MECHANICS OF TRANSPARENT POLYMERIC MATERIAL ASSEMBLIES UNDER PROJECTILE IMPACT: SIMULATIONS AND EXPERIMENTS

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ABSTRACT

Polymeric materials exhibit a wide range in all aspects of mechanical behavior including elastic stiffness, yield stress, crazing versus yielding, post-yield deformation, and failure mechanisms. Recent developments to further manipulate the microstructure of polymers by the incorporation of nanoscale particles further expand the ability to tailor mechanical behavior. Exploitation of the differences in mechanical response of different polymers provides the potential to design multiscale heterogeneous material assemblies that provide dramatic enhancements in energy absorption of projectile impacts while maintaining the light weight of the homopolymer. This paper presents recent research conducted at the MIT Institute for Soldier Nanotechnologies on a study of the high rate deformation and projectile impact behavior of two amorphous polymers which exhibit significantly contrasting deformation and failure behavior: polycarbonate (PC) and polymethylmethacrylate (PMMA). Projectile impact tests were conducted on 6.35 mm thickness plates using a single stage gas-gun. Small (1.4 gm) round-nosed projectiles (5.46 mm diameter) made of 4340 AISI steel were projected into the polymeric plates at velocities ranging from 300 to 550 m/s. High-speed photography was used to visualize the sequence of dynamic deformation and failure events. Numerical simulations of the projectile impact events were conducted using a new constitutive model which captures the high rate behavior of polymers together with finite element analysis. These simulations provide information on the stress and deformation fields in the polymer during projectile impact loading conditions. A new hierarchical material assembly was then designed to alter the stress and deformation fields during impact loading conditions and thus enable greater energy absorption; the new design capitalizes on the contrast in mechanical response between PC and PMMA, in particular on the differences in their inelastic deformation and failure mechanisms, and also takes into account the length-scales of the stress and deformation disturbances resulting from the projectile impact. The new material assembly designs were fabricated, tested, and found to provide strong improvements in the energy absorption of the projectile impact with no weight penalty.

1. INTRODUCTION

Polymers are an appealing choice for many armor related applications due to their rate dependent mechanical properties, low densities, low cost, dimensional stability and high durability. The applications range from visors, shields, windows, canopies, and portals of vehicles to non-transparent composite body armor. A comprehensive understanding of the dynamic behavior of polymers is essential. The high strain-rate properties of polymers are studied under ideal loading conditions with equipment such as the Hopkinson bar. For armor studies, it is also necessary to study the effects of shock loading during high velocity impact. These studies are often conducted experimentally with gas-guns, high-speed photography and flash-radiography.

Previous studies have predominantly concentrated on polycarbonate. Wright *et al*., 1993, studied the impact of cylindrical projectiles on PC plates of varying thickness. They identify five main types of plate behavior: elastic dishing, petalling, deep penetration, cone cracking and plugging. Numerical analyses with finite element codes play a consequential role in the evolution of understanding. Nandlall and Chrysler, 1998, used LS-DYNA2D to simulate the ballistic performance of PC plates under impact by spherical and fragment simulating projectiles. They adjust the erosion constant in a simple hydrodynamic elastic/plastic model to fit the residual velocity data over a range of impact conditions. Composite armors usually involve the combination of high stiffness and resilient materials. In the past, most polymer-based composite armors have been fabricated in the form of laminates and/or fiber-reinforced thermosets.

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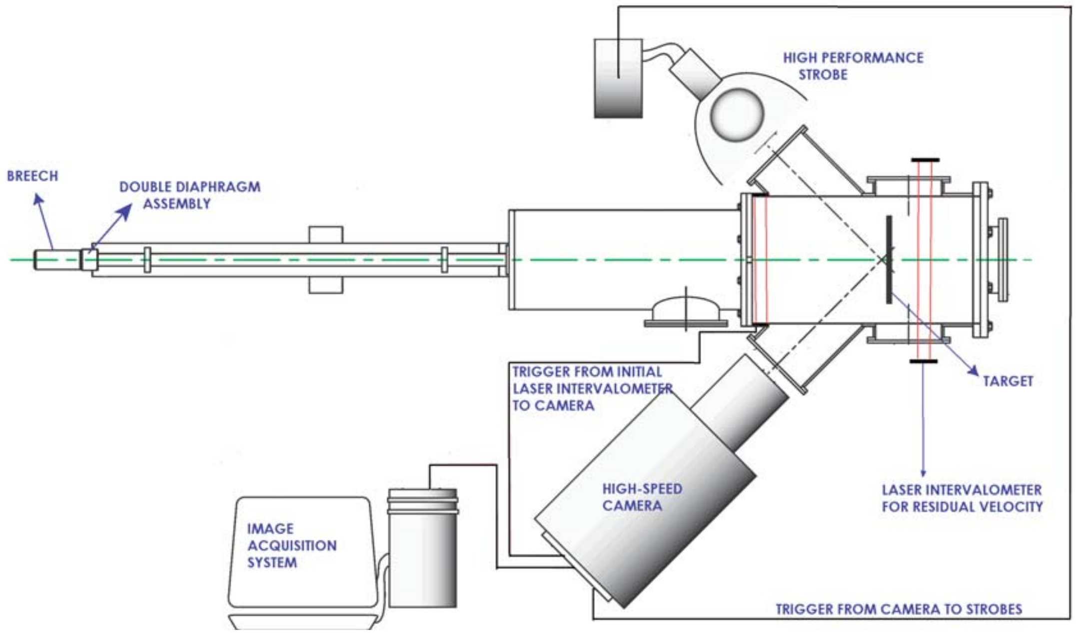


Figure 1. Schematic of experimental set-up

For transparent armor applications, laminates are usually manufactured from PC, PMMA, ceramics and glass; Patel *et al.*, 2000; Dehmer and Klusewitz, 2002; Hsieh *et al.*, 2004. Though laminates improve the mechanical properties considerably and are easy to manufacture, they are prone to poor modes of failure. Often, cracks induced in the more brittle and stiffer components travel extensively, which limits structural integrity. Hence, resourceful designs that address these inadequacies are necessary.

2. INVESTIGATION PROTOCOLS

2.1 Experimental Protocol

2.1.1 Single stage gas gun

A 12.7 mm bore gas-gun is used to perform projectile impact tests of polymeric samples. The barrel is 2.13 m long and nitrogen is used as the pressurizing gas. The breech is capable of pressures up to 10,000 psi (690 bar). A double diaphragm assembly is burst to propel the projectile at the requisite speed. A four piece fly-away sabot helps launch the projectile. Figure 1 shows a schematic of the experimental set-up. The sabot and projectile separate in the middle separation chamber. A sabot stopper at the end of this chamber stops the sabot pieces and allows the projectile to travel further. The sample is mounted on a steel frame and clamped on the top and bottom edges. The initial and residual velocities of the projectile are measured with laser ribbon inter-valometers. After the perforation of the sample, the projectile is arrested and recovered with the help of paper stacks. A Cordin 32 frame rotating mirror high-speed digital camera, which is capable of acquiring images at a frame rate of 2 million fps, is used to photographically record the dynamic event. The camera is triggered by the initial velocity sensor and a built-in trigger delay is used to synchronize it with the event. The camera in turn triggers a high performance strobe for better illumination.

2.1.2 Projectile design

The projectiles are made of 4340 AISI steel. The projectile diameter is 5.46 mm and its length is 8 mm. The injection-molded sabot is made of glass-filled epoxy. The projectile and sabot assembly weigh about 3.2 gm; see Figure 2. The projectile design is shown in Figure 3. The rounded nose helps minimize the scatter in data. It also minimizes contact and meshing problems during finite element simulations.

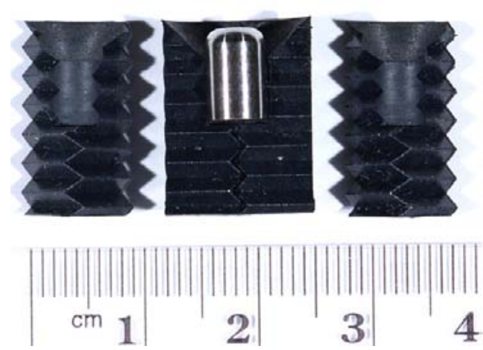


Figure 2. 4-piece sabot and projectile assembly

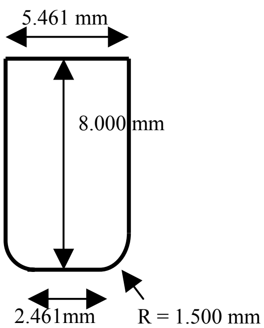


Figure 3. Projectile design

2.2 Modeling and Simulation Protocol

In complementary work, a combined experimental and analytical investigation was carried out in order to better understand the high-rate behavior of glassy amorphous polymers and develop a new three-dimensional large strain rate-dependent elastic-viscoplastic constitutive model. The model was compared to the uniaxial compression data and shown to be predictive of material behavior over a wide spectrum of strain rates; Mulliken, 2004; Mulliken and Boyce, 2004. This new constitutive model was numerically implemented into a commercial finite element code, ABAQUS/Explicit. Preliminary numerical simulations were conducted to study the stress and deformation conditions in polymeric samples under impact.

3. RESULTS

3.1 Monolithic Materials

Studies were performed on two amorphous glassy polymers: PC and PMMA.

3.1.1 Simulations

Simulations were performed to study the impact of a round-nosed projectile on a 6.35mm thickness PC plate. The projectile design was the same as discussed in detail in section 2.1.2. The impact velocity was 300 m/s. Both projectile and plate were modeled as 2-D axi-symmetric and 4-node quadrilateral reduced-integration elements were used. Failure has not yet been incorporated and the results are used for a qualitative understanding only. Current research is addressing the incorporation of material failure mechanisms into the modeling.

Upon impact, compressive waves emanating from the projectile are evident in the contours for displacement in the direction parallel to the projectile flight (Figure 4). The target shows elastic dishing around the impact area. As the projectile penetrates further, elastic deformation rings emanate from the dish, travel outwards and reflect back from the edge of the plate. The evolution and travel of these displacement contours is also seen in Figure 4. Elastic-viscoplastic deformation is evident in the region beneath the projectile; in particular, a concentrated circumferential region of localization that is ultimately responsible for shear plugging failure observed in the experiments (Figure 4d), as discussed next.

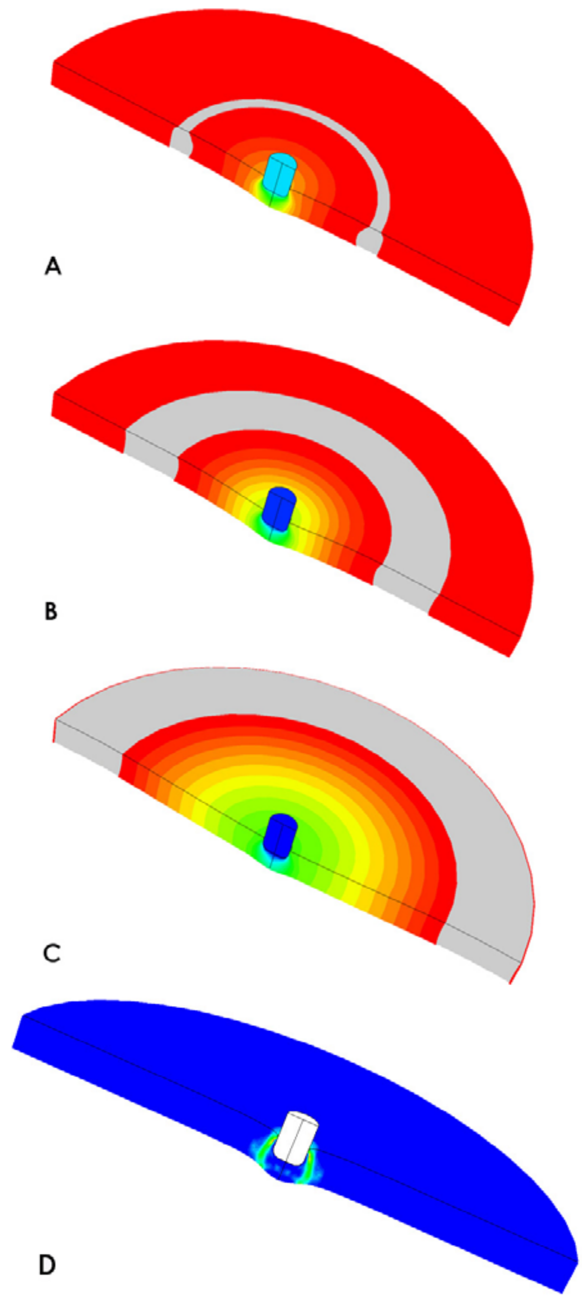


Figure 4. Displacement contours (A: 25 μs, B: 50 μs, C: 100 μs) and plastic strain-rate contours (D: 20 μs) in PC

3.1.2 Experimental results

Experiments were performed on Lexan™ 9034 PC and PlexiGlas™ G PMMA plates (100 mm × 100 mm) acquired from GE Polymershapes. The homopolymer samples were impacted by projectiles at velocities ranging from 300 to 550 m/s. At these velocities, the projectiles perforated the 6.35 mm thickness samples. The incident and the residual velocity of the projectile were measured in each experiment, to evaluate the absorbed energy.

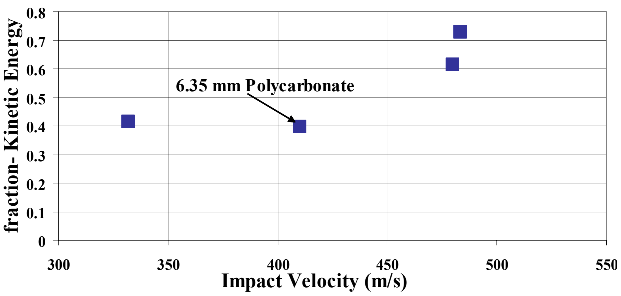


Figure 5. Residual kinetic energy of 6.35 mm thickness PC after impact

The residual kinetic energy fraction, $f_{K.E}$ was calculated by normalizing the residual kinetic energy by the initial kinetic energy of the projectile. If it was determined by the high-speed images that the projectile yaw was more than 10 degrees, the data was discarded. Figure 5 indicates that, as expected, the residual kinetic energy for PC increases with increasing impact velocity.

High-speed photographs

The failure and deformation modes were examined by means of high-speed photography and post-mortem analysis of the recovered samples. Figure 6 shows the high-speed photographs of projectile impact on a 6.35mm PC plate at 331 m/s. Each frame is 25 μs apart. Soon after impact, elastic dishing is observed in the target area surrounding the projectile. As the projectile penetrates further the dish extends in size. The circumferential area around the dish bulges in the direction that is opposite to impact as predicted by the simulations.

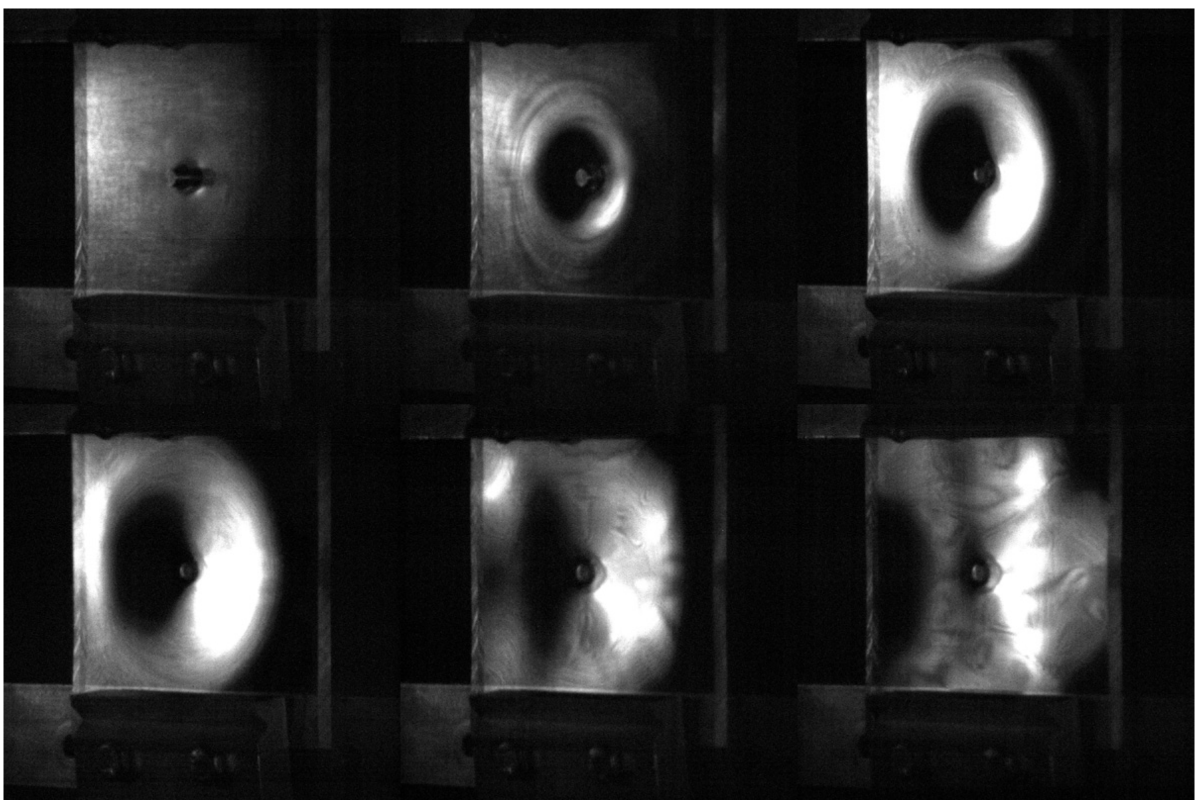


Figure 6. High-speed photographs of impact on 6.35 mm PC plate at 331 m/s (each frame is 25 μs apart)

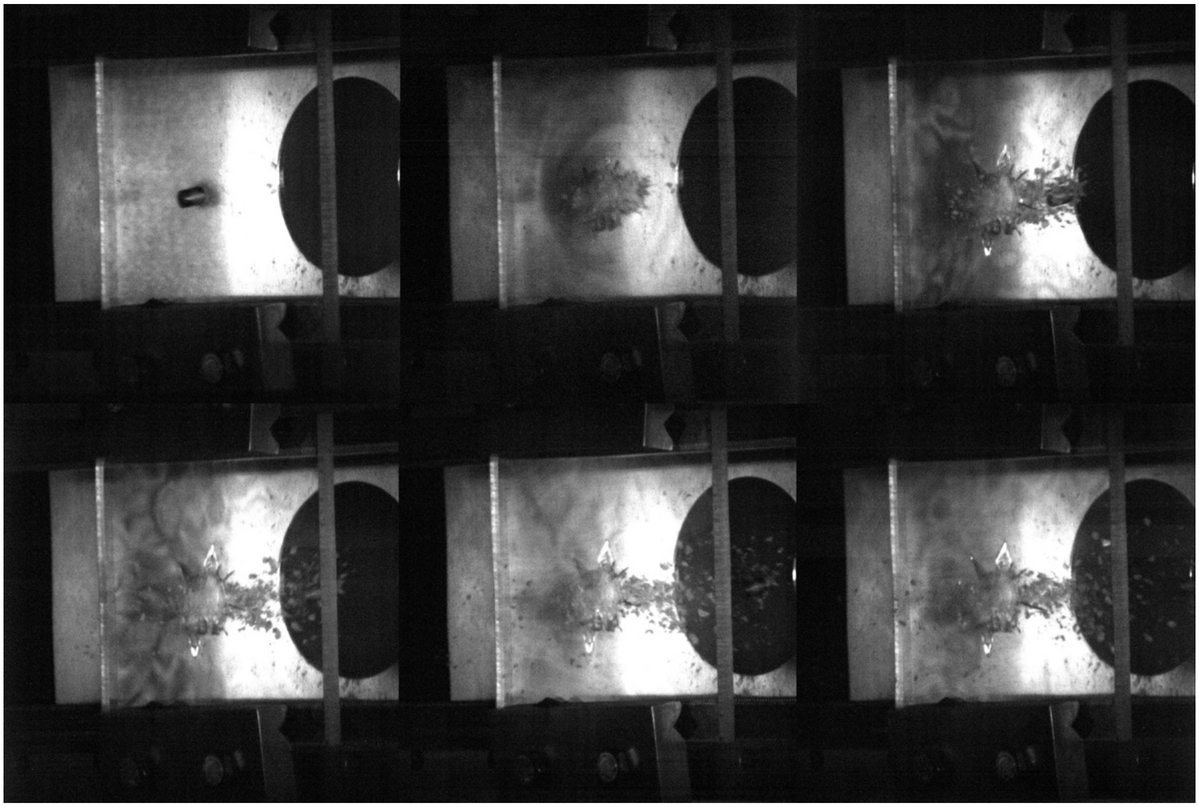


Figure 7. High-speed photographs of impact on 9.25 mm PMMA plate at 430 m/s (each frame is 25 μs apart)

The experimentally observed dynamic deformation contours and the time scales of their movement match reasonably well with those generated in the simulations shown in Figure 4. The projectile perforates the sample by shear plugging and very little plastic deformation is observed in the material immediately adjacent to the plug, further demonstrating the highly localized shear deformation. The failure is locally ductile and no radial cracking is observed. For the above shot, the residual velocity of projectile is 213 m/s. The recovered projectile shows no visible damage.

Figure 7 shows high-speed photographs of the impact on PMMA at 430 m/s. It is observed that the failure is much more brittle. The zone of impact indicates a large number of micro-cracks in the immediate region of the projectile impact. In addition, a few large radial cracks are seen to grow towards the edge of the sample. Extensive spall is observed from the rear surface. This spall interferes with the measurement of the residual velocity and the consequent calculation of absorbed energy. The recovered projectile shows no signs of damage. Additional comparison of the ballistic performance of PC and PMMA homopolymers can be found in Hsieh *et al.*; 2004.

3.2 Hierarchical Material Assemblies

Homopolymers are inadequate at providing superior protection individually but offer the potential to exhibit enhanced ballistic performance when assembled in combination with complementary materials. A new hierarchical material assembly, which improves the impact resistance and also helps inhibit catastrophic failure after impact, is proposed.

3.2.1 Design

The composite material assembly involves distribution of discrete lightweight components such as platelets, discs, tablets etc. in a continuous matrix of another lightweight material; see Figure 8. The materials for the discrete components and matrix are chosen such that they exhibit contrasting and complementary mechanical behavior (e.g. hardness, stiffness, ductility, failure modes). The dimensions of the discrete components are considerably smaller in comparison to the matrix. In addition to the choice of various materials, a number of geometrical parameters such as the size and distribution can be controlled. An understanding of the effect of each of these parameters on the energy absorption characteristics can lead to tailoring of the properties for optimum performance based on the impact conditions.

The distribution of these platelets can be random, graded or ordered (e.g. planar array). When dispersed along multiple layers, a configuration in which platelets along adjacent layers are slightly offset but still overlapping will provide a more efficient method of load/deformation/energy transfer from the projectile to the assembly. For transparent armor applications, all elements of the assembly can be chosen to be transparent.

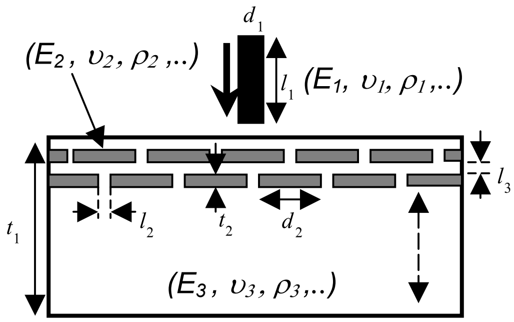


Figure 8. Hierarchical material assembly

The parameters that can be explored are numerous and an in-depth experimental study of the effect of each of these parameters would be extremely time consuming and expensive. Numerical simulations provide an invaluable tool in the facilitating of understanding and the guiding of experimental studies of these assemblies.

3.2.2 Simulation results

To study the effect of interaction between discrete components in a hierarchical assembly, simulations were conducted on a simplified assembly. The design is shown in Figure 9. The design was also used for experimental validation. A 6.35 mm thickness plate of PC with distributed platelets of PMMA was considered. The plate had the PMMA platelets distributed over six planes. Alternate layers containing one platelet (2.54 cm diameter, 0.79 mm thickness) and four platelets (each 1.9 cm diameter, 0.79 mm thickness) respectively were arranged in an ABABAB configuration. The layers embedded with one platelet had the platelet located centrally and aligned normal to the line of flight of the projectile. On alternating layers, the four platelets were arranged along a circle around the axis of impact in a symmetric fashion. Each platelet was offset from the center such that it partially overlapped with the single platelet in the layer above/below. For simulations, the PMMA discs were also described by the material model developed by Mulliken, 2004. The model parameters for PMMA were separate from those for PC and were derived from experimental studies on PMMA.

Figure 10 shows the comparison of Mises stress contours induced in a monolithic PC plate with those induced in a hierarchical assembly sample. Figure 11 shows the comparison of plastic strain-rate. It is observed that the overlapping discs increase the interaction zone between the projectile and the target by forming a network of interacting components.

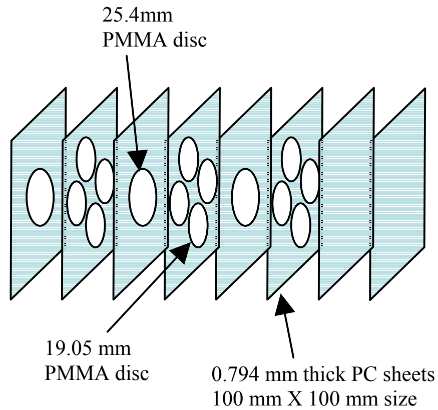


Figure 9. Design of simplified hierarchical assembly

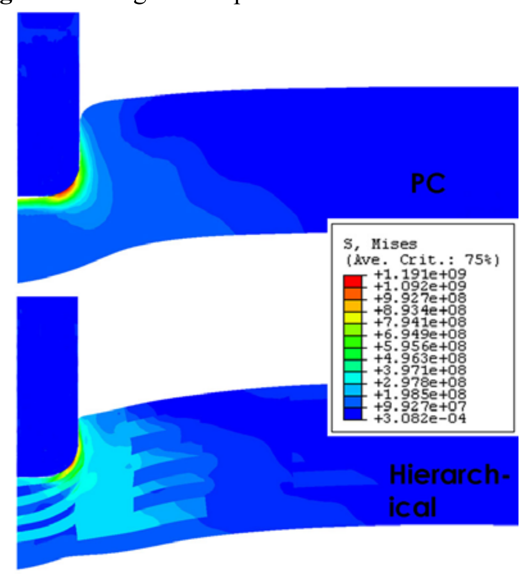


Figure 10. Comparison of Mises stress at 20 μs

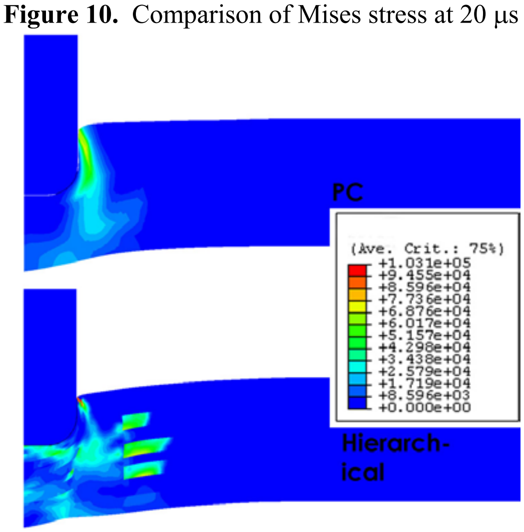


Figure 11. Comparison of plastic strain-rate

To compare the penetration resistance, the kinetic energies of the projectiles are compared in Figure 12. The kinetic energy is consumed at a higher rate for the hierarchical assembly sample, indicating an increased energy absorption and faster arrest. Numerical simulations also predict that the depth of penetration for the hierarchical sample is nearly 40% less than the monolithic sample. It should be noted again that since failure has not been incorporated, this is a qualitative comparison only.

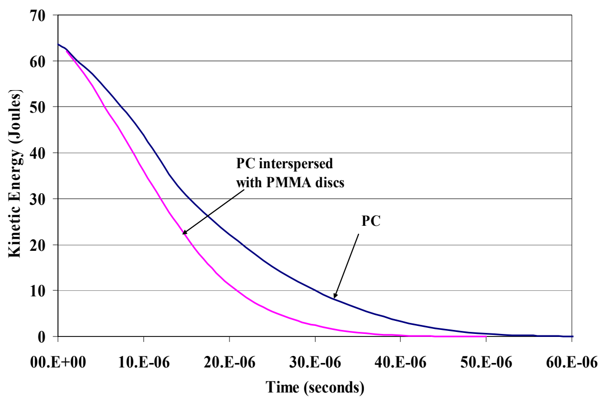


Figure 12. Comparison of the K.E of projectiles

3.2.3 Experimental results

Hierarchical assembly samples were prepared in two simplified designs. *Assembly-1*: These samples had 6 layers of PMMA discs distributed through a PC sample (the design is discussed in section 3.2.2). *Assembly-2*: The layout of this design was similar to Assembly-1, but only two layers of PMMA discs were distributed. One single PMMA disc (3.81 cm diameter, 1.59 mm thickness) was located centrally and on the next layer, four PMMA discs (2.54 cm diameter, 1.59 mm thickness) were arranged in a circle, offset from the center but overlapping with disc in the plane above. The assemblies were prepared with a hot press by bonding the samples above the glass transition temperature.

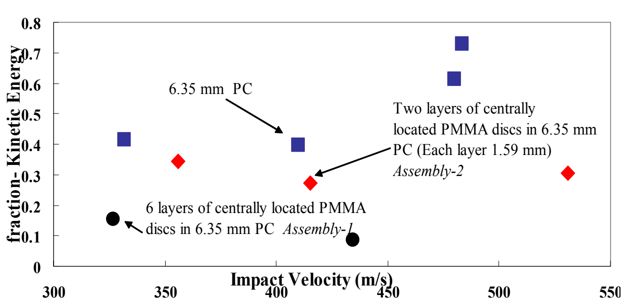
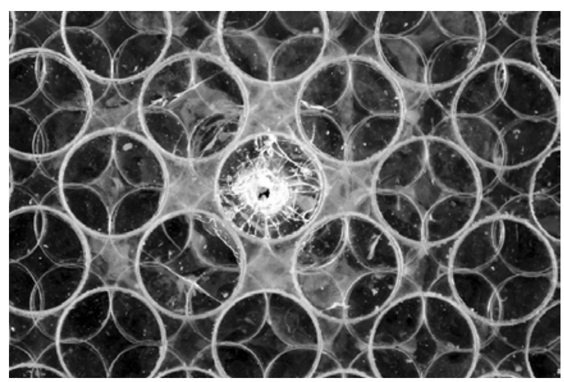


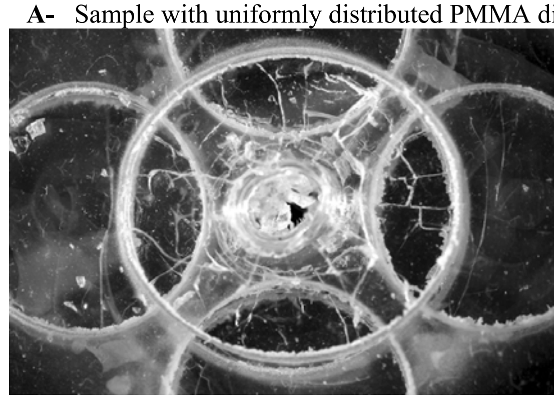
Figure 13. Comparison of residual energy

In Figure 13, it is observed that the residual kinetic energy fraction (f_{KE}) for monolithic PC plates is 0.41 at an impact velocity of 331 m/s and 0.39 at a velocity of 410 m/s. Under similar impact conditions, the f_{KE} for hierarchical assembly samples with six layers of PMMA discs [Assembly-1] is 0.15 and 0.08. This indicates that the residual energy upon exiting the armor is reduced by 65-75%. Since the densities of PMMA and PC are similar, this improvement is achieved without the expense of additional mass. Amongst the hierarchical assemblies, six layer PMMA samples [Assembly-1] perform better than the samples with two layers of PMMA discs [Assembly-2], which can be attributed to a larger amount of PMMA interacting with the projectile. Furthermore, the damaged zone is contained.

Figure 14 shows the impact zones of recovered hierarchical assembly samples. As can be seen, the brittle failure of PMMA discs is confined locally. The cracks are arrested at the matrix-platelet interface. It is also observed that the platelets which are not directly in the line of impact show failure/damage, indicating that the effect of overlap is successful. Figure 15 shows the rear surface view of a failed sample. A large back plate plug is observed. This indicates that, unlike PC, in which no residual damage is observed outside of the perforation area, the interaction zone between projectile and assembly sample is much larger. Hence, a greater amount of kinetic energy is absorbed and the impact is spread over a wider area.



A- Sample with uniformly distributed PMMA discs



B- Sample with 6 layers of PMMA discs [Assembly -1]

Figure 14. Cracks arrested at matrix-platelet interface

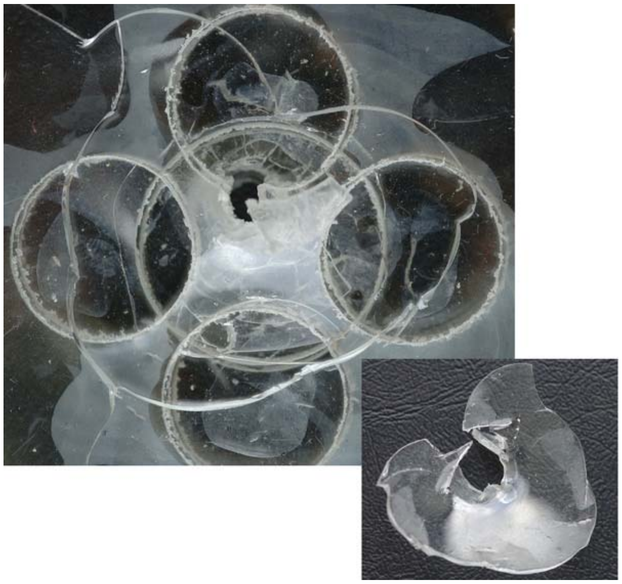


Figure 15. Rear view of a failed assembly sample

4. SUMMARY

Impact-perforation tests were performed on PC and PMMA plates at velocities ranging from 300 to 550 m/s. The failure and energy absorption mechanisms have been studied using high speed photography and numerical simulations.

A new hierarchical material assembly has been implemented. The hierarchical assembly distributes discrete components in a continuous matrix. The components and matrix are chosen to have contrasting mechanical deformation and failure mechanisms and properties. The impact failure zone is magnified due to an interacting network created by the arrangement of these discrete components. This leads to an activation of multitude of energy absorption regions. The matrix which has high ductility acts to accommodate the failure and deformation of the components and contain the structural failure to the impact zone. This helps maintain the structural integrity during and after impact. An in-depth finite element analysis of the effect of various geometric parameters on the energy absorption mechanisms is required.

In the future, the hierarchical assembly can be extended to include more than two materials with different properties. It can also be extended to include material constituents, which are not monolithic but composites themselves at a smaller length scale.

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Institute for Soldier Nanotechnologies

ASC2004

Introduction

Amorphous polymers (*e.g. Polycarbonate, Polymethylmethacrylate*)

- Find extensive usage in impact related applications requiring optical transparency (civilian and military)
- Exhibit strain rate sensitivity
- Exhibit varied modes of failure ranging from ductile to brittle

visors, riot gear, vehicular windshields, windows, canopies etc.

Impact resistant application requirements

- Maximum energy absorption to improve survivability
- Minimal weight to enhance mobility
- Minimal structural damage after impact
- Inexpensive and ease of construction

Approach

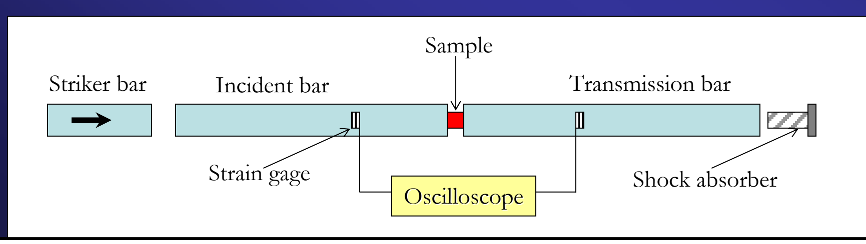
Mechanical Testing
- Quasistatic (Instron)
- Dynamic (Hopkinson bar, Gas gun)
- Dynamic Mechanical Analysis

Failure Mode Analysis
- Post-Mortem
- High Speed Photography
- Microscopic Characterization

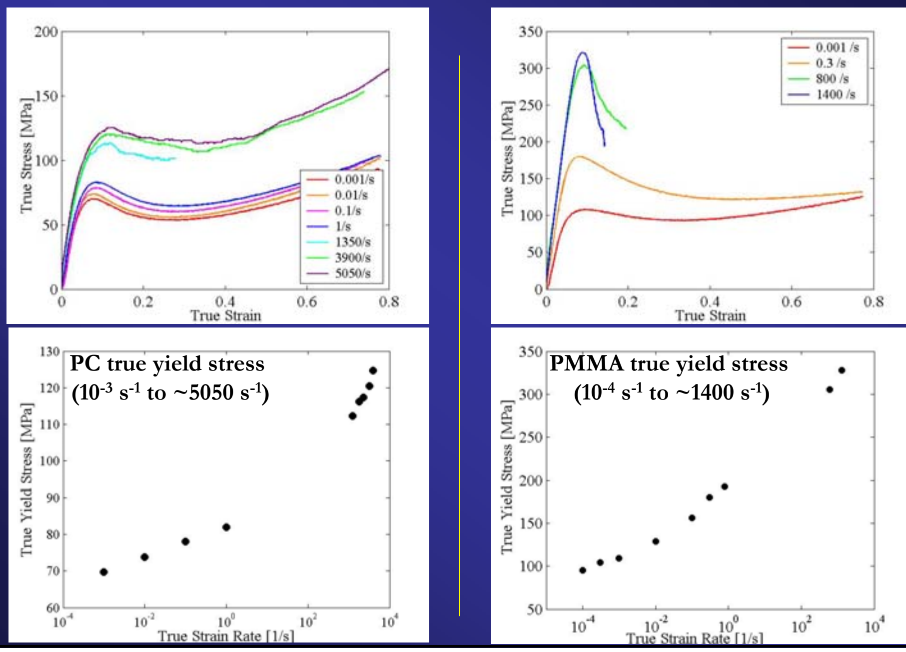
Physically based models
Computational implementation

Better design
Predictive ability

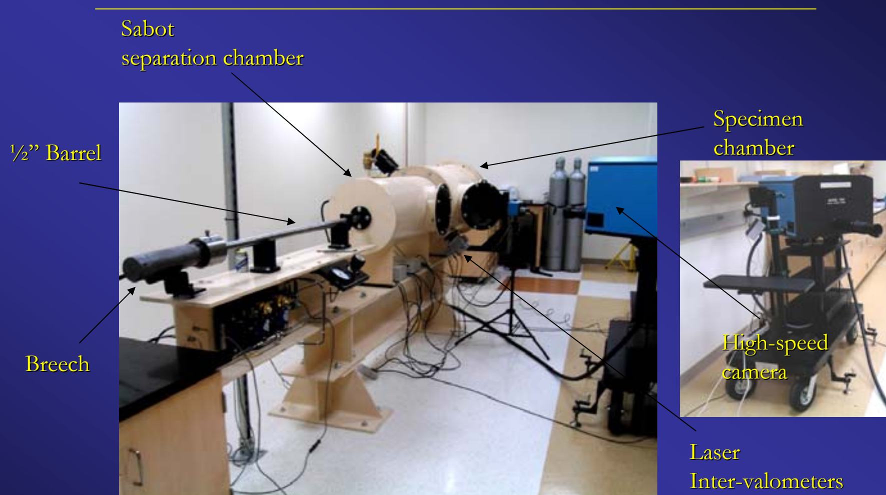
Hopkinson Bar at ISN High-rate Lab



Strain rate sensitivity in PC and PMMA

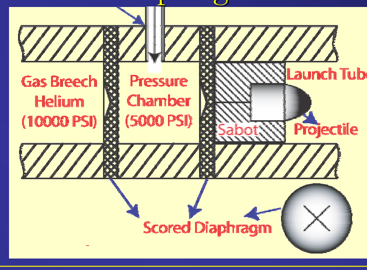


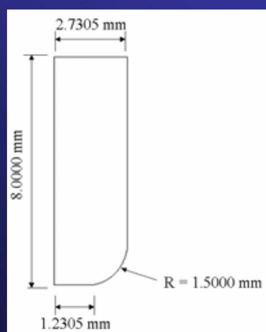
Experimental Techniques-Single Stage Gas Gun



- Capable of 10,000 psi breech pressure by means of a compressor gas booster system
- Current tests have been performed at pressures ranging from 900 psi to 2500 psi (He or Ni)
- Under these conditions, projectile velocities range from 350 m/s to 800 m/s for a 3 gm projectile-sabot assembly

Double Diaphragm Assembly





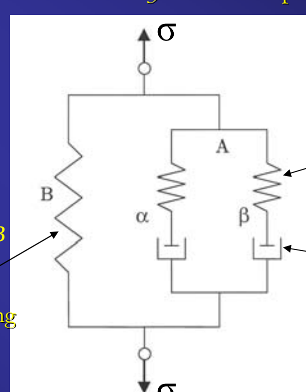
Mass – 1.4 gm
Material – AISI 4340 steel

4 piece fly-away sabot and projectile

Computational Modeling

Constitutive model built by *Mulliken and Boyce* and incorporated via ABAQUS/Explicit

1D Interpretation:



$$\sigma = \sigma_{A,\alpha} + \sigma_{A,\beta} + \sigma_B$$

Elastic spring

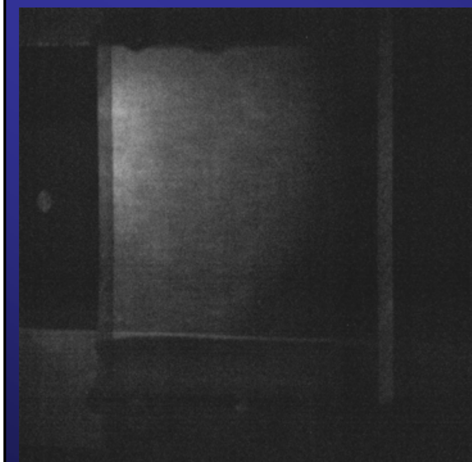
Viscoplastic dashpot

Non linear spring

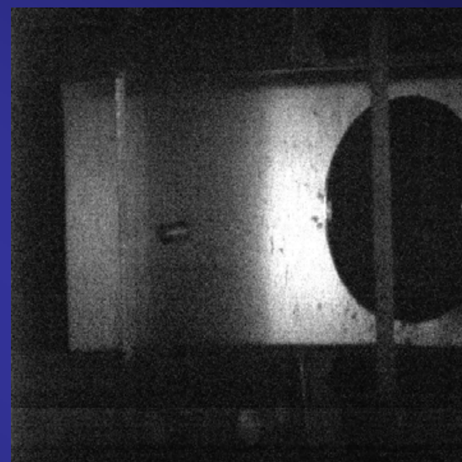
A: intermolecular resistance to chain segment rotation
(α – rotations of main-chain segments β – rotations of ester side [PMMA] or phenyl [PC] group; dominant at high rates)
B: captures entropic strain hardening due to chain alignment

Model implemented to predict the elastic-viscoplastic high strain rate behavior of PC and PMMA

Impact Behavior of Monolithic Polymers



¼" (6.35 mm) PC, 331 m/s



¼" (6.35 mm) PMMA, 785 m/s

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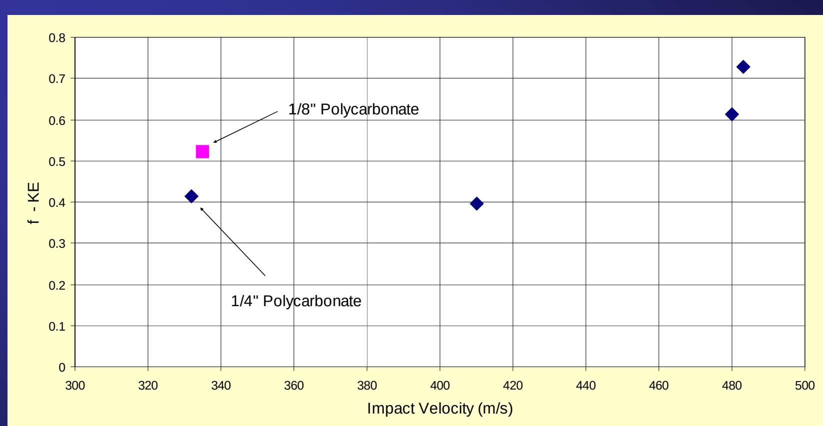

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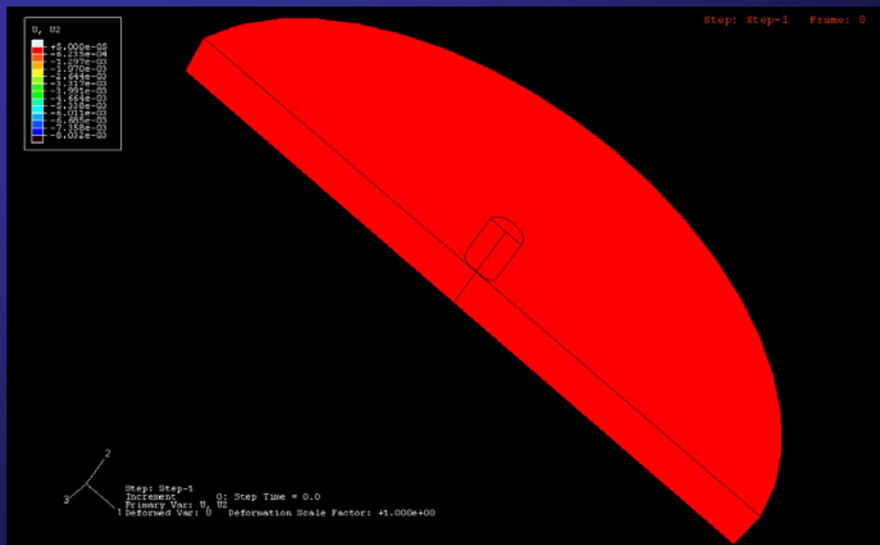

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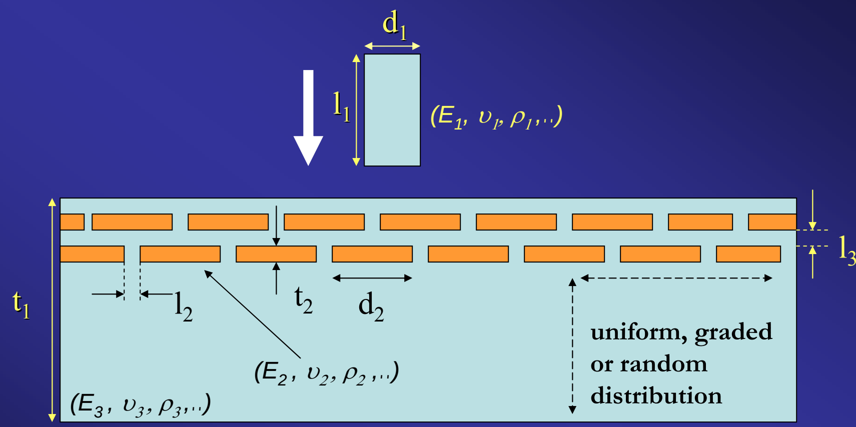

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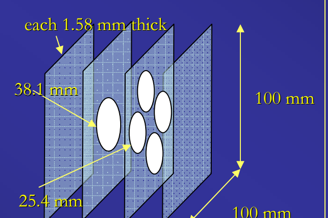

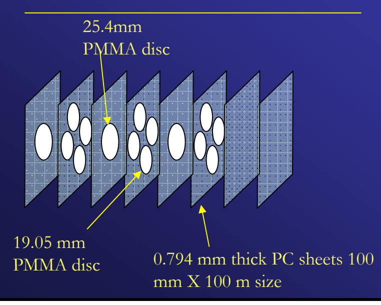

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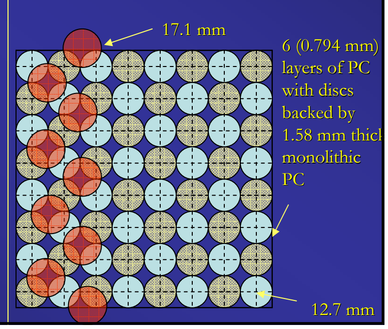
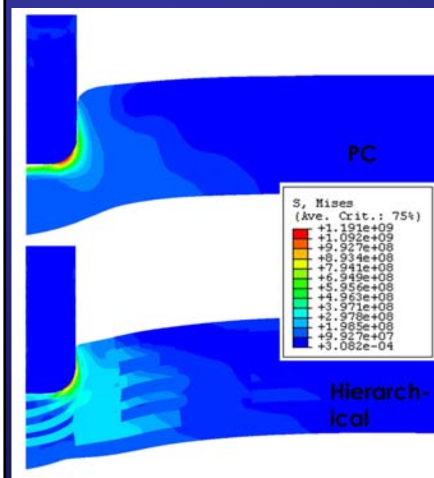
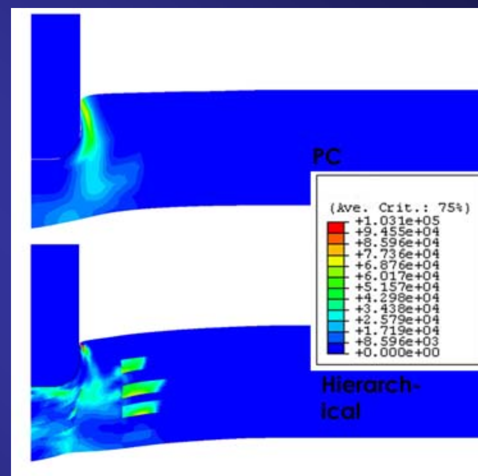


Comparison of the induced stress fields

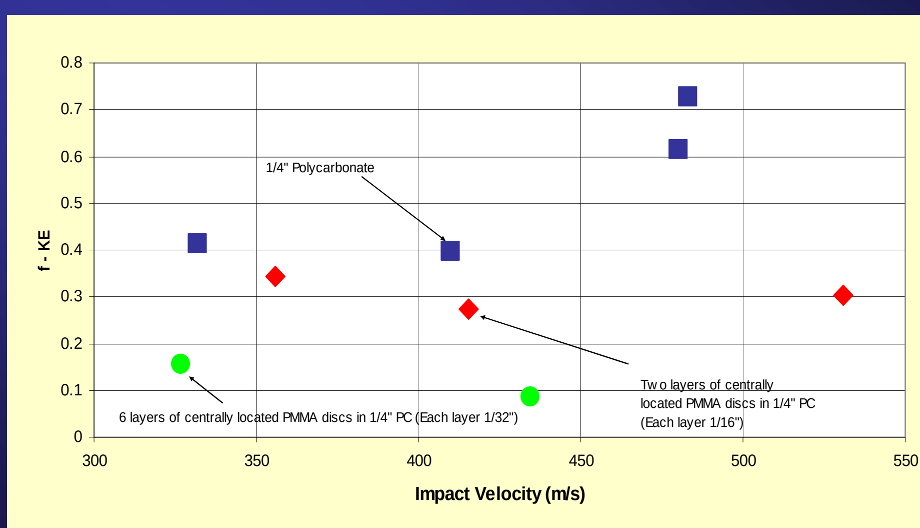


Mises Stress

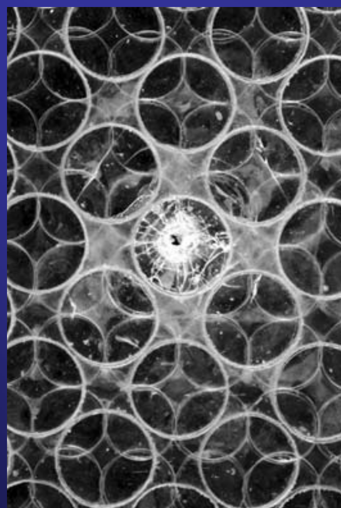


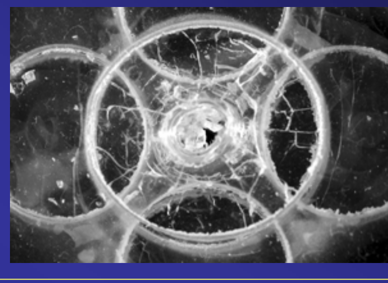
Plastic Strain-rate

Comparison of performance



Cracks arrested at the platelet-matrix interface





Rear surface shows large plug formation

Summary

• A new hierarchical assembly design has been implemented

• Improved energy absorption due to synergistic interactions between discrete components increasing the interaction zone between projectile and target

• Failure is restricted to the impact zone, thus preventing catastrophic failure and helping retain structural integrity

• The design can be extended to non transparent materials

• The design can also be extended to new age materials at lower scales (micro, nano)

• For implementation improved processing methods are required to enhance transparency

• Drop weight tests can help understand failure initiation and evolution

Acknowledgement – Research supported by US Army Research Office under contract DAAD-19-02-D0002 with MIT

Mechanics of Transparent Polymeric Material Assemblies under Projectile Impact: Experiments and Simulations

Sai Sarva, Adam D. Mulliken, Prof. Mary C. Boyce
Mechanical Engineering
Massachusetts Institute of Technology

Alex J. Hsieh
Army Research Laboratory

December 1st, 2004

Institute for Soldier Nanotechnologies

ASC2004

Introduction

Amorphous polymers (*e.g. Polycarbonate, Polymethylmethacrylate*)

• Find extensive usage in impact related applications requiring optical transparency (civilian and military)
• Exhibit strain rate sensitivity
• Exhibit varied modes of failure ranging from ductile to brittle

visors, riot gear, vehicular windshields, windows, canopies etc.

Impact resistant application requirements

• Maximum energy absorption to improve survivability
• Minimal weight to enhance mobility
• Minimal structural damage after impact
• Inexpensive and ease of construction

Approach

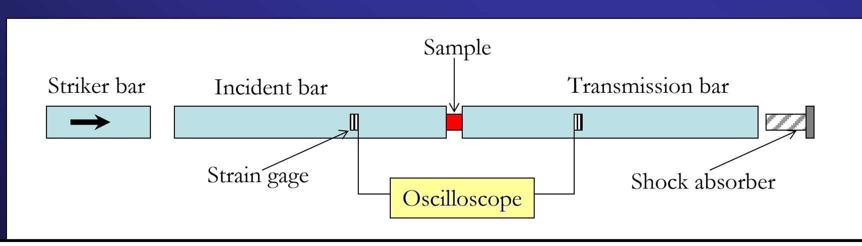
Mechanical Testing
- Quasistatic (Instron)
- Dynamic (Hopkinson bar, Gas gun)
- Dynamic Mechanical Analysis

Failure Mode Analysis
- Post-Mortem
- High Speed Photography
- Microscopic Characterization

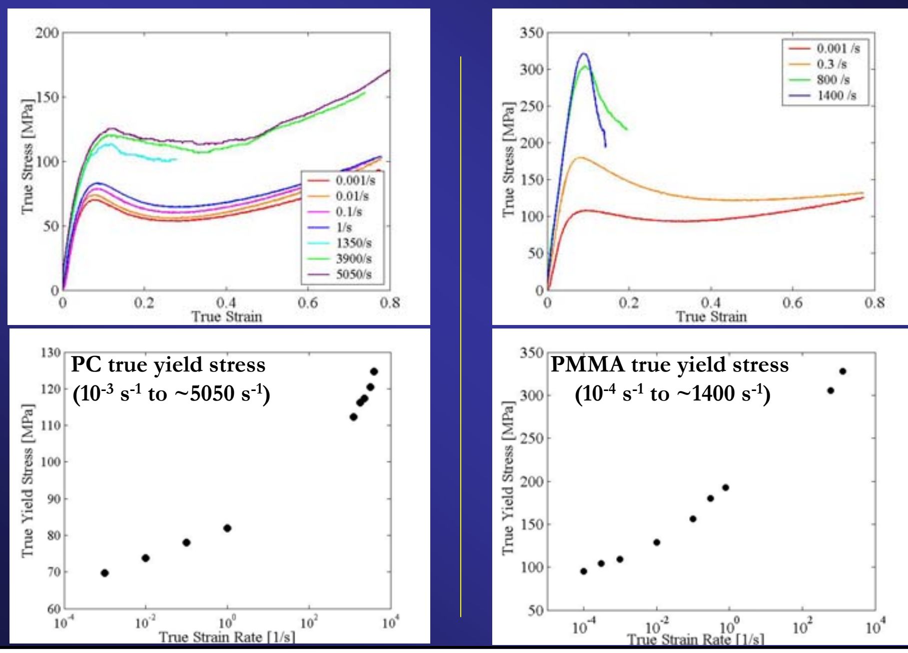
Physically based models
Computational implementation

Better design
Predictive ability

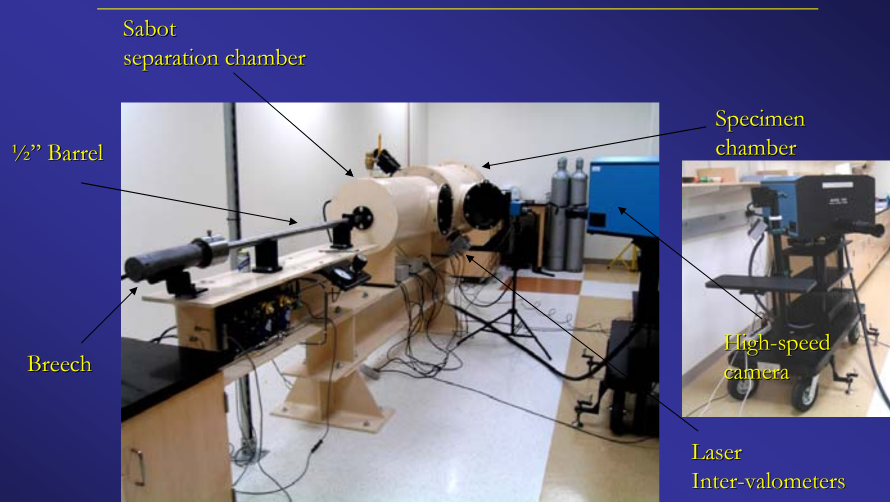
Hopkinson Bar at ISN High-rate Lab



Strain rate sensitivity in PC and PMMA

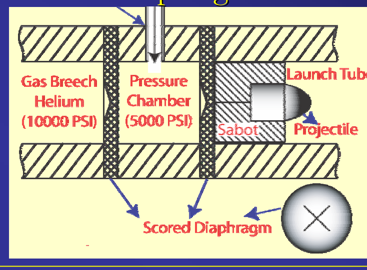


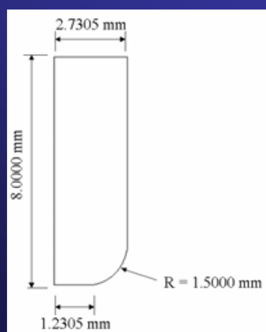
Experimental Techniques-Single Stage Gas Gun



- Capable of 10,000 psi breech pressure by means of a compressor gas booster system
- Current tests have been performed at pressures ranging from 900 psi to 2500 psi (He or Ni)
- Under these conditions, projectile velocities range from 350 m/s to 800 m/s for a 3 gm projectile-sabot assembly

Double Diaphragm Assembly





Mass – 1.4 gm
Material – AISI 4340 steel

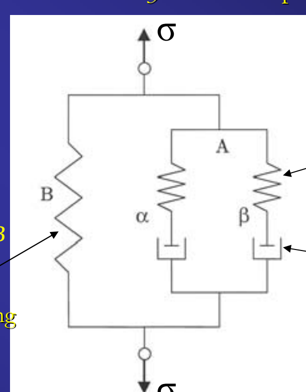
4 piece fly-away sabot and projectile

Computational Modeling

Constitutive model built by *Mulliken and Boyce* and incorporated via ABAQUS/Explicit

1D Interpretation:

$$\sigma = \sigma_{A,\alpha} + \sigma_{A,\beta} + \sigma_B$$



Elastic spring

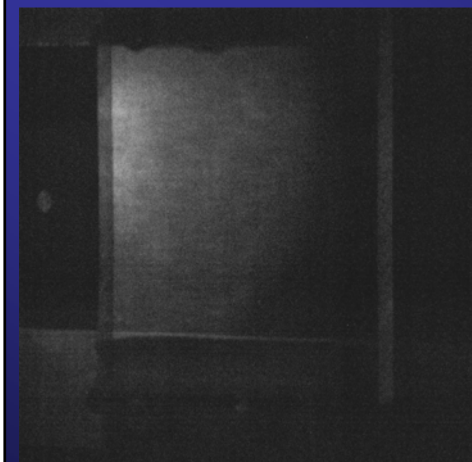
Viscoplastic dashpot

Non linear spring

A: intermolecular resistance to chain segment rotation
(α – rotations of main-chain segments β – rotations of ester side [PMMA] or phenyl [PC] group; dominant at high rates)
B: captures entropic strain hardening due to chain alignment

Model implemented to predict the elastic-viscoplastic high strain rate behavior of PC and PMMA

Impact Behavior of Monolithic Polymers



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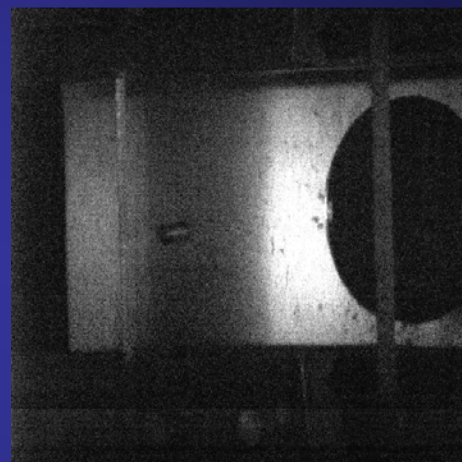

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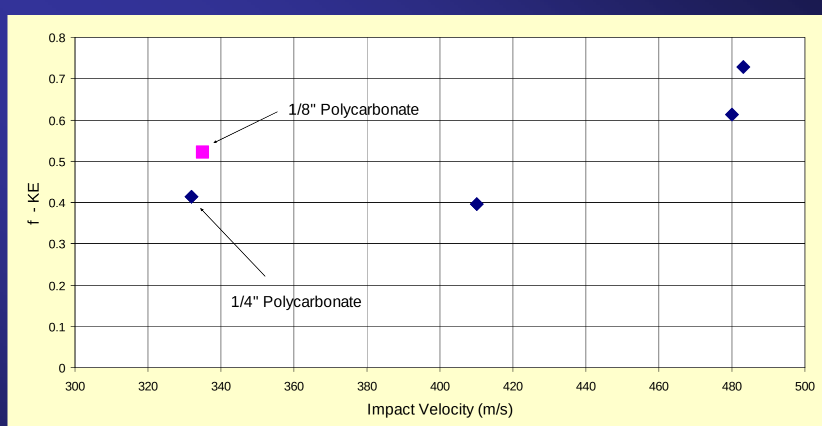

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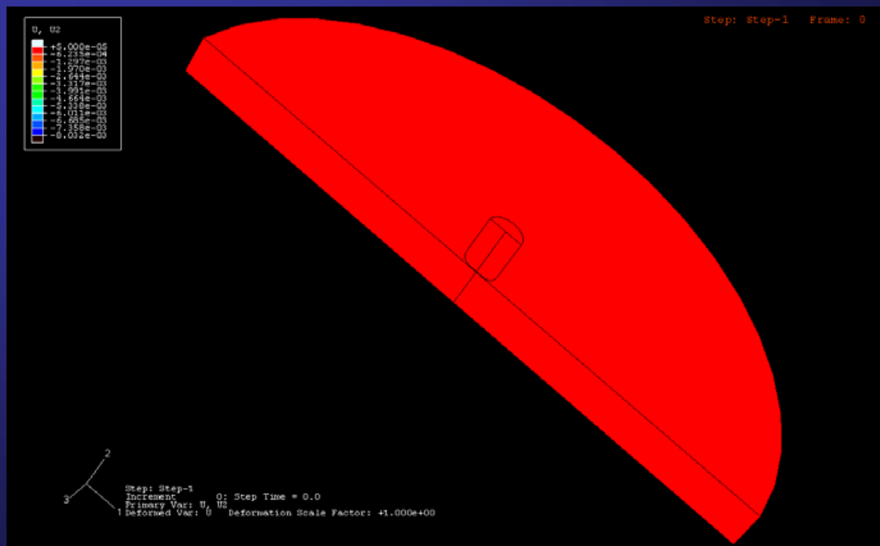

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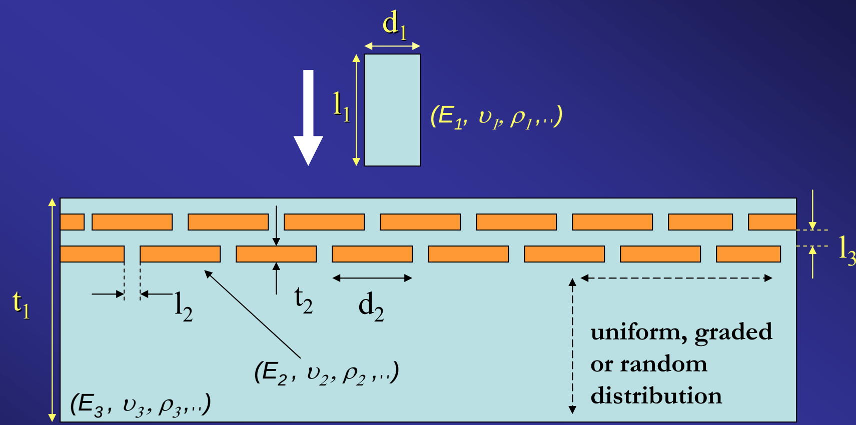

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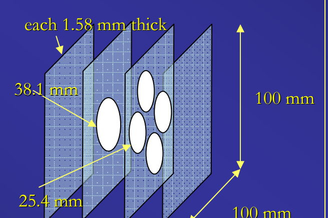

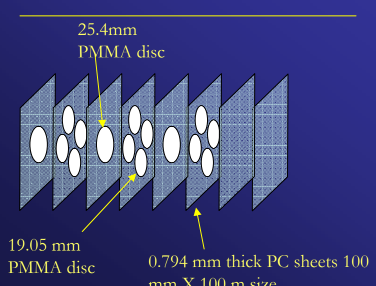

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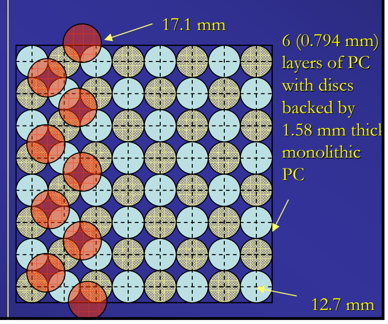
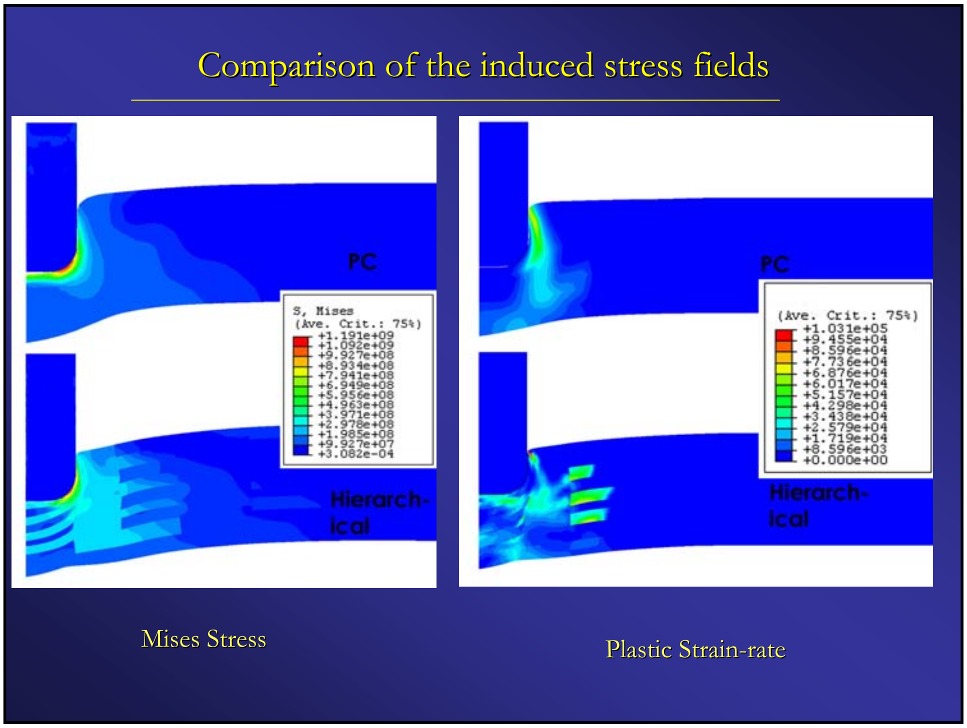
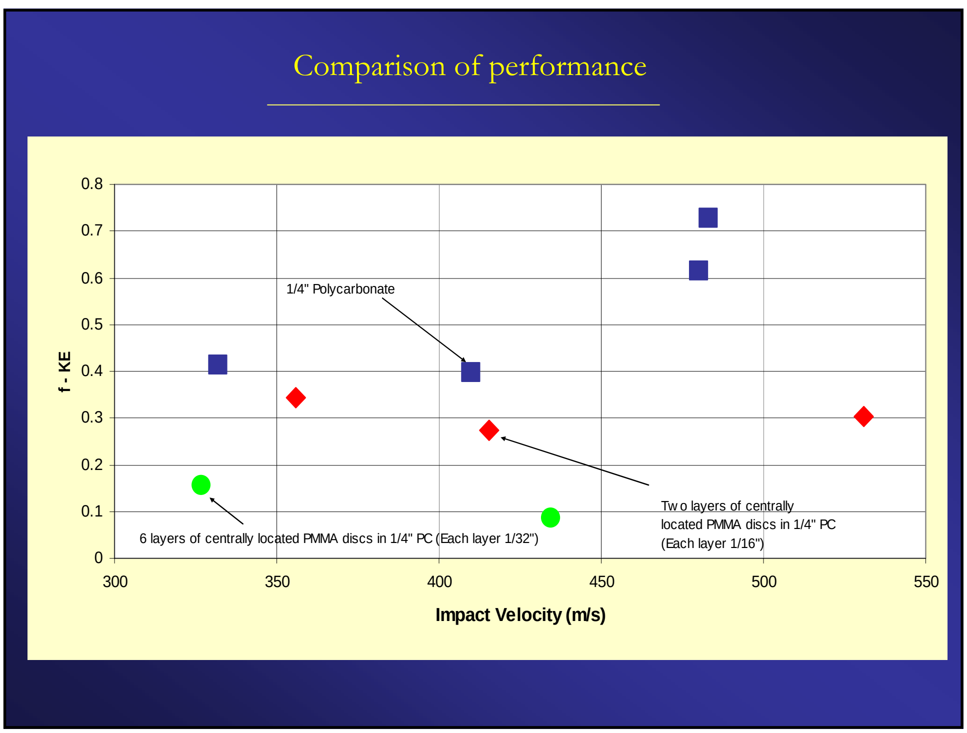
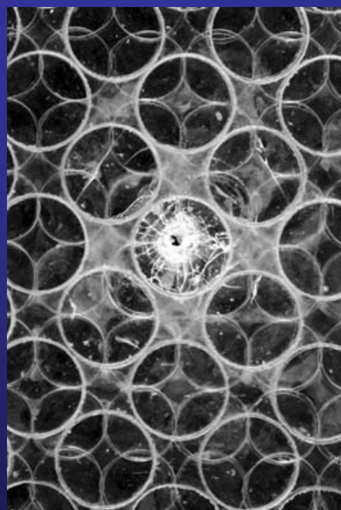
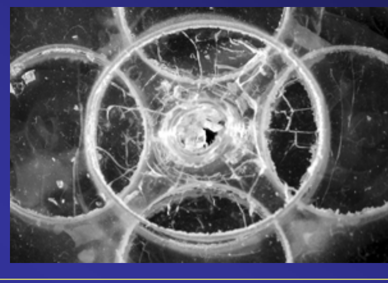



Comparison of the induced stress fields
PC
S, Mises
(Ave. Crit.: 75%)
+1.191e+09
+1.092e+09
+9.927e+08
+8.934e+08
+7.941e+08
+6.949e+08
+5.956e+08
+4.963e+08
+3.971e+08
+2.978e+08
+1.985e+08
+9.927e+07
+3.082e-04
Hierarch-
ical
PC
(Ave. Crit.: 75%)
+1.031e+05
+9.455e+04
+8.596e+04
+7.736e+04
+6.876e+04
+6.017e+04
+5.157e+04
+4.298e+04
+3.438e+04
+2.579e+04
+1.719e+04
+8.596e+03
+0.000e+00
Hierarch-
ical
Mises Stress
Plastic Strain-rate


Comparison of performance
f - KE
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1/4" Polycarbonate
6 layers of centrally located PMMA discs in 1/4" PC (Each layer 1/32")
Two layers of centrally located PMMA discs in 1/4" PC (Each layer 1/16")
300
350
400
450
500
550
Impact Velocity (m/s)

Cracks arrested at the platelet-matrix interface





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