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Performance Metrics for Composite Integral Armor

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Abstract

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Performance Metrics for Composite Integral Armor

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KEY WORDS: composite, armor, resin transfer molding, CIRTM, co-injection, ballistic, armored vehicle, ballistic shock, metal foam, ceramic armor.

INTRODUCTION

Military Requirements

EVER-INCREASING POST–World War II ballistic threats and multifunctional survivability requirements (e.g., overhead indirect fire fragments, direct fire tank munitions, and increasingly potent infantry weaponry), coupled with a U.S. strategy of "forward-presence" of ground-based forces, encouraged the evolution of ground fighting vehicles to their present 70+ ton status (Figure 1). For decades, the Army focused on the development of strategic deployment, tactical maneuver, and materiel acquisition for the anticipated European battlefield. Our strong forward presence in Europe and our ability to, over time, upgrade and reclassify roads and bridges to suit our heavy forces and their associated massive supply requirements made an overweight ground force palatable.

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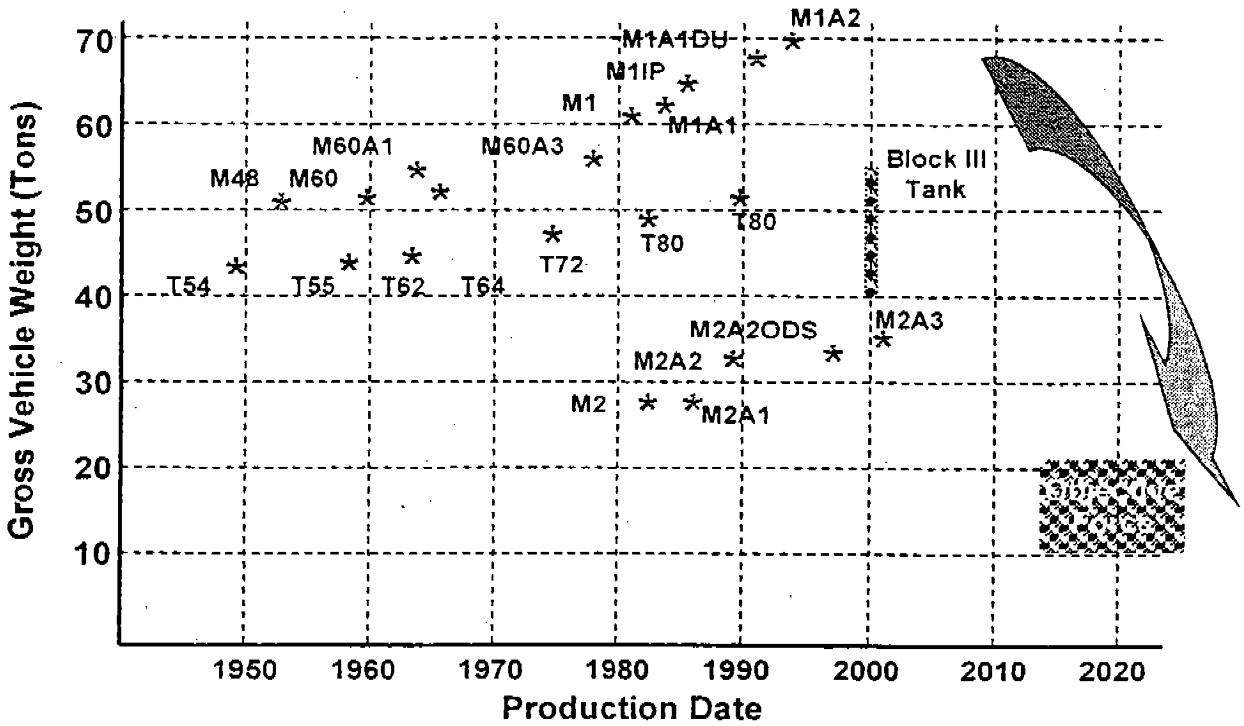

Figure 1. Evolution of U.S. and Soviet armored vehicles. Some Army plans call for a fighting vehicle weight distribution shown on the right (adapted from Reference [1]).

Global political dynamics and a return of public sentiment for a stronger U.S. role in global peacekeeping, in parallel with the cyclic return of desire for a smaller standing military, quickly led to unprecedented changes in when and how ground forces are deployed. A smaller, continental U.S. (CONUS)–based ground force that can be deployed to any environment anywhere in the world requires revolutionary changes in strategy, tactics, and weaponry. Strategically and tactically, the Army has adapted to the rapid changes of the last decade with incredible agility. Changes in doctrine and tactical training, and even complete reorganization of forces, were documented and carried out within the active and reserve forces through the various Army schools and via aggressive leadership within serving units.

However, the required revolutionary changes in weaponry have not followed. A new vision of weaponry is required to enable a CONUS-based force to deploy and operate within a wide range of terrain and environmental conditions against an equally wide range of potential threats from over-matched force-on-force open-terrain armies to urban-terrain guerilla warfare. Concurrent to adapting the strategic and tactical use of existing weaponry to optimize deployability and war-fighting capability in remote locations, the Army is developing mid- and long-range plans for changes in weaponry to suit its changing mission and role in global peacekeeping. These plans are embodied under an umbrella vision called Army 2010 and Beyond designed as a transformation of the Army to an Objective Force in the 2025 timeframe. Under current Army Chief of Staff GEN Eric K.

Shinseki's leadership, the Army is aggressively implementing his transformation vision into a lightweight, strategically deployable, dominant, and sustainable ground combat force through the Future Combat Systems (FCS) program.

In addition, an important factor contributing to the need for a new generation of lightweight multifunctional materials is the American public's near-zero tolerance for the loss of U.S. lives—even in combat situations—leading to a desire for significant increases in survivability for light vehicles and for individual soldier protection. FCS plans call for significant decreases in the weight of our "heavy" forces and large increases in lethality and survivability for our "light" forces and for individual soldiers. The Army's plan [2] focuses on a rapidly deployable force that can be transported on abundantly available and widely deployable C-130 type aircraft. This "fly-in/drive-out" force would have to not only weigh significantly less (one-third current weights) than conventional forces but also have significantly reduced (one-third) basic load and resupply requirements. The anticipated weight reductions (Figure 1) and the imposition of significant life-cycle cost limitations dictate the use of lightweight materials serving multiple survivability and structural roles (Figure 2).

Additionally, the broad range of such multifunctional structures that could be anticipated for optimal weight-performance levels and the increased emphasis on rapid insertion of these materials into new structures and weapon platforms, requires the development of integrated design tools that allow the optimization of armor designs to be both rapid and accurate using a variety of constituent materials. This family of structural armor solutions needs to be based on the integration of models and the application of advanced optimization techniques.

The multifunctional requirements of future armor systems necessitate role sharing among various material constituents. One such multifunctional armor

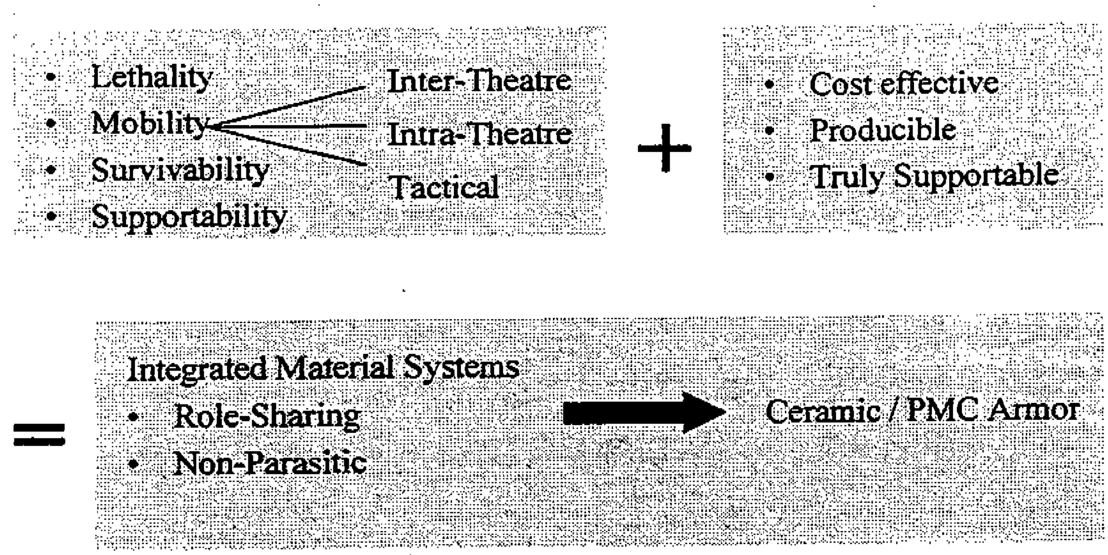

Figure 2. *The requirement to increase strategic and tactical mobility while maintaining maximum survivability, coupled with a drive for decreased acquisition and life-cycle costs, leads to an unprecedented requirement for lightweight materials for army ground weaponry.*

concept involves a unique integration of polymer-matrix composite (PMC) and ceramic materials wherein the best attributes of each material (structural and ballistic, respectively) are combined to allow the structural material to contribute to the overall ballistic performance and the ballistic material to contribute to the overall structural performance. Multiple synergistic effects between materials are taken advantage of in such composite integral armor (CIA) solutions.

While a broad range of protection levels is possible, it is recognized that such significant reductions in weight for the highly mobile force must necessarily result in a reduced level of static survivability compared to traditional heavy forces. However, overall combat system survivability can be improved by considering the dynamic survivability of lightweight tactical vehicles with significantly improved mobility in terms of speed, agility, and obstacle/hit avoidance. The integration of advanced signature reduction techniques (material borne and geometric) will also serve to increase the survivability of lightweight combat forces. Revolutionary advances in lightweight armor are required to close the risk gap between highly mobile combat teams and heavier, more lethal forces. Depending on the systems under consideration, multiple scenarios concerning protection levels and mid- and far-term goals exist. While these goals are classified and cannot be published here, they generally point to objective areal densities (weight per unit planar area) that are one-third the current armor solutions for the whole range of threats from small arms (e.g., 7.62-mm armor piercing) to large caliber tank ammunition (120–140-mm kinetic energy projectiles).

To reach these goals, especially at the higher threat levels, some protection schemes may include active or reactive armor enhancements. Such enhancements reduce the weight available for static structural, ballistic, and shock protection. The base armor required to back up active protection systems (APS) is still a significant challenge for developers of lightweight armor. It is also likely that a variety of lightweight materials such as titanium will be used in the overall vehicle protection. It is generally recognized, however, that PMCs integrated with other material systems such as ceramic tiles will provide the most profound advancements in lightweight armor for FCS.

It is important to understand that with or without APS, a family of lightweight armors covering an order-of-magnitude range in areal densities will be required for each vehicle design. These vehicles may be manned or unmanned, tactical or non-tactical, wheeled or tracked. Such armors also have applicability in aircraft crew compartments, command post shelters, electronic enclosures, generator housings, and a variety of commercial personnel protection and infrastructure enhancement applications.

Composite Integral Armor

Through several key research and development programs, the Army has established a confidence-building baseline for the application of PMCs in fulfilling this role of lightening heavy forces and improving survivability for light forces. The first application of thick-section PMCs to armored vehicles was in a demonstration program in the late 1980s under which a polyester/glass composite hull was developed to replace the aluminum hull on the Bradley Infantry Fighting Vehicle. The resulting vehicle, with a thick-section composite hull and applique armor tiles, became known as the Composite Infantry Fighting Vehicle and demonstrated the ability of PMCs to perform well structurally in an armored vehicle [3]. In the mid-1990s, the Composite Armored Vehicle (CAV) program assessed the application of PMCs in the ground-up design of an armored vehicle [4]. To meet stringent weight and ballistic performance requirements, a multifunctional PMC-based armor (Figure 3) was developed under the CAV program. This CIA performed exceptionally well and was subsequently adapted for incorporation into large components of the Army's new self-propelled howitzer, Crusader.

Each layer within the CAV CIA serves a specific purpose, yet combinations of layers provide role-sharing multifunctionality. Often, single layers also serve multifunctional roles (e.g., structural, multi-hit ballistic, ballistic shock) through uniquely designed interactions with adjacent layers. The figure shows a thin protective PMC facesheet on the outside of the vehicle to protect the ceramic ballistic tiles from incidental damage and provide through-thickness ceramic confinement; ceramic tiles to absorb most of the kinetic energy of the projectile through a combination of projectile dwell, mixed-mode fracture under high pressure, and erosion/deformation of the projectile; a layer of rubber to prevent premature failure of the composite backing plate, improve multi-hit ballistic performance, and attenuate the propagation of high-frequency stress waves; a thick-section composite plate to provide structural backing for the ballistic tiles and structural properties for the vehicle; and a fire-protective "spall" layer on the inner surface of the vehicle. Additional layers can be incorporated for electromagnetic groundplanes, signature control, greater ballistic shock protection, etc.

While the CIA developed under the CAV and Crusader programs did much to

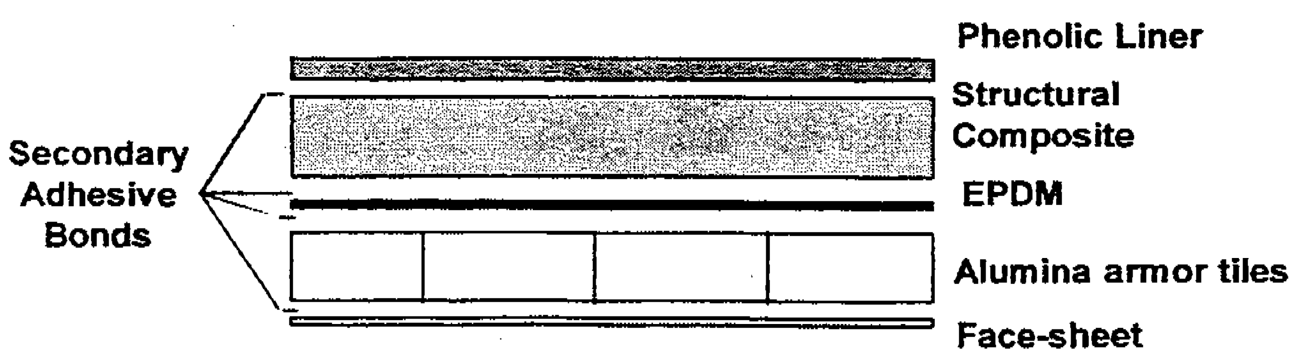

Figure 3. *Example of the composite integral armor developed under the CAV Program.*

build confidence in the ability of PMCs to simultaneously meet ballistic and structural properties in combat vehicles, the mass efficiency (roughly, ballistic performance per unit areal density) falls significantly short of Army requirements. Figure 4 shows the historical development of lightweight materials to one particular threat condition (0.50 cal armor piercing). The CAV/Crusader armor followed an evolutionary path of taking full ballistic credit for the PMC backing plate and full structural credit for the sandwich structure created by the ceramic tiles and outer cover resulting in a ~25-psf armor for this protection level. Since that time, various enhancements to the CAV armor have yielded an areal density of approximately 20 psf; however, these lower weight armors have not been demonstrated in a manufacturing environment or on a vehicle.

Despite evolutionary advancements, current capabilities are a long way from FCS goals of approximately 10 psf for that particular base-armor protection level. Revolutionary advances in materials, physics of failure, computational modeling, design optimization, processing of integrated structures, and reduced-cost manufacturing are required to meet FCS goals. A recently initiated Army-wide Strategic Research Objective (SRO), "Armor Materials by Design," [5] is aimed at focusing in-house and outsourced research efforts on identifying and exploiting innovative concepts and approaches to solving these problems and enabling revolutionary advances in lightweight armor capability. The goal of the SRO is to establish the ability to design armor materials to specific requirements from basic properties of constituents and detailed understanding of material and process-related energy-absorbing phenomena.

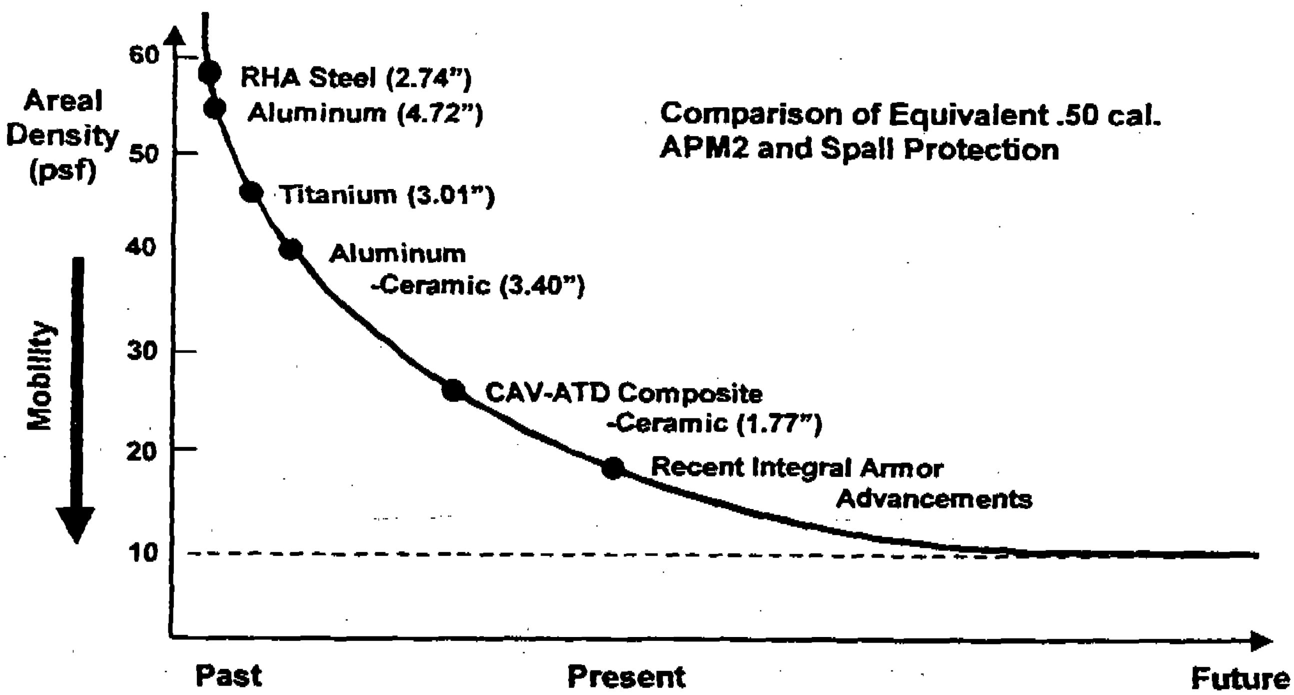

Figure 4. Current status of lightweight armor for .50 cal armor piercing protection.

PERFORMANCE METRICS

Ballistic Performance Metrics

Cost, manufacturability, and ballistic/shock/structural performance are interdependent requirements in the design of CIA structures (among others such as fire protection, thermal signature, electromagnetic shielding, etc.). As a result, there are many ways to increase the performance of one requirement while decreasing the performance of another. Material and design trade-offs also occur within these requirements with competing performance metrics. A prominent example in ballistic performance is single-hit ballistic performance versus multi-hit performance, where a particular armor panel must sustain multiple hits at a particular threat condition within a specified radius without penetration. Improving the V_{50} single-hit performance does not necessarily lead to an improved multi-hit capability and vice versa.

While the overall objective in armor design is a balance of all performance requirements, the ballistic performance metrics generally control the design. A common test is the V_{50} ballistic limit [6], defined as the projectile striking velocity at which complete penetration and partial penetration of the armor are equally likely events. Armors are designed to achieve sufficiently high V_{50} for a particular threat while minimizing the areal density. While the V_{50} probability peak of traditional ductile and brittle armor materials is generally identifiable as a single velocity, Chang and Bodt [7] demonstrated that ceramic-based armors can have a bimodal probability of penetration caused by a velocity-dependent change in failure mode. This led to a recommended change in how V_{50} testing is carried out. This particular behavior is indicative of the complex rate-dependent failure modes during ballistic impact of ceramic-based armors against machine gun threats. It is also obvious that ballistic limit tests that measure the residual velocity of penetrating projectiles and then calculate ballistic limit are grossly inaccurate for these armor structures. It also raises issues of penetrator defeat mechanisms and the transition from penetration-dominated defeat to material-interaction-dominated defeat for lightweight armors and of the computational codes that discount the contributions of far-field structural effects to the penetrator defeat mechanisms within the ceramic.

During a ballistic event, the ceramic material undergoes successive stress waves, inducing large alternating compressive and tensile stress waves in the material. Fracture of the ceramic occurs under both tensile loads (Mode I fracture) and in shear during compressive waves (mixed-Mode II/III fracture), and a good ballistic tile undergoes massive rubblization, resulting in large energy dissipation and deformation of the projectile before it reaches the composite backing plate. The longer the ceramic (virgin or fracture) stays in front of the projectile, the better the performance of the armor at defeating the projectile. An efficient ceramic tile shape is hexagonal, since this allows optimal packing and near-circular shape to maximize the percentage of tile that is fractured during the ballistic event. The areal dimensions of the tile are optimized by considering the threat, the tile thickness, and the failure pattern in the ceramic. Of course, a point of weakness is the point at which three tiles meet; a shot directly on this triple point must also meet the ballistic requirements for the armor.

Another critical metric affecting the overall ballistic performance is dynamic deflection—the maximum (plastic + elastic) deflection that the armor undergoes during the ballistic event. This distance dictates the stand-off distance required for equipment attached to the inside of the vehicle. On one hand, large dynamic deflections are desirable, since they generally result in improved ballistic efficiency; yet they also lead to undesirable space claims available for basic load and soldiers inside the vehicle. When comparing thicknesses of armor designs, it is important to consider the "dynamic thickness," which is the total of static thickness plus dynamic deflection. There is significant risk associated with the comparison of armor solutions by considering only singular performance metrics.

Along with the failure mechanisms within the composite, the deflection response of the panel during the ballistic event also affects the extent of areal damage. Damage in adjacent ceramic tiles (sympathetic damage) or damage in the composite backing plate beyond a critical size affects both the multi-hit performance and post-impact structural characteristics of the armor. In fact, damage to the composite backing plate can occur prior to the projectile reaching the composite, resulting in reduced V_{50} performance and/or increased dynamic deflection and propagation of delamination failure beyond critical dimensions. Hence, additional ballistic performance metrics are transient ballistic damage resistance (measured as extent of damage incurred as a result of the impact during and after the ballistic event) and post-ballistic damage tolerance (measured in terms of retention of mechanical or ballistic properties after impact). Ballistic performance metrics are closely linked to structural and damage tolerance performance metrics. In fact, in lightweight armors such as these designed to defeat projectiles that travel slower than the speed of sound in the constituent materials, these metrics are necessarily interdependent. It is precisely this ballistic-structural interdependence that is leading materials research, computational analysis, and innovative armor design efforts. Traditional assumptions of far-field effects (ballistic-structure interdependence) in terms of both defeat mechanisms and computational design are being reassessed.

Ballistic shock is another armor design requirement that becomes critical for lighter vehicles—potentially to the point that the armor design follows a shock-critical path. Ballistic shock damage occurs when the transient stress waves (covering the frequency range from ballistic to static) move from the point of ballistic impact throughout the vehicle. These shock waves can damage everything from structural joints to electronic components in the vehicle. Lighter vehicles have a more difficult time damping out these stress waves, making joint design and shock isolation of electronic components more difficult, heavier, and more expensive. The good news is that CIAs offer tremendous flexibility in design and new potential to design inherently shock-tolerant lightweight armors. The key to simultaneously designing for ballistic performance, ballistic damage tolerance, and ballistic shock mitigation is to practice concurrent stress wave management through models that cover and link together the full frequency spectrum and quantifiable damage physics in the constituents.

Structural and Damage Tolerance Performance Metrics

With or without damage and regardless of the source of damage (manufacturing defect, fatigue-induced degradation, low-velocity impact, ballistic impact, etc.), CIA is subject to the same structural and damage tolerance performance metrics as other thick-section composites. Current materials of choice for composite backing plates in CIA are woven fabrics and structural resins. It is often desirable to provide additional through-thickness reinforcement in the backing plate to control initiation energies of damage modes and to limit in-plane delamination damage to critical defect dimensions. The resulting thick-section composite structures have unique nonlinear mechanical behaviors compounded by varying strain-rate loadings, high-load, low-cycle fatigue, and unique post-damage military performance requirements.

Critical defect size is determined from multi-hit ballistic, damage propagation (under static, dynamic, and fatigue loadings), and residual stiffness and strength considerations. Fatigue considerations include high-load, low-cycle fatigue of both undamaged and damaged material, fatigue of adhesive bondlines in the CIA structure, pulse-vibration fatigue due to gun loadings, and the effects of finite strain-rate cyclic loading. Residual stiffness and strength are affected not only by the size of the damaged region but also by the modulus reduction within the damaged region. Damage criticality can also be defined by location of damage (e.g., near corners of the vehicle) and by repair considerations. Non-critical defects can become critical through normal cyclic vehicle loads or subsequent local loading due to ballistic events. Since immediate repair of military ground vehicles is not always practical, critical damage assessments must include fatigue loading property reduction and predictions of remaining life.

Manufacturability, Cost, and Repair Performance Metrics

Manufacturability and cost-effective manufacturing of CIA structures are different, but related, metrics. Particular issues of manufacturability for CIA structures include near-net-shape preforming, ballistic tile manufacture and placement, cost-effective ceramic tile confinement strategies, incorporation of multiple resins (structural, fire-protective, conductive), residual stress management, through-thickness reinforcement methods, dissimilar material adhesion, and process-specific issues such as resin viscosity and cure control. Of course, changes in manufacturing affect acquisition costs, and manufacturability issues such as through-thickness reinforcement, tile placement, and dissimilar material bonding affect repairability and subsequent life-cycle costs. Repair of thick-section composites—particularly CIA structures—is an undeveloped art. Transferring sufficient load into repaired sections to obtain recovered strengths near ultimate values is impossible using traditional flush repair procedures. Innovative approaches are required. Furthermore, repairs must consider the recovery of both structural and ballistic functionality. Other issues control the acquisition costs such as material selection (e.g., toughened epoxies vs. low-cost vinyl esters), process (e.g., tow placement vs. vacuum-assisted resin transfer molding), and process preparation (e.g., hand-layup vs. automated preforming). Changes in manufacturing and materials selection affect both ballistic and structural performance requirements. The nature of the interrelationship between performance metrics in CIA structures requires an integrated approach to research.

INTEGRATED RESEARCH EXAMPLES

Processing Example

As an example of the integration of performance requirements and manufacturing changes, ARL and the University of Delaware developed a process designed to reduce the costs associated with the manufacture of CIA structures. Co-Injection Resin Transfer Molding (CIRTM) [8,9] is a variation of VARTM and the Seemann's Composites Resin Infusion Molding Process (SCRIMP®) [10]. A distinct advantage of the CIRTM process is the ability to include all of the composite armor elements in a single preform assembly, including various fiberglass fabrics, an elastomer layer, and ceramic tile (Figure 3). The development of CIRTM resulted in a reduced-cost process that provides for a balance in ballistic, structural, and fire properties of CIA structures. Figure 5(a) shows a micrograph of a CIRTM composite in the interphase region that demonstrates the quality of each laminate. Furthermore, the Army has used CIRTM to process stitched laminates with superior multi-hit ballistic performance and damage tolerance compared to baseline composite integral armor structures [Figure 5(b)]. Figure 5(c) shows a panel manufactured by United Defense, L.P. that exhibited 6-shot multi-hit performance without separation of the ballistic liner.

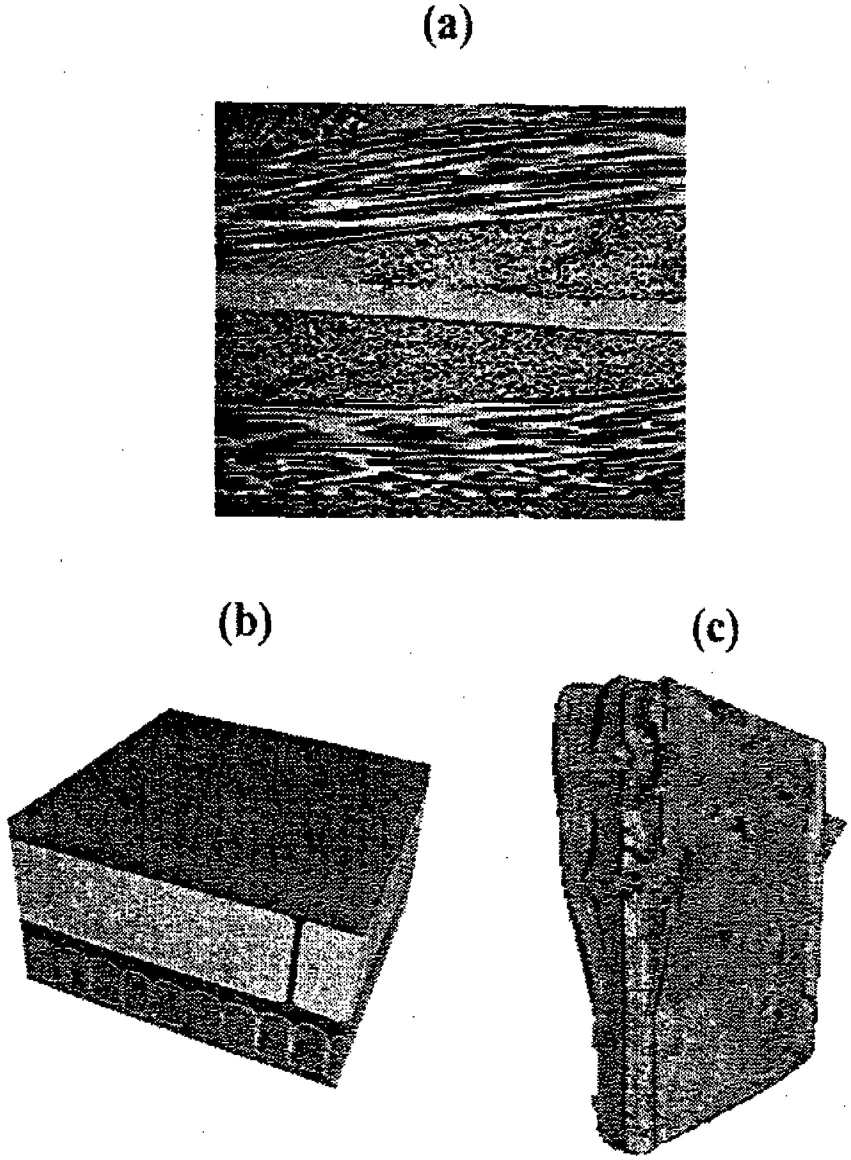

Figure 5. (a) Micrograph of CIRTM composites near separation layer; (b) photograph of stitched integral armor; (c) co-injected, stitched integral armor target exhibiting 6-shot multi-hit performance without separation of the ballistic liner.

Materials Example

Truly multifunctional structures, especially those optimized for minimal weight, minimize the parasitic nature of any individual constituent. The structural, ballistic, and shock performance of the CIA can be, and generally is, affected by each individual material layer. In this example, we replace the CAV-based 0.125-in EPDM rubber layer that provides enhanced multi-hit ballistic performance with an aluminum foam at 40% density as shown in Figure 6.

Ballistic panels were fabricated with both a baseline 20-psf CAV-type armor with the 0.125-in rubber and a 20-psf foam-based armor. Some S-2 glass fiber/vinylester resin material in the backing plate was removed to accommodate the slightly heavier 0.75-in aluminum foam. The objective was to ascertain potential

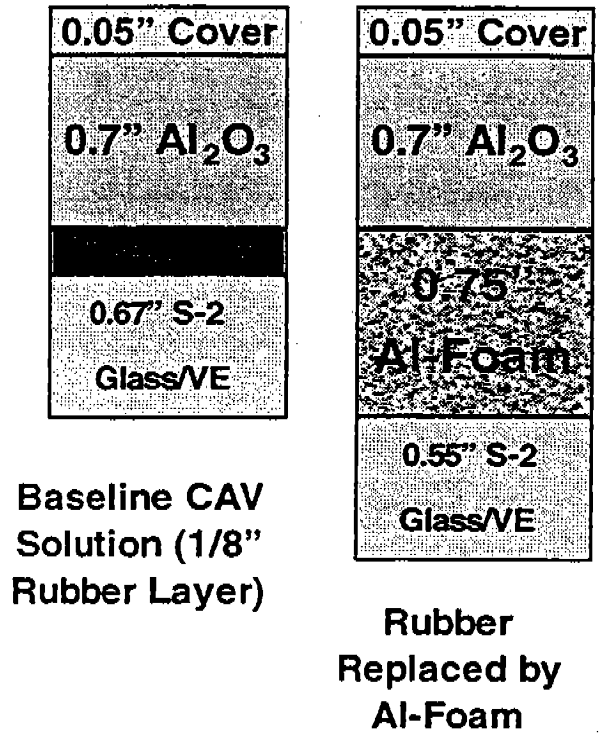

Figure 6. Baseline (left) and aluminum-foam-based (right) 20-psf armors.

benefits of the replacement of a single constituent material (the rubber) with another material (foam) based on our understanding of various mechanisms of damage, load transfer, defeat mechanisms, and stress wave propagation in the CAV armor. In addition to providing similar functionality in terms of protection of adjacent ceramic tiles for improved multi-hit performance, the aluminum foam also serves other multifunctional roles including improved structural performance by increasing the structural rigidity at no increase in weight, potentially improved single-hit ballistic performance through increased energy dissipation in the aluminum foam during the ballistic event, increased static thickness but decreased dynamic thickness through decreased dynamic deflection without adversely affecting V_{50}, improved ballistic shock performance through efficient damping of shock waves through the thickness and in-plane, and improved ballistic and structural damage tolerance through decreased damage to the composite backing plate.

Armor test panels measuring 12 inches square were manufactured using the same techniques as described by Fink and Gillespie [11] and ballistically impacted at nominally 2750 fps with a 20-mm fragment-simulating projectile (FSP). The velocity was chosen to ensure that the targets were not fully penetrated and that the projectiles were captured within the armor. While full results will be reported elsewhere, some benefits of the aluminum foam panels over the baseline panels can be seen in the X-ray computed tomography (CT) scans shown in Figures 7 and 8 for the baseline and aluminum foam-based armors, respectively.

A comparison of the CT scans in Figures 7 and 8 indicates less apparent sympathetic damage to adjacent tiles, less delamination damage to the composite back-

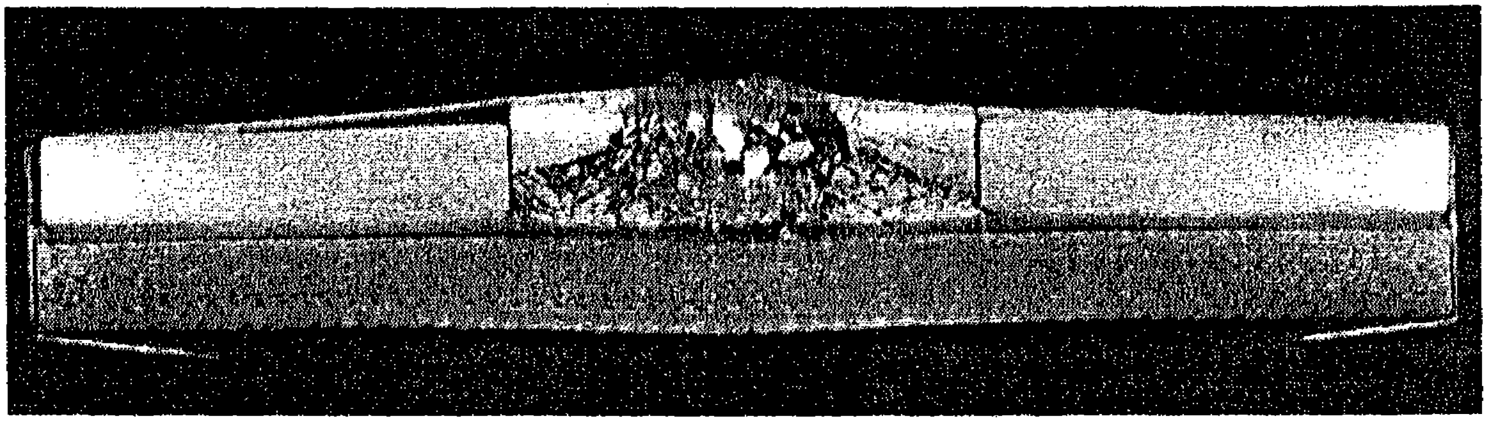

***Figure 7.** CT scan at impact-center of baseline CAV-type armor test panel with 0.125-in EPDM rubber between the alumina ceramic tiles and the composite backing plate.*

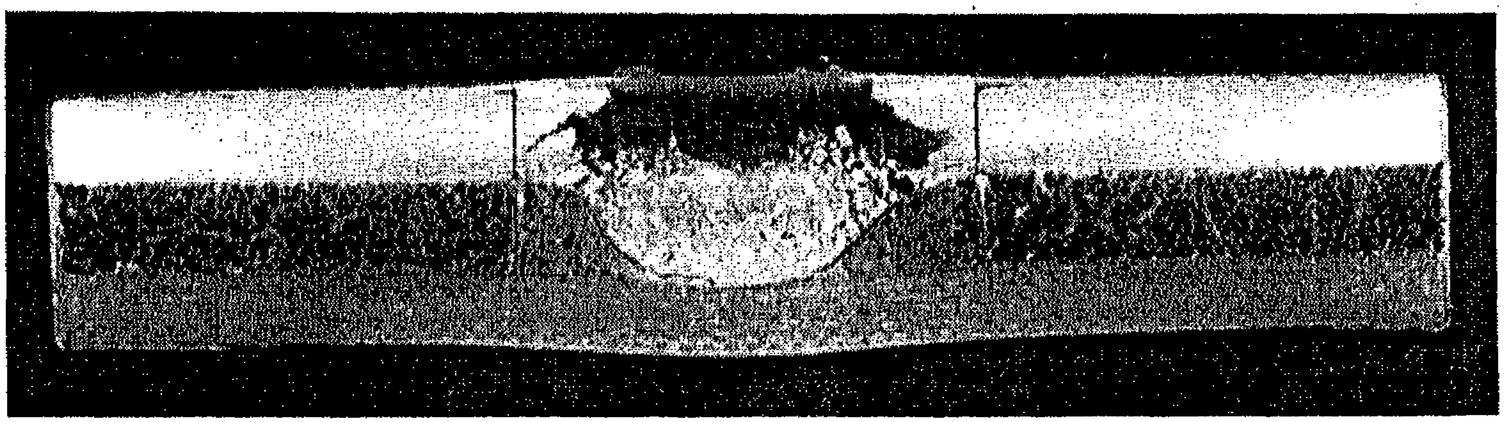

***Figure 8.** CT scan at impact-center of armor test panel with 0.75-in aluminum foam between the alumina ceramic tiles and the composite backing plate.*

ing plate, and more rubblization of the impacted tile indicating a potential increase in penetrator dwell. Additionally, the measured dynamic deflection was significantly reduced from 1.6 in for the baseline panel to 0.9 in for the aluminum foam-based panel. While what is presented here is insufficient to draw specific conclusions about how to optimally use metal foams in CIA survivability structures, there is valid evidence that material selection can positively influence non-parasitic multifunctionality providing combined structural and multi-parameter ballistic performance improvements. Details are provided by Gama, et al. [12].

CONCLUSIONS

Army requirements for the next quarter century point to large increases in the use of polymer-matrix composite materials for ground combat vehicles. PMC-based armors have been developed that significantly improve the specific ballistic performance of rapidly deployable lightweight vehicles. However, revolutionary thinking about how lightweight armors defeat projectiles and revolutionary improvements in armor design are required to reach Army performance goals. An armor-materials-by-design approach is needed in which multifunctional mate-

- **Ballistic Performance**
  - Single-Hit V_{50}
  - Multi-Hit V_{50}, Sympathetic Damage
  - Dynamic Deflection
  - Triple-Point
  - Ballistic Damage Resistance
  - Post-Ballistic Damage Tolerance
  - Ballistic Shock
  - Spall/Secondary Projectiles
- **Structural Performance**
  - Static Performance Variables (Strength, Stiffness)
  - Low-Velocity Impact Damage Resistance
  - Low-Cycle and Pulse-Vibration Fatigue
  - Damage Tolerance
  - Critical Defect Size/Location
- **Other Competing Metrics**
  - Areal Density
  - Reparability
  - Manufacturability
  - Manufacturing/Assembly Costs
  - Fire/Smoke/ Toxicity
  - Thermal & Electromagnetic Shielding/Signature
  - Internal Space Claim
  - Joint Design/Fit Tolerances

Figure 9. *Competing performance metrics for CIA design.*

rials and processes are integrated to optimize complex trade-offs in the myriad performance metrics including ballistic, structural, shock, fire, cost, and signature (Figure 9). Weight is minimized through creative role-sharing of multifunctional materials. An improvement in one performance metric is often accompanied by sacrifices in other performance metrics. An understanding of the interactions between performance metrics and of the micro-to-macro rate-dependent behavior of composites and integrated composite armors, coupled with a materials-by-design approach, can lead to the lightweight armor solutions required for FCS.

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Future combat systems necessarily focus on lightweight, highly mobile and transportable armored vehicles. Lightweight composite integral armor systems are being developed to meet these needs. The goal of this paper is to centrally document the myriad design requirements for composite integral armors that serve multifunctional roles including ballistic, structural, shock, electromagnetic, and fire protection. Structural and ballistic performance requirements as well as manufacturing and life-cycle performance issues of integral armor are presented. Specific areas addressed include high-strain-rate testing and modeling, ballistic testing and modeling, low-cycle fatigue, damage tolerance, repair, reduced-step processing, through-thickness reinforcement, energy dissipation and rate-dependent failure mechanisms, and non-linear mechanics.

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