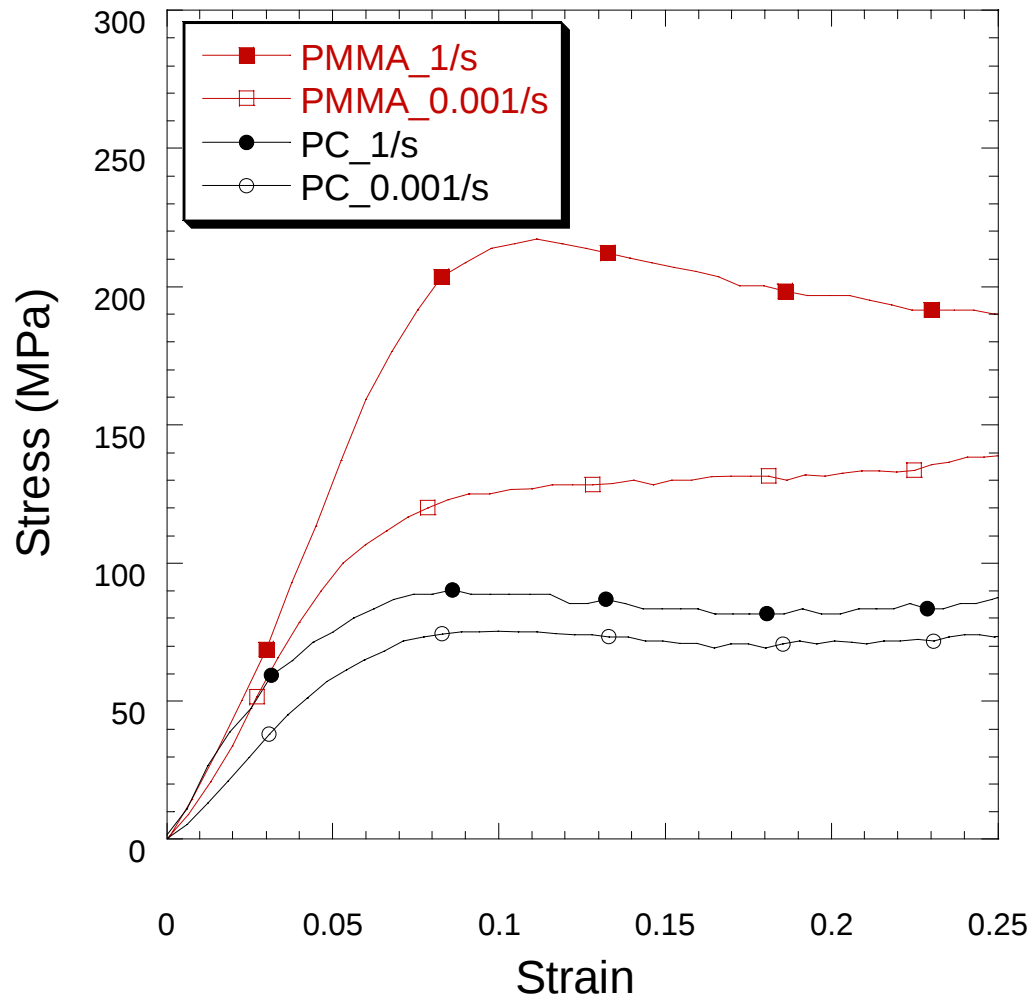


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# Strain-Rate Sensitivity of PMMA and PC

## Uni-axial Compression



## Ballistic Impact



$V_s < V_{50}$



$V_s > V_{50}$



$V_s \gg \gg \gg V_{50}$

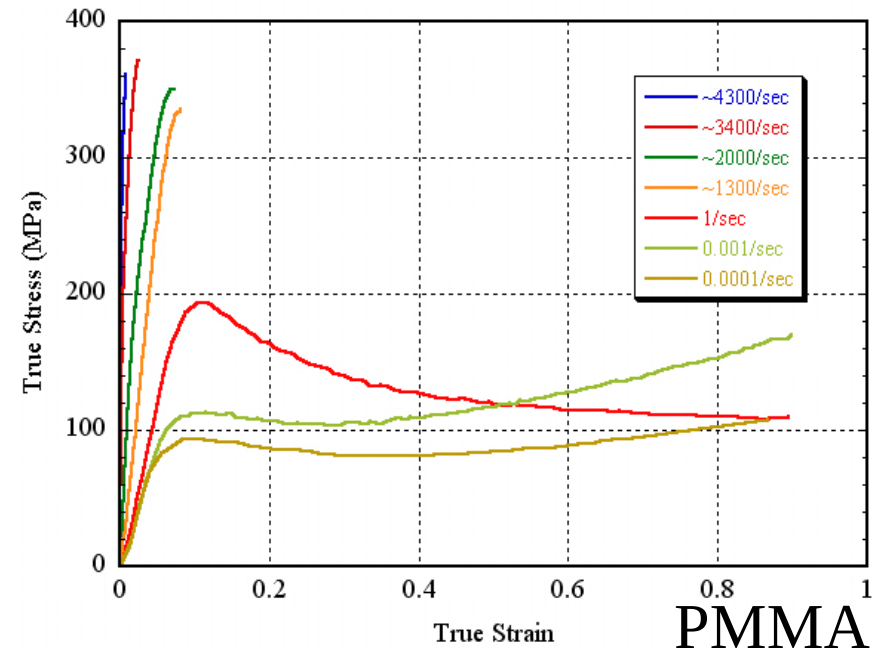
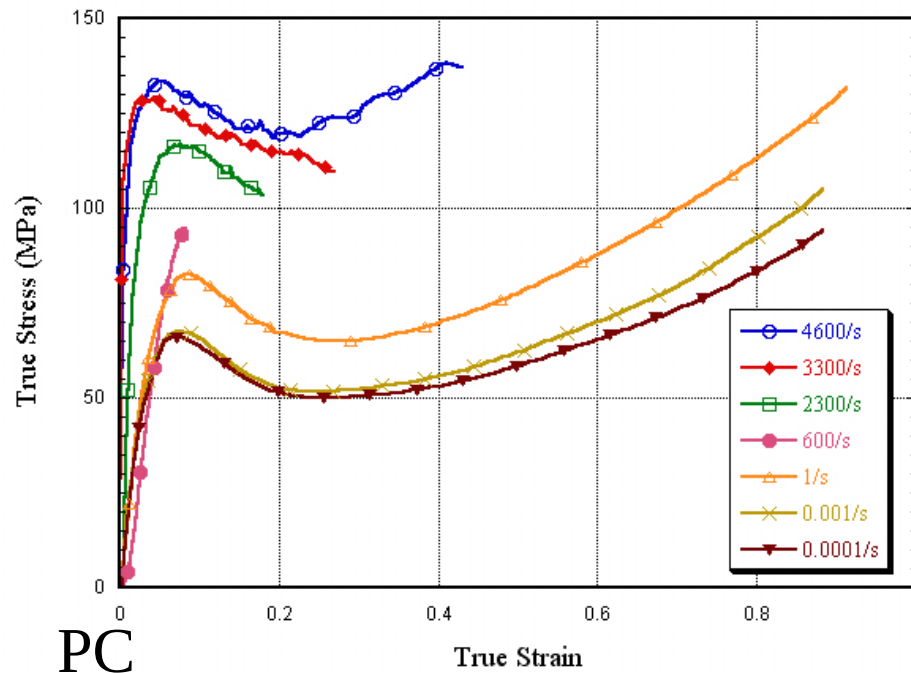
3 mm Thick Monolithic PMMA

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## Split Hopkinson Bar Compression Measurements of PC and PMMA



Moy, Weerasooriya, Hsieh, Chen, SEM (2003).

Moy, Weerasooriya, Chen, Hsieh, ASME IMECE (2003)

PMMA displays significantly higher rate sensitivity and higher dynamic hardness than PC

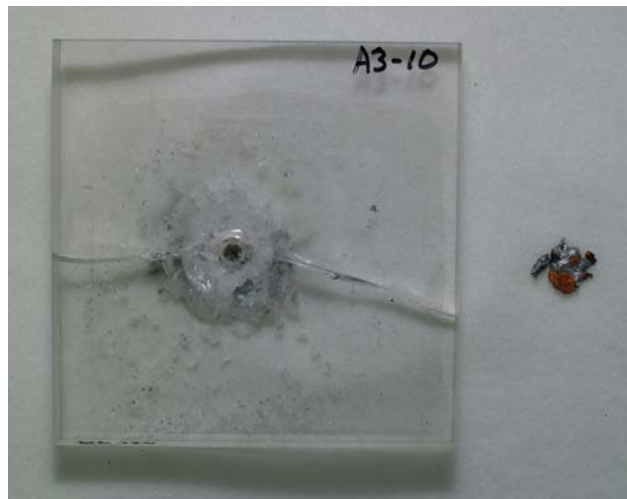
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## Fracture of PMMA vs. PC



Striking  
Velocity

480 m/sec

390 m/sec

399 m/sec

3mm PC/12mm PMMA/3mm PC

3mm PC/12mm PC/3mm PC

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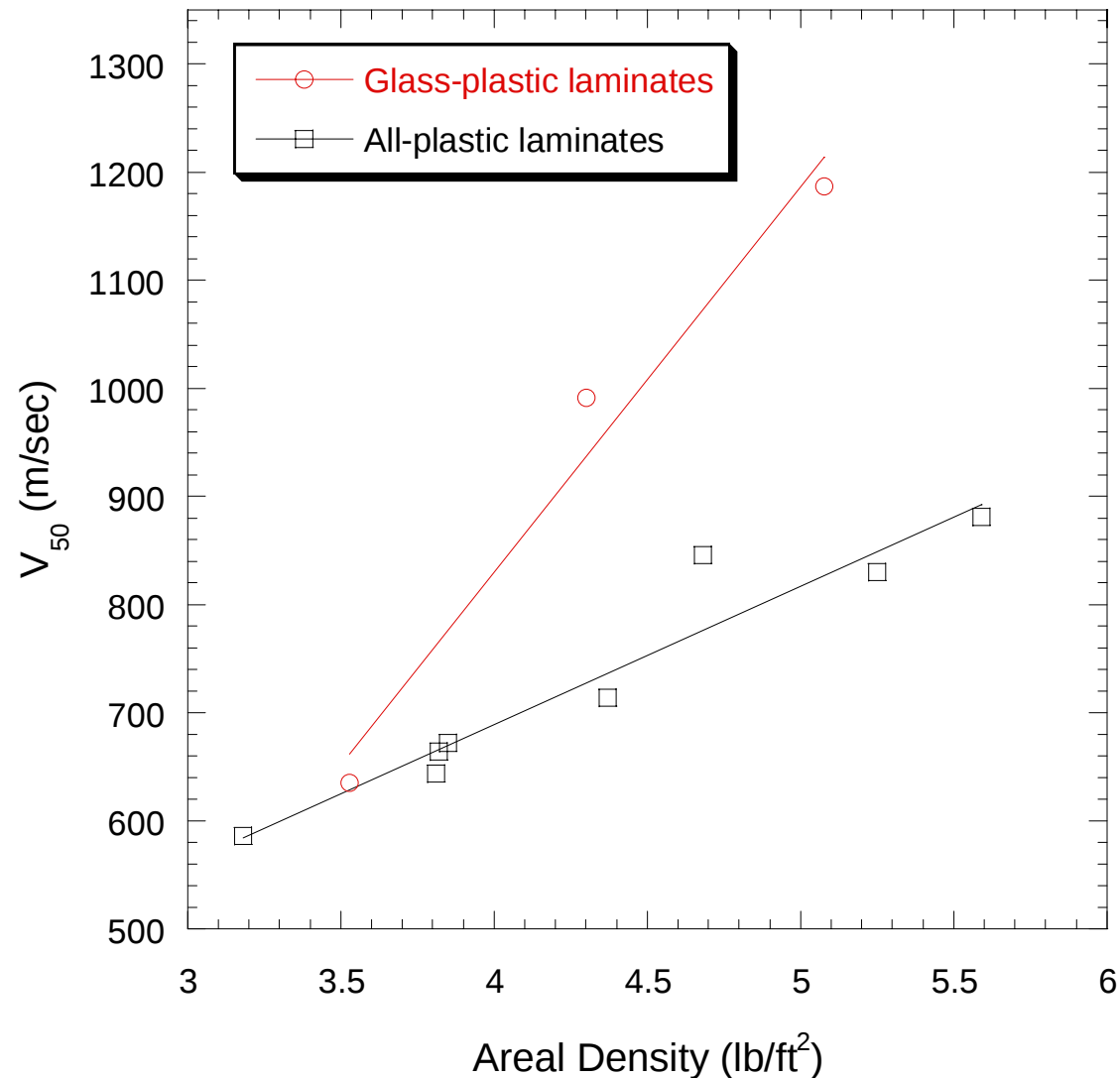
## Dynamic Hardness of PMMA in Glass-Plastic Laminates

### Glass-Plastic

- Constant Strike ply thick
- Vary PMMA thickness

### Plastic-Plastic

- Increase PMMA thickness
- Vary PC to PMMA ratios



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Hsieh et al. ARL-TR-3155, (2004).



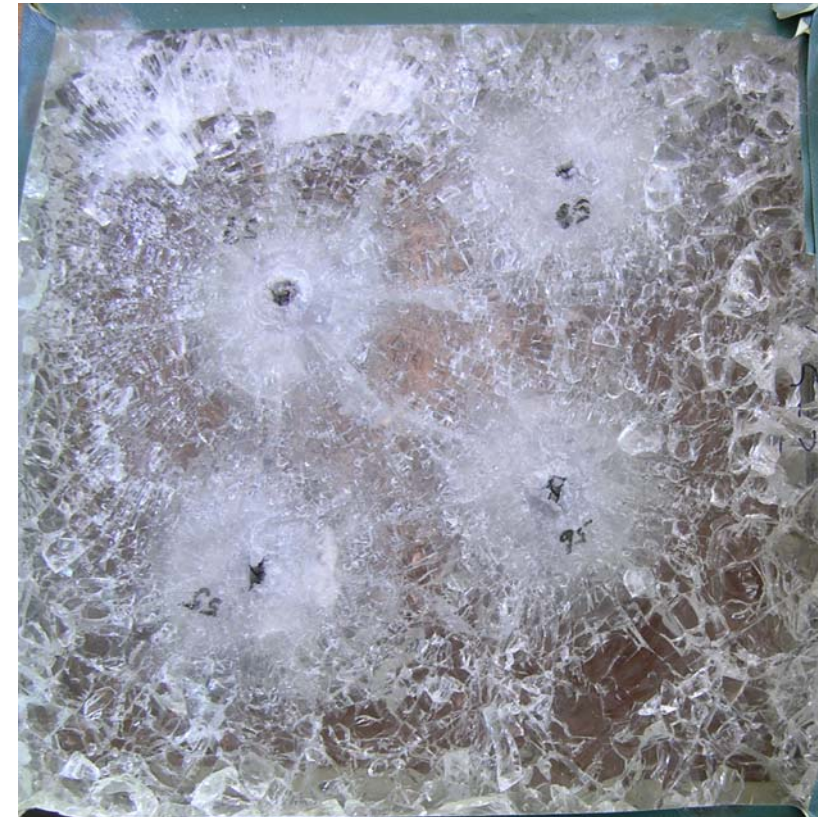
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# ***ARL Glass-plastic Armor***

***(Patents Pending)***



- For small arms threats where
  - Glass can act as the striking ply
  - Fused silica, borosilicate, soda-lime glass, etc.
- Experimental ARL design uses similar materials
  - Unique design using glass and plastic
  - ***Similar cost to conventional***
  - Similar manufacturing processing
  - Significant fragment protection
  - No integration issues



***This ARL design provides multi-hit capability at 25 percent weight reduction (TRL4)***

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## ***Environmental Testing***

- Accelerated aged ARL Glass Plastic Windows for ten months under humidity and temperature cycles
- Observed some degradation at edges but no significant impairment in visibility
- Ballistic testing to compare results to pristine armor
- Conclusion: No reduction in ballistic performance

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## *Conclusions*



- Using a Materials by Design Approach
  - Developed a lighter multi-hit transparent armor using commercially available, low cost materials
- Identified technology gaps
  - Addressed by design optimization
  - Addressed by materials research and development
- Continuing efforts to reduce weight and increase performance

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