LIGHTWEIGHT COMPOSITE INTEGRATED STRUCTURAL ARMOR

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1. INTRODUCTION

ShieldStrand® reinforcements have demonstrated weight and cost savings for ballistic fragmentation, blast mitigation and behind armor overmatch application, including spall liners, IED/EFP kits and LTAS compliant armor kits. ShieldStrand® high strength reinforcements and phenolic laminate technology meet MIL-DTL-64154B requirements, ensure a reliable industrial base, and stimulate innovation for integrated structural armor to address light weight armor upgrades necessary in LTAS and DoD priorities for situational awareness and force protection. Composite structural armor made with ShieldStrand® meets durability requirements for mitigation of behind armor effects, fire resistance, corrosion resistance, fatigue resistance, NBC resistance, impact resistance, and joint fastener pullout resistance for integration with metal plate or extrusions. ShieldStrand® also enhances the structural performance and durability of ceramic, aramid or HMWPE hybrid composite armor materials. The demonstrated weight and cost performance improvements bring value to composite integrated structural armor for a new generation of lightweight armored vehicle.

2. COMPOSITE MATERIAL FOR ARMORED VEHICLES

Over the past two decades, army defense departments including TACOM, TARDEC, RDECOM and ARL have sponsored over a dozen composite manned ground vehicle technology demonstrators. The programs have demonstrated up to 50% vehicle weight savings depending on the design criteria, degree of armor integration in the structure, the level of part consolidation, and amount of composite material usage. Composite technology though has not yet spiraled into a full vehicle production platform due to the perceived risk of high cost and production capacity.

Composites are needed to help meet the manned ground vehicle requirements for protection, mobility and reduced fuel consumption. To prove adequate capacity is available, a study was proposed to the OSD to assess the ability of the industrial base to produce light weight composites that meet the Army’s demand of 1000 vehicles per month. Recent material and production advancements have created lower cost composite materials that are more conducive to use in large structures. Other industries have adopted these large composite structures to reduce weight, corrosion, and environmental impact. Applications include ships, wind turbine blades, chemical transport and storage containers, and structural aircraft components. Glass fiber reinforcements have the largest volume in these applications because of good utility, durability, reliability, and cost-performance.

2.1 MILITARY NEEDS

The Department of Defense uses composites that are designed to have properties with utility in military specific applications. The unique composite characteristics for military needs depend on the application and are generally categorized in terms of weight performance, multi-functionality, and part count reduction. For a vehicle application the weight performance improvements are balanced with protection and payload depending on the platform system and mission requirements. Manned ground vehicle system and mission requirements are driving the need for strategic deployability and tactical mobility which is improved by light weight composite materials. The performance improvements of composites or composites integrated with metals are demonstrated in simulation and full scale testing for ballistic survivability, mechanical performance, and life cycle cost. Composite parts are acquired through purchase agreements with requirements to meet performance or detailed material specifications. Recent DoD force protection material shortages show the need for higher volume of high performance composites meeting military specifications.

ShieldStrand® is part of a new family of high performance reinforcements (HPR) with higher strength, stiffness and temperature stability for consideration in the substitution of traditional materials like steel and aluminum. The manufacturing readiness level (MRL) of ShieldStrand® is 9 and production quality and consistency meet MIL-DTL-64154B. The glass formulation and melting technology allow the capability to produce consistent, high volume, affordable reinforcements. The HPR family consists of two products for military armor applications, ShieldStrand® and ShieldStrand® S. ShieldStrand® is fielded in several applications including spall liners and add-on armor kits. ShieldStrand® is based on R-glass chemistry and is qualified to MIL-DTL-64154B Class B. ShieldStrand® S is based on S-glass chemistry and is under evaluation for approval to Class A requirements.

ShieldStrand® reinforcements enable an affordable solution in composite armor applications using various manufacturing processes for flat plate, curvilinear or complex composite shapes. The large scale production process developed to manufacture the ShieldStrand® glass reinforcements is based on innovation in glass chemistry formulation, glass melting, fiber forming, fiber delivery and surface treatment. This cutting edge technology is enabling large-scale, direct-melt production of high-quality, high-strength glass fiber reinforcements.

In 2006 ShieldStrand® was selected as an alternative for S-2 Glass® or aramid spall liners. The incentive was low cost and availability with equivalent ballistic performance at equivalent weight. ShieldStrand® was also validated for use in IED and EFP protection kits by ARL and several OEMs. Large complex composite structural parts were successfully demonstrated up through 2009, including a cab, full sidewall, and V-hull for validation of integrated structural armor weight and cost performance. Today vehicle OEMs are using composite spall liners, add-on armor kits and other structural components such as hoods, fenders and floors to help reduce weight. Further weight reduction would be realized by integrating armor in the vehicle structure, as validated by many of the technology demonstrators.

2.2 BALLISTIC PERFORMANCE

The ballistic performance is delivered by a robust armor system and consistent supply chain. It is proven by several years of commercial production. In 2006 a Value Engineering Change Proposal (VECP) was submitted by AM General to TACOM for the use of ShieldStrand® as an alternative for S-2 Glass® spall liners in the HMMWV. The incentive was low cost and availability with equivalent ballistic performance at equivalent weight. Since this initial change proposal, ShieldStrand® was validated for use in IED and EFP protection kits by ARL and several OEM armor suppliers for the HMMWV and MRAP platforms.

The ballistic armor system technology follows an understanding of composite laminate plate energy absorption mechanisms. Ballistic kinetic energy is absorbed through: 1. a global plate response which is usually minimal at velocities above 100 m/sec and the elastic energy is stored in the plate temporarily relative to plate stiffness (thickness) and dissipates during the transient deflection through shear deformation and inertial motion of mass; 2. a local plate and material response which increases with velocity in classical plug and membrane behavior and is dependent on ballistic projectile geometry and hardness, the k factor, $KE=k/2(MV^2)$.

Composites work best for larger projectile tip footprints. From a local macro perspective the projectile compresses the laminate until the front layers rupture and then the punch shear plugging behavior fractures and delaminates the front and back layers through the laminate moment of inertia during rebound of the membrane behavior in the back layers as illustrated in Figure 1. The plugging and membrane fracture and delamination behavior during ballistic penetration depend on several micro-mechanisms in the matrix and

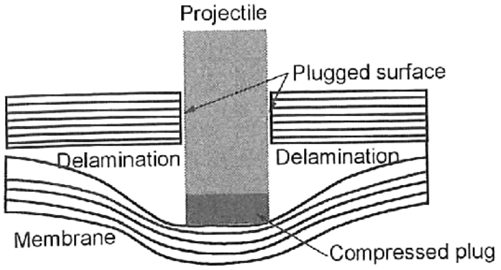


Figure 1. Ballistic Penetration Mechanism

fiber interface such as: impedance mismatch for initial fracture from shock stress wave, hardness and radial crack formation for compressive indentation, spall fracture of resin matrix, plugging fiber/bundle debonding and pullout friction interface energy for front compressive shear punch and back flexural tension fracture, friction between projectile and composite during penetration, plastic deformation of the projectile and plug formation, interlaminar micro-cracking of matrix front and back surface, ejection of fiber matrix debris, fiber/bundle strength and strain energy for fiber fracture, and the cumulative number of fibers/bundles involved in energy absorption [1].

The ballistic fracture mechanisms suggest a higher fiber strength and strain energy, higher number of fibers within the bundle with lower fiber diameter, and a reduced fiber/bundle debonding stress or higher interfacial toughness >240 kJm^{-2} should contribute to improved ballistic energy absorption performance. An indication of this in the composite cross-section after ballistic penetration would be a fiber pullout length of >0.6mm and a bundle debond length of >5mm.

Ballistic energy absorbed in ShieldStrand® phenolic laminates depend on higher strain energy performance and consistency of the fiber, fabric, prepreg and molding conditions for durability and reliability. The general composite matrix mechanism for improving ballistic fragmentation and blast protection in high strength glass reinforced resole phenolic composites are as follows:

- Desire composite structural behavior at normal loading rates with good cold/dry and hot/wet environmental stability which is influenced by phenolic matrix Tg, beta and interphase transitions with plasticization caused by moisture swelling or cold cracking.
- Desire composite ballistic performance at instantaneous loading rates (strain rate 4-7x magnitude of normal rate) with high strain energy influenced by protecting the glass fiber strength from premature fracture with a ductile interface which also spreads the ballistic kinetic energy across a greater area of work in the laminate.

The ShieldStrand® phenolic composite armor system meeting MIL-DTL-64154B is based on woven R-glass roving for Class B specifications. ShieldStrand® S is based on woven S-glass roving and is currently under evaluation for the approval to Class A specifications. Figure 2 compares the ballistic performance from panels produced in the phenolic composite armor supply chain. ShieldStrand® S glass is made from a boron-free glass formulation that meets S-glass standards as defined by ASTM C162, DIN 1259, ISO 2078, ASTM D578, and JIS R3410 standards. This glass formulation is designed for higher strain energy, tensile strength and modulus.

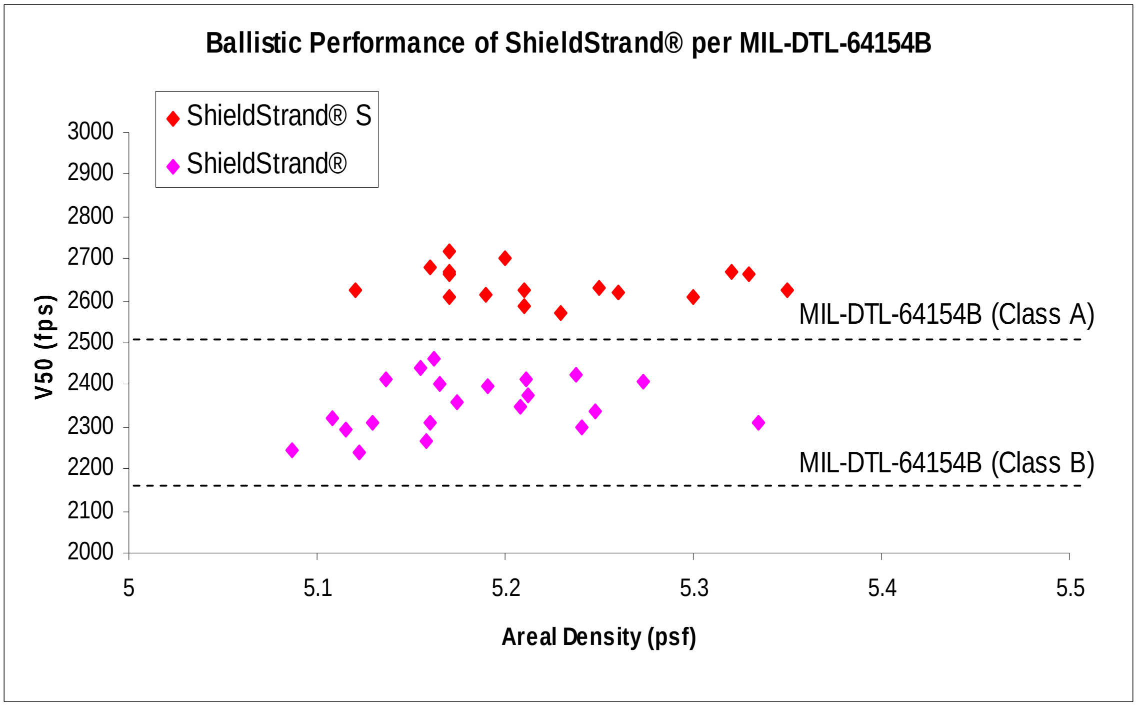


Figure 2. Ballistic V50 performance of ShieldStrand® per MIL-DTL-64154B

It is similar to S-2 Glass® as shown in Table 1, and offers significantly better thermal and corrosion resistance properties than conventional E-glass [2,3]. ShieldStrand® S glass meets the tensile strength requirements for MIL-R-60346 Type IV Class 1 and 2. Because of the important synergy between the reinforcements and the matrix, ShieldStrand S is currently available in an epoxy compatible sizing, which is ideal for ballistic applications using phenolic, vinylester, and thermoplastic resins. ShieldStrand® S can reduce weight up to 40% when replacing aluminum and up to 50% when replacing steel depending on the application performance needs.

2.3 STRUCTURAL PERFORMANCE

Composite structural armor made with ShieldStrand® meets blast overpressure and structural durability requirements for mitigation of behind armor effects through instantaneous and longer term fire resistance, corrosion resistance, fatigue resistance, NBC resistance, impact resistance, and joint fastener pullout resistance. Table 2 elastic and strength constants used in LS Dyna blast simulation codes indicate fracture strength or blast rupture performance exceeds prediction by about a magnitude depending on thickness and structural or fastener compliance. Further work with composite material codes are improving prediction capability. The composite dissipates shock energy lateral and normal to the plane without spallation and rupture which mitigates behind armor effects and debris from overmatch threats to an exit angle of typically less than 20-25 degrees or a 30-50% reduction in cone angle compared to metals.

The composite spall liner demonstrates multiple hit capability without loss of performance provided fastening systems continue to hold the spall liner in place. The improved structural performance of ShieldStrand® enables higher fastener pullout resistance and continual multiple hit performance based on the high longitudinal bending and bearing strength shown in Table 2. ShieldStrand® has higher plate structural properties more like metals than aramid and HMWPE armor systems. Yet it mitigates behind armor effects like spall, enabling the opportunity to combine spall liner and structure as one for weight savings.

2.4 THERMAL PERFORMANCE

Overmatch threats of roadside bombs, IED and EFP typically involve significant mechanical and thermal effects. Incendiary effects of API bullets, RPG, and EFP are significant thermal events. Explosive blast, fragmentation and incendiary effects are reduced with composite spall liners and add-on kits. The high speed successive photo frames from testing at Southwest Research Institute show the thermal energy involved with blast and fragmentation events in Figure 3. Table 1 and 2 glass bulk properties and thermal data support shock mitigation, thermal stability, insulative qualities, and dimensional stability for ballistic and blast application. Composite stability is maintained relative to the rate of thermal ablatement in IED and EFP events. The composite resistance to combined threats helps avoid sympathetic reaction with slow or fast heating (MIL-STD-2105C). The high thermal oxidative stability of the ShieldStrand® phenolic composite plate coincides with its higher fire and smoke resistance.

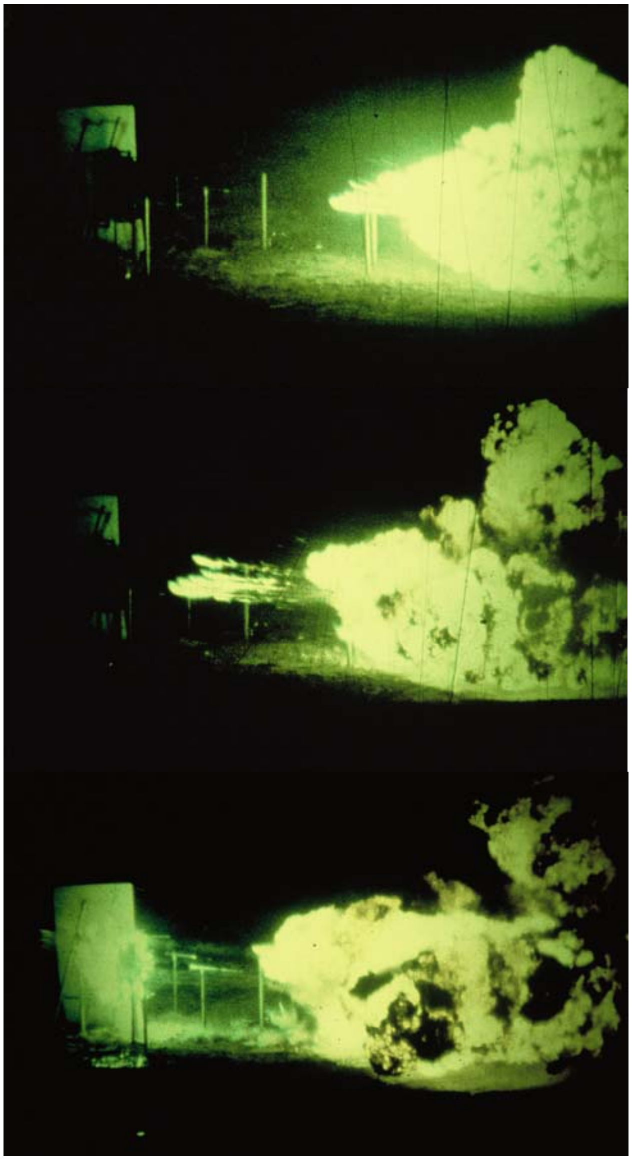


Figure 3. Ballistic fragmentation and blast testing

2.5 FIRE PERFORMANCE

In recent years, the effects of smoke and toxic gases were singled out as one of the leading causes of injury and death in fire. For this reason high strength glass and aramid spall liners approved for use inside military vehicles are based on phenolic resin systems. The requirements for interior finish materials onboard U.S. Naval ships are stated in MIL-STD-1623. The requirements for shipboard installations are given in Naval Surface Weapons Center Report 80-302, "Material Characterization Tests Program". The requirement for ASTM E162 is a flame spread index less than 25. The oxygen index should be greater than 27% at 25C and 150C per ASTM D2863. And the smoke obscuration index for flaming and non-flaming tests should be less than 250 under ASTM E662.

Improved polymer resistance to ignition and reduced rate of burning are key properties to delay or lessen the onset of total obscuration or combustibility for escape or rescue. A phenolic resin matrix complements the high heat resistance of glass fiber. Phenolic resins are fire-resistant materials with low smoke emissions and toxicity levels. In addition, the phenolic polymer structure facilitates the formation of an ablative high carbon char that radiates heat and functions as an insulator against certain explosions and fire threats. Table 2 includes a summary of fire, smoke and toxicity properties of ShieldStrand® phenolic composites. The ASTM E1354 cone calorimeter data is used to determine Maximum Average Heat Release (MAHRE) performance typical for a given heat flux. The oxygen index is the percent oxygen required to sustain a flame in a burning test specimen where the higher the percent oxygen, the less flammable the material. The performance of ShieldStrand® phenolic exceeds the guidelines by a factor of three. Smoke obscuration index are expressed in terms of specific optical density or absorbance. As noted, ShieldStrand® far exceeds guidelines established for this test. The flame spread index is an indication of the rate a fire may spread. Since the glass is a noncombustible inorganic and the phenolic resin is nonflammable, this data was also correlated with cone calorimeter data. MAHRE cone calorimeter data at a 50kW/sm heat flux demonstrated significantly higher fire resistance for ShieldStrand® with a maximum average heat release of 25 kW/sm, compared to 126 kW/sm for aramid and 568 kW/sm for HMWPE armor systems [4].

2.6 FATIGUE AND CORROSION RESISTANCE

Durability is a key feature that defines the value of modern composite materials. Since the mid-1940s, composite materials have enhanced their reputation as being chemically resistant and providing excellent long-term performance. Products such as chemical storage tanks for strong acids that provide many years of excellent performance have replaced steel, stainless steel, rubber lined steel and aluminum tanks that provided limited service lives. The glass fiber composite bodies of the Corvette, introduced in the early 1950s are still functioning while steel bodies of autos built only 15 years ago have severe rusting and have reached the end of their usefulness. The marine industry has transformed from wood and corrosion-resistant metals to composites, as the composite material will not corrode when continuously exposed to fresh or salt water environments. Composite materials perform as chemically resistant, long life, durable materials that have excellent strength and functional capabilities [3,5].

The U.S. Army's Belvoir Research, Development and Engineering Center at Fort Belvoir, Virginia, conducted a series of Chemical Agent Resistant Coating (CARC) tests on various laminate constructions. The Test Report 2426, "CARC Finishes on Laminate Armor Materials" [6], points out NBC cleaning agent durability, environmental water absorption, and paint blistering problems are overcome in glass fiber composites with CARC finishes of urethane for interior and epoxy for exterior components. The CARC surface finish on the ballistic panels further preserves the excellent corrosion resistance and durability.

Chemical corrosion resistance is often attributed to the resin matrix measured according to ASTM C581. However, recent testing of improved glass fibers has also demonstrated the importance of the glass fiber, resin surface and sizing chemistry [3,5]. The measured corrosion rate of composites in seawater is nil compared to metals at 0.01-9.4 mm/yr depending on metal type and coating maintenance [5]. Independent testing of

ShieldStrand® has shown clear advantage with use of commercial resin systems, processes, and improved fiber sizing chemistry. ShieldStrand composite fatigue and corrosion resistance was an improvement to E-glass and the best E-CR glass, Advantex®, that is used routinely for corrosive chemical transport and industrial chemical treatment environments. There was a lower weight and strength loss in typical chemical environments. Superior corrosion resistance in stress-rupture testing is shown in Figures 4-6. To assess the stress-rupture behavior of E-glass, Advantex® and ShieldStrand® unidirectional rods, the static fatigue test was conducted in air at room temperature 23°C ± 2°C. The results are shown in Figure 4. The tensile stress of composite rods was plotted versus time to failure in a log scale. Extrapolation of the results indicated that ShieldStrand® had significantly higher tensile stress in air after 50 years service time.

To simulate composite applications in marine environments, the stress-rupture test was conducted in 5% salt water in Figure 5. ShieldStrand®

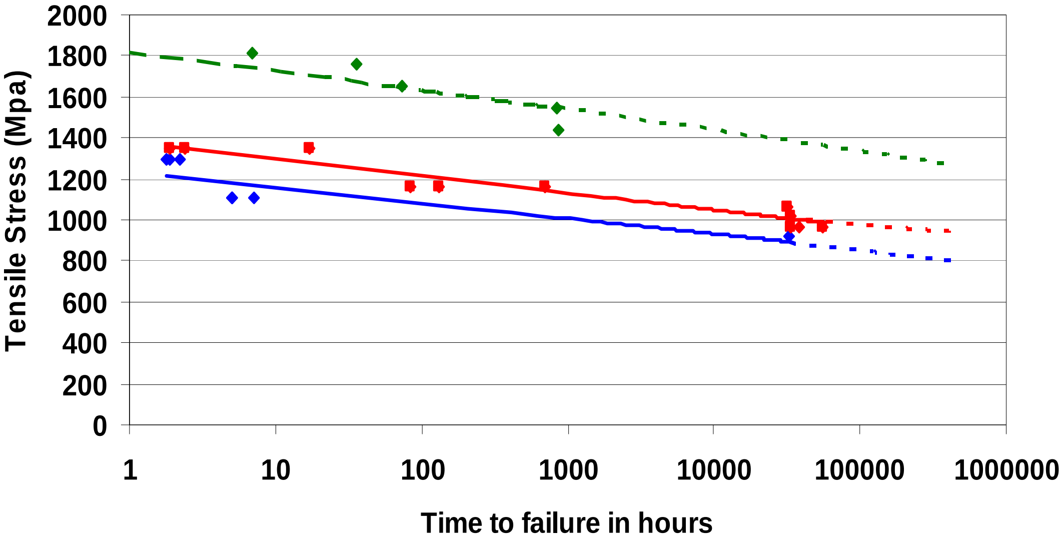


Figure 4. E-glass, Advantex, and ShieldStrand in Air @ 23C

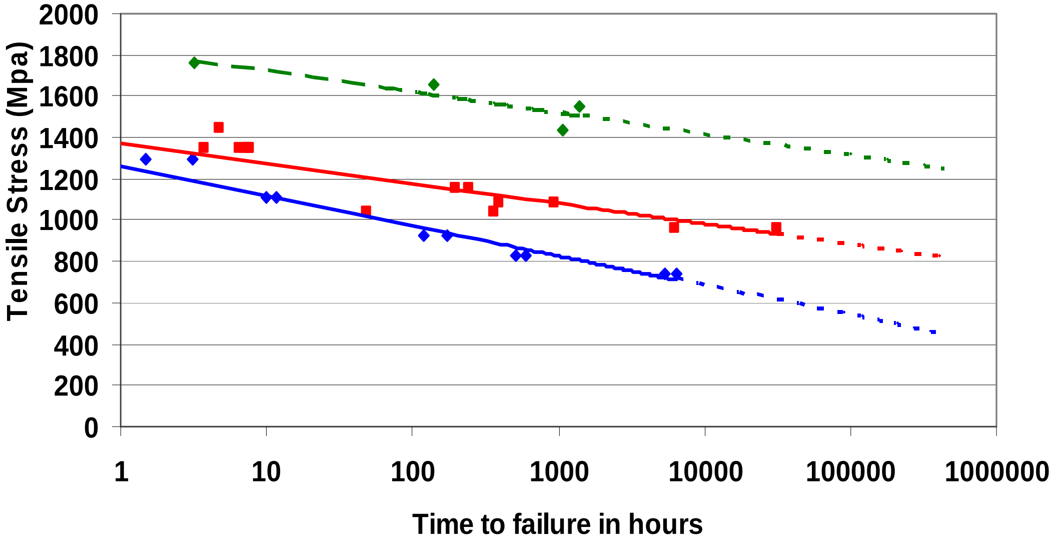


Figure 5. E-glass, Advantex, and ShieldStrand in Salt Water @ 23C

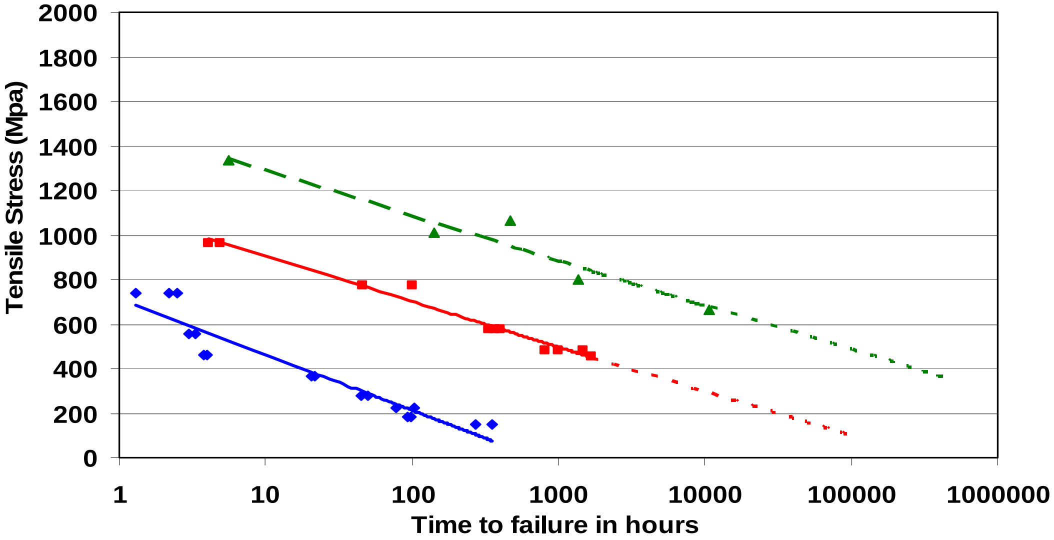


Figure 6. E-glass, Advantex, and ShieldStrand in 1N Acid @ 23C

maintains significantly higher tensile stress in salt water after 50 years of service time.

For many vehicle applications there is exposure to acidic environments like battery acid. E-glass, Advantex® and ShieldStrand® reinforced unidirectional rods were tested in 1N sulfuric and hydrochloric acid solutions. The results obtained at room temperature for 1N sulfuric acid are shown in Figure 6. Again ShieldStrand® displayed significantly higher stress limit after 50 years [3,5].

According to standard ISO 720, ShieldStrand® was recently rated by INISMa Laboratory report 101300 as HGA1 class [8], the best hydrolysis resistance class. Other E-CR glasses are typically rated HGA2. HGA2 classification is less than 0.85ml volume of 0.02N HCl per gram of glass. The lower the amount of required HCl for neutralization, the more hydrolysis resistant the glass is. HGA1 is less than 0.10ml volume of 0.02N HCl per gram of glass.

The stress-rupture data supports the claim of superior long term performance of ShieldStrand® to E-glass and Advantex® composites in corrosive environments. Based upon the referenced work [2,3,5,7,8], ShieldStrand® is significantly more fatigue and corrosion resistant than traditional boron-containing E-glass. Therefore, ShieldStrand® is a high strength and high modulus glass fiber which can be safely used in corrosive E-CR glass composite applications for the substitution of traditional metallic materials [9,10]. Durability of composite materials extends beyond fatigue and corrosion resistance. Composite materials also demonstrate excellent vibration dampening and shock energy absorption [7,11].

3. ARMOR SYSTEMS USING SHIELDSTRAND®

The typical performance range of ShieldStrand® against various NIJ 0108.01 and STANAG 4569 requirements are given in Table 3. ShieldStrand® was tested in several armor systems to meet the requirements of the U.S. Army's Long Term Armor Strategy (LTAS). LTAS uses a modular concept to provide different levels of protection as the threat changes. The modular concept provides basic protection as an integral part of the vehicle's structure, called the A-Kit. Increased protection is added as the B-Kit. Different B-kits can be used to provide various protection levels as the mission dictates. Since the B-kit can be removed, the overall vehicle weight can be kept low during peacetime, increasing the life of the vehicle. Glass fibers that provide structure as well as ballistic and blast protection are ideal for vehicles that use the A+B kit approach. ShieldStrand® was tested in conjunction with other materials as add-on B-kits as well as used in the integral structure that provides armor protection.

Hard steel or ceramic facing are used where needed to improve performance for armor piercing projectiles. ShieldStrand® composite armor performs very well against armor-piercing threats when used in conjunction with a steel or ceramic frontal plate. Table 3 provides a typical data range where noted for hard faced or hybrid panels that meet the various levels of performance. The hard facing weight efficiency follows the relative order of performance: SiC > Al_2O_3 > HHS > RHA. Depending on multiple hit and multi-threat requirements, the weight efficiency can favor steel or hybrid facing over ceramic faced armor.

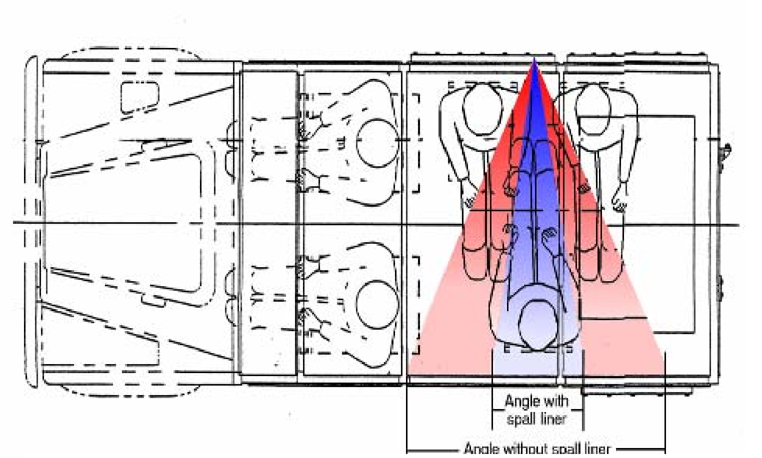
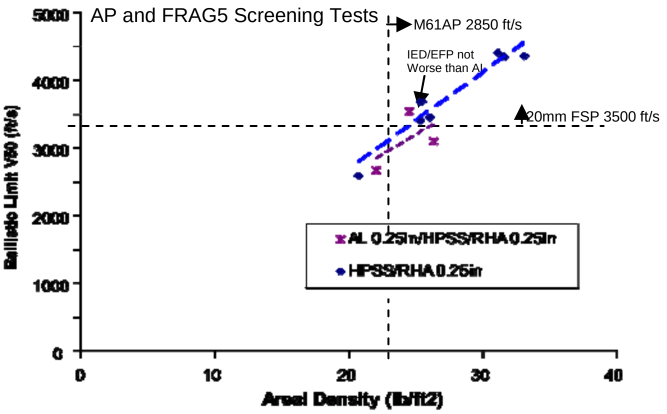


Figure 7. Spall liner mitigation of behind armor effects

Spall liner and IED/EFP kits are designed to work with base armor systems which are integrated or added to the vehicle structure. Figure 7 illustrates how add-on kits protect vehicle occupants by mitigating behind armor effects and debris from overmatch threats to an exit angle of typically less than 20-25 degrees or a 30-50% reduction in cone angle compared to metals. Protection against overmatch threats are screened by fragment simulating projectile (FSP) V50 protection ballistic limit and IED or EFP simulation tests. Figure 8 compares ShieldStrand® phenolic FK5 kit multi-threat screening tests of 20mm FSP and M61AP to arena tests for IED and EFP simulation. Figure 9 compares 20mm FSP V50 performance for ShieldStrand® vinylester as standalone armor, backed by HMWPE and RHA, or hard faced with various metals or ceramics. The highest weight efficiency for 20mm FSP is a hybrid of ShieldStrand® and HMWPE. But AP requirements require the addition of a thin HHS facing or to help contain the HMWPE deformation a backing of RHA. Both STANAG and LTAS requirements are met with ShieldStrand® armor using integrated structural armor.



Areal Density Includes 10.5 lb/ft2 RHA Steel Door Skin

Figure 8. Multi-threat integrated armor- FSP and AP compared to EFP simulation

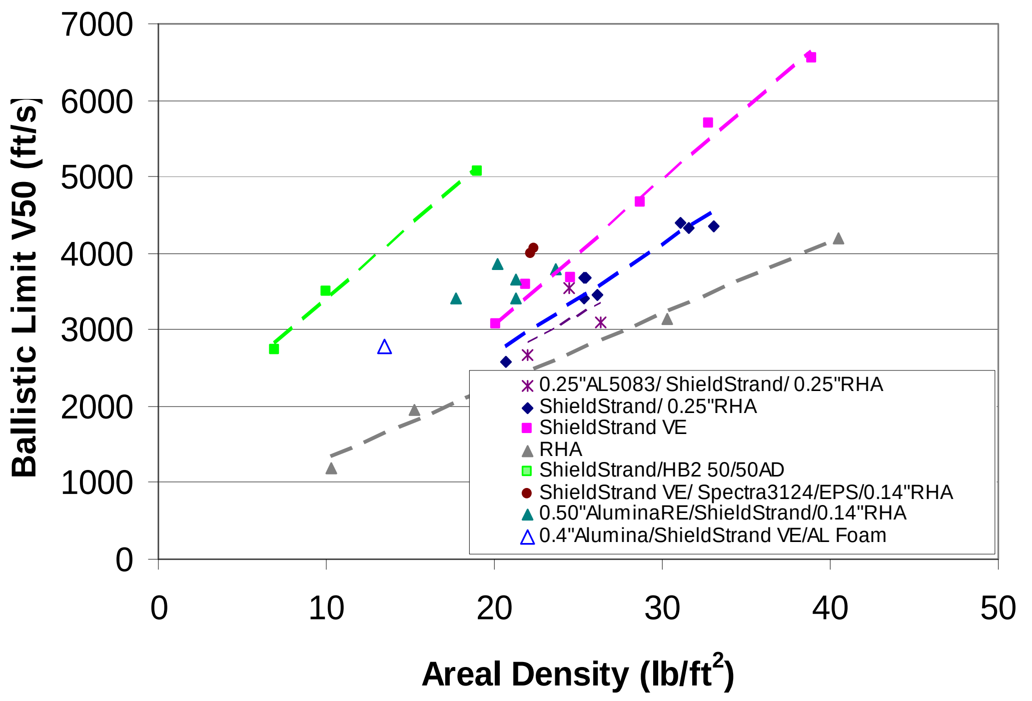


Figure 9. 20mm FSP Screening Comparison of Standalone and Hard Face ShieldStrand® Armor

4. SHIELDSTRAND® SPALL LINER AND EFP KIT FABRICATION

The most common application for ShieldStrand® is spall liners and add-on armor kits. The ShieldStrand® phenolic composite armor system meeting MIL-DTL-64154B is based on OCV HPR fabric reinforcement and high temperature, ablative phenolic resole resins. The ShieldStrand® fabric reinforcement is woven S-glass or R-glass roving meeting MIL-R-60346C, Type III or IV. The resin is a resole phenolic that meets MIL-R-9299C, Grade B. The structural composite armor system allows weight efficient ballistic blast and fragmentation protection along with outstanding fire performance. It effectively mitigates behind armor effects from overmatch threats. The system is robust for producing flat or shaped panels using compression molding, vacuum prepreg consolidation, resin infusion, or pultrusion processes. Structural elastic and strength constants are given in Table 2 for engineering and design. The ShieldStrand® armor panel provides up to 50% weight savings over metals and up to 40% cost savings over comparable performing S-2 Glass and aramid armor panel systems. ShieldStrand® spall liners are in production at multiple manufacturing companies to provide consistent, affordable, and assured availability of the product to MIL-DTL-64154B. The armor system is under evaluation for a number of additional structural and ballistic applications.

ShieldStrand® composite armor kits were successfully fabricated and fastened to existing vehicle metal structures such as doors, sidewalls, and hulls. Typically the kit and fasteners must meet bearing requirements for structural functions along with the ballistic requirements. An example of this is illustrated for a door kit in Figure 10 which must meet depot or field installation tooling and training, as well as all functional requirements such as field abuse, acceptance of accessories, door slam and lifetime utility. The composite armor kits were an alternative to aluminum exterior mounted kits accepting the existing fasteners and hardware used with typical metal systems. This allowed a weight savings of up to 25% over aluminum armor depending on the application and mission requirements. A guide for kit manufacturing specifications and assembly procedure for the door kit fabrication, tooling, and fastener hardware is given in Appendix 1.

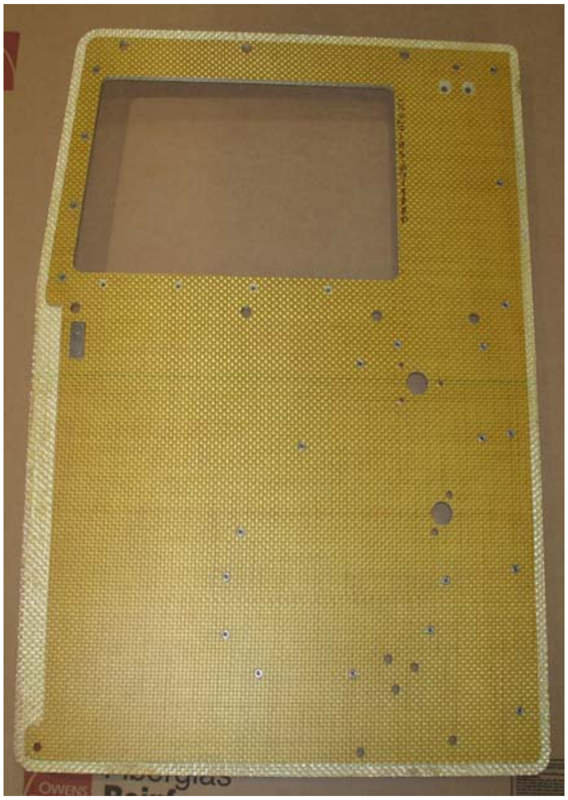


Figure 10. ShieldStrand® phenolic FK5 door kit

5. COMPOSITE INTEGRATED STRUCTURAL ARMOR

Over the past two decades, DoD has sponsored over a dozen composite manned ground vehicle technology demonstrators. These programs include the M113, Bradley turret, AAAV, CIFV, CAV, HCH, FCS, HMMWV, M35, M939 and A3 cab. The composite vehicle programs have demonstrated up to 50% vehicle weight savings, depending on the design criteria, the level of part consolidation and composite material usage. Composite technology has not spiraled into a full vehicle production platform due to the perceived risk of production capacity. Today vehicle OEMs are using composite spall liners, add-on armor kits and other structural components such as hoods, fenders and floors to help reduce weight. Further weight reduction would be realized by integrating armor in the vehicle structure, as validated by many of the technology demonstrators.

Table 4 lists multifunctional performance improvements for several of the composite technology demonstrators. An example of a composite vehicle proof of principle satisfying the Bradley M2A1 system requirements was demonstrated by ARL and previous United Defense (FMC), now BAE Systems, with ballistic protection equivalent to the aluminum hull at 27% reduced weight. Ballistic survivability was enhanced by elimination of spall and improving blast load capacity. The composite infantry fighting vehicle demonstrated mechanical improvements such as a higher fatigue resistance, with 5-10 dB noise reduction, a 67% reduction in heat and cooling loss, plus a reduced infrared, radar and acoustic signature.

Another example was the CAV which demonstrated the feasibility of producing lighter weight ground combat vehicles from composites. The CAV met or exceeded the operational capability for lightweight integrated structure and armor, strategic deployability, enhanced survivability, improved producibility, and affordability. The CAV was an integrated demonstration of composites and lightweight armors on a C-130/C-141 air deployable 22-ton vehicle emphasizing manufacturability, repairability, non-destructive testing, and structural integrity. The vehicle structure and armor weighed at least 33 percent less than the comparable steel or aluminum depending on payload options. The CAV's operational advantages improved deployability and survivability through inherent signature reduction of composite materials with vehicle shape, improved agility and integrated structure and armor. During the program there was validation of composite materials design, models and simulation [12,13]. There was successful integration of structure, armor, and signature materials.

The HMMWV composite vehicle developed by TPI Composites and BAE Systems demonstrated improved durability and up to 30% weight savings depending on payload with the required protection and performance. The prototype composite tactical vehicle used structural composite technology and a proven manufacturing platform to demonstrate utility, durability and survivability.

Table 4. Composite Vehicle Technology Demonstrators and Pre-Production Platforms

Vehicle	**Composites Multifunctional Performance Improvements**	
CIFV	Ballistics	>Equivalent Ballistic Protection at 27-35% Reduced Weight >Enhanced Survivability by Elimination of Spall >Improved Blast Load Capacity
CAV	Mechanical	>Noise Reduction (5 - 10 dB) >Thermal Reduction in Heating/Cooling Loss (60 - 70%) >Reduced Signature (IR, Radar, Acoustic) >Higher Fatigue Resistance
HMMWV	Life Cycle Cost	>Parts Consolidation >Corrosion Resistance >Enhanced Damage Tolerance and Repairability

The weight savings associated with each one of these demonstrators was different, depending on the amount of composites utilized. It was determined that additional weight savings can be realized if the vehicle is designed from the base with composites, rather than converting a metal design to composites [12]. Common risks associated with fielding a vehicle that utilizes composites or integrated composites and metal as the vehicle structure include:

1. Supply chain's ability to meet demand
    - A production rate of 1000 vehicles per month is about the maximum capacity expected.
2. Lack of military vehicle production history with composites versus metals.
3. Improved simulation code capability for prediction of performance.
4. Perceived increased cost associated with composites.
5. Difference in manufacturing techniques required
    - OEM's know metal fabrication and are reluctant to switch
    - Different assembly and fastening techniques required

Recently none of the JLTV submissions were composite based. They all used aluminum due to the perceived risks. To drive technology shifts, the performance criteria must reflect significant requirements for new platforms. The current acquisition process also creates problems for new materials, processes and vendors.

There is a recent increase in requests from OEMs for integrated structural composites. These are usually part requests like hoods, fenders and floors rather than complete vehicle platforms. However there are a few proposals like a composite cab for FMTV. There is significant interest in composite V-hull prototypes with several OEMs. One such program demonstrated successful performance in full scale tests of V-hull ballistic fragmentation and blast as well as diesel fuel fire tests.

Recent material and production advancements have created lower cost composite materials, more conducive to use in large structures. Other industries have adopted these large composite structures to reduce weight, corrosion, and environmental impact. Applications include ships, wind turbine blades, chemical transport and storage containers, and structural aircraft components. Composites enable lower life cycle costs with potential for lower initial costs from assembly and part consolidation, and longer lifetime with enhanced durability from fatigue and corrosion resistance.

Composites are needed to meet the manned ground vehicle requirements for protection, mobility and reduced fuel consumption. To prove adequate capacity is available, a study was initiated to assess the ability of the industrial base to produce light weight composites that meet the Army's demand of 1000 vehicles per month.

6. SHIELDSTRAND® TECHNOLOGY

ShieldStrand® is part of a new family of high performance reinforcements (HPR) with higher strength, stiffness and temperature stability for consideration in the substitution of traditional materials like steel and aluminum. ShieldStrand® manufacturing readiness level (MRL) is 9 and production quality and consistency meet MIL-DTL-64154B. The glass formulation and melting technology allow the capability to produce consistent, high volume, affordable reinforcements. HPR WindStrand® materials are used in the wind energy industry to enable the production of lower cost renewable energy with longer, lighter, and stiffer turbine blades. In the aerospace industry, HPR FliteStrand® is under evaluation for aircraft cargo liners, flooring and blast protection due to its higher modulus, strength and impact toughness. HPR XStrand® is also under evaluation in industrial markets where the high tensile strength, modulus, fatigue resistance, toughness, and corrosion resistance enable lighter pressure vessels for alternative energy storage and longer life high pressure pipe for chemical transport in corrosive environments.

SHIELDSTRAND® MANUFACTURING TECHNOLOGY

Proprietary technology began a new era in reinforcements in 1997 with the introduction of Advantex® glass, a patented boron- and fluorine-free platform that produced higher-performing glass fiber and a significantly smaller environmental footprint compared with standard E-glass processes. By 2006, Owens Corning had extended the use of advanced glass melting technology to bring large-scale production to high-strength glass fiber, an achievement previously thought to be technically unfeasible. The company's first application of this high-strength glass fiber technology was based on an R-glass formulation. The technology was recently extended again to include enhanced S-glass. Capacity for the new direct-melt process is about 50 times the size of paramelters typically used to produce high-strength glass. This large scale production process was developed to make HPR widely available and achieve a level of value that enhances their competitiveness.

ShieldStrand® was developed in 2006 and is a structural and ballistic fiber which exceeds the performance of E-glass, E-CR glass and Advantex® fiber which are used in commercial structural and ballistic applications. Owens Corning conducted structural static, dynamic, and stress-rupture testing to validate that Advantex® was structurally superior with improved modulus and corrosion resistance compared to traditional E-glass [2]. Based on these results Advantex® was qualified in the late 1990's as an E-CR glass according to ASTM D578-00 and DIN1259. ShieldStrand® exceeds these structural and corrosion requirements to allow either longer design life or lighter weight structural composites [3]. R-glass gives benefits such as high tensile strength, modulus, fatigue resistance, and corrosion resistance. ShieldStrand® S further improves strength, modulus and toughness shown in

Figure 11. Fiber Forming

Table 1 which enables lighter weight structural and ballistic performance.

6.2 SHIELDSTRAND® PRODUCT TECHNOLOGY

ShieldStrand® reinforcements are produced with an epoxy compatible sizing. The chemical sizing is applied during the fiber forming process as shown in the Figure 11 illustration. The sizing system promotes resin wetting and level of adherence to the resin matrix. The sizing allows ShieldStrand® to be used in a wide variety of different processes such as pultrusion, filament winding, compression molding and vacuum infusion molding. This epoxy compatible sizing provides optimum performance in most ballistic applications that utilize phenolic, vinylester and thermoplastic systems. It is also ideal for integrated structural applications that use epoxy or blended resin systems. Good sizing interfacial compatibility and adhesion with proper resin system consolidation enables high structural and corrosion performance [3,5]. Structural ballistic performance is enabled with the appropriate sizing formulation for different resin systems and composite processes. This allows engineering the best design for integrated structural armor with multi-functional capability.

Table 1. Reinforcement Fiber Property Comparison

Property	Test Method	Unit	E-Glass	AGY S-2 Glass	OCV S-Glass
Fiber and Bulk Glass Properties					
Density	ASTM C693	g/cm^3	2.55-2.58	2.46-2.49	2.45
Refractive Index (bulk annealed)	ASTM C1648	-	1.547-1.562	1.520-1.525	1.522
Conductivity	ASTM C177	watts/m•K	1.0-1.3	1.1-1.4	1.34
Pristine Fiber Tensile Strength	ASTM D2101	MPa	3450-3790	4830-5205	4826-5081
Specific Pristine Strength	Calculation	$\times 10^5$ m	1.36-1.50	1.98-2.13	2.01-2.12
Young's Modulus		GPa	69-72	86-90	88
Specific Modulus	Calculation	$\times 10^6$ m	2.73-2.85	3.52-3.69	3.67
Elongation at Break		%	4.8	5.4	5.5
Thermal Properties					
Coefficient of Thermal Expansion, 23-300 °C	ASTM D696	$\times 10^{-6}$ cm/cm•°C	5.4	2.8	3.4
Specific Heat @ 23 °C	ASTM C832	kJ/kg•K	0.807	0.737	0.810
Fiber Tensile Strength v. Temperature					
Pristine Fiber Tensile Strength, -196 °C	ASTM D2101	MPa	5310	7970-8270	7826
Pristine Fiber Tensile Strength, 22 °C	ASTM D2101	MPa	3450-3790	4830-5137	5047
Fiber Tensile Strength v. pH, 24 hours @ 96 °C					
Air **(load/initial area)**	ASTM D2101	MPa	3496	5155	4849
Initial pH=1 (HCl + H_2O)	ASTM D2101	MPa	371	3556	4173
Initial pH=4 (HCl + H_2O)	ASTM D2101	MPa	3032	4525	4706
Initial pH=7 (H_2O)	ASTM D2101	MPa	2499	2114	3790
Initial pH=9 (NaOH + H_2O)	ASTM D2101	MPa	2647	2134	2743
Initial pH=11 (NaOH + H_2O)	ASTM D2101	MPa	1884	1456	1781
Fiber Weight Retention v. pH, 24 hours @ 96 °C					
Initial pH=1 (HCl + H_2O)		%	69.25	94.18	97.23
Initial pH=4 (HCl + H_2O)		%	98.79	99.37	98.67
Initial pH=7 (H_2O)		%	98.71	99.20	98.51
Initial pH=9 (NaOH + H_2O)		%	98.88	99.05	98.27
Initial pH=11 (NaOH + H_2O)		%	98.47	97.52	97.63
Impregnated Strand[1] and Shear[2] Properties					
Tensile Strength	ASTM D2343	MPa	2000-2500	3268-3868	3410-3830
Tensile Modulus	ASTM D2343	GPa	78-80	91-92	86.9-95.8
Toughness	ASTM D2343	MPa	37	66-91	82-90
Shear Strength (NOL Ring) - Dry	ASTM D2344	MPa	52.2	63.1	70.7
Shear Strength (NOL Ring) - 96 Hour Boil	ASTM D2344	MPa	46.9	54.0	62.3
Unidirectional Composite Properties[2]					
Tensile Strength	ASTM D3039	MPa	889-1013	1420-1448	1503-1538
Tensile Modulus	ASTM D3039	GPa	41-44	48-54	50-55
Poisson's Ratio	ASTM D638	-	0.29	0.26	0.27
Resin Content by Weight	ASTM D2584	%	26-30	26	25-28
Fiber Volume Fraction	ASTM D2734	%	49-55	53-56	55-58
Biaxial Composite Properties[2]					
Instrumented Impact - Total Energy (V_f = 0.74)	ASTM D3763	J	56.9	56.5	60.2

[1] Hexion MGS RIM 135 epoxy resin + RIMH 137 hardener

[2] Hexion Epon 826 epoxy resin + Albemarle Ethacure 100 hardener

Table 2. Structural, Thermal and Ballistic Plate Properties

Property	Test Standard ASTM	ShieldStrand® Phenolic Plate (Typical range)
Elastic Constants		**10^6 PSI**
Longitudinal Modulus	D3039, D638	3.5 - 4.6
Transverse Modulus	D3039, D638	3.5 - 4.6
Axial Shear Modulus	D3518	0.5 - 0.7
Axial Comp Modulus	D695	5.2 - 6.7
Poisson's Ratio	D3039	0.24 - 0.27
Strength Properties		**10^3 PSI**
Longitudinal Tension	D3039, D638	60 - 100
Longitudinal Compression	D3410, D695	20 - 80
Transverse Tension	D3039, D638	60 - 100
Transverse Compression	D3410, D695	20 - 80
Normal Compression	D695	100 - 120
In-Plane Shear	D3518	17 - 30
Interlaminar Shear	D2344	1.9 - 4.0
Longitudinal Flexural	D790	20 - 45
Longitudinal Bearing	D953	35 - 80
Ultimate Strains		**%**
Longitudinal Tension	D3039, D638	1.5 - 4
Longitudinal Compression	D3410, D695	0.7 - 2
Transverse Tension	D3039, D638	1.5 - 4
Transverse Compression	D3410, D695	0.7 - 2
In-Plane Shear	D3518	2 - 2.5
Physical Properties		
Fiber Volume	D2734	61 - 66%
Resin Weight	D2584	16 - 24%
Water Absorption	D570, D792	<1%
Longitudinal Flexural, Wet Ret.	D790	>70%
Thickness (in.)	25 ply	0.470 - 0.530
Ply Thickness (in.)	25 ply	0.019 - 0.020
Areal Density (lb/sf)	25 ply	4.6 - 5.4
Density (lb/ci)	D792	0.072 - 0.074
Hardness (M scale)	D785	>80
Speed of Sound (ft/sec)		8000-9500
Shock Velocity Plate Impact (mm/us)		2.6-3.0
Thermal Properties		
Thermal Shock -65°F to 250°F	MS810	No delamination
Coef Thermal Expansion (in/in/°Fx$10^{-6)}$		4.1-5.8
Thermal Transition (°F)	D4065	210 - 340
Thermal Conductivity (W/m-°K)		0.25-0.30
Flammability UL	UL 94	V0
Flammability DOT FMVSS	302	Pass
Time to Ignition @50kW/sm (s)	E1354	500 - 600
Total Heat Release (MJ/sm)	E1354	25 - 60
MAHRE (kW/sm)	E1354	20 - 35
FIGRA	E1354	0.10 - 0.20
Flame Spread Index	E162	1
Oxygen Index 23C, 150C	D2863	56, 75
Smoke Obscuration Flaming, NonFlaming	E662	30, 2
Ballistic Properties		
7.62mm FSP PBL V50 (ft/sec)	MIL-DTL-64154B	>2455

Table 3. Ballistic Specifications and Typical ShieldStrand® Performance Range

Vehicle Armor Standards and Protection Levels

		Projectile	**Required Velocity**		**Typical Areal Density Range**	
NIJ 0108.01 - Ballistic Resistant Protective Materials			**(ft/s)**	**(m/s)**	**(lb/ft2)**	**(kg/m2)**
I	A	22 LRHV Lead 2.6g	1050	320	0.7-1.2	3.5-5.8
	B	38 Special RN Lead 10.2g	850	259	0.7-1.0	3.5-4.9
II-A	A	357 Magnum JSP 10.2g	1250	381	1.0-1.3	4.9-6.5
	B	9 mm FMJ 8.0g	1090	332	0.8-1.0	3.9-4.8
II	A	357 Magnum JSP 10.2g	1395	425	1.1-1.5	5.5-7.4
	B	9 mm FMJ 8.0g	1175	358	1.1-1.2	5.4-5.9
III-A	A	44 Magnum Lead SWC Gas Checked 15.55g	1400	426	1.7-2.4	8.1-11.7
	B	9 mm FMJ 8.0g	1400	426	1.4-1.6	6.8-7.9
III		7.62 mm 308 Winchester FMJ 9.7g	2750	838	9.6-10.6	47-52
IV		30-06 AP 10.8g	2850	868	8.8-13.5	43-66*
STANAG 4569 - Protection Levels for Occupants of Light Armored Vehicles						*with facing
Level 1	A	5.56 mm X 45 mm M193	3074	937	7.6-8.6	37-42
	B	5.56 mm X 45 mm SS109	2953	900		
	C	7.62 mm X 51 mm NATO ball	2733	833	6.6-8.0	32-39*
Level 2		7.62 mm X 39 mm API BZ	2280	695	6.6-9.6	32-47*
Level 3	A	7.62 mm X 54R mm B32 API	2772	845	13-14.2	64-69*
	B	7.62 mm X 51 mm AP (WC core)	3051	930	13.7-14.8	67-72*
Level 4		14.5 mm X 114 mm API/B32	2989	911	16-19.5	78-95*
Level 5		25 mm X 137 mm APDS-TM-791, TLB 073	4127	1258	53-59.5	260-290*

Table 4. Composite Vehicle Technology Demonstrators and Pre-Production Platforms

Vehicle	**Multifunctional Performance Improvements**	
CIFV	Ballistics	>Equivalent Ballistic Protection at 27-35% Reduced Weight >Enhanced Survivability by Elimination of Spall >Improved Blast Load Capacity
CAV	Mechanical	>Noise Reduction (5 - 10 dB) >Thermal Reduction in Heating/Cooling Loss (60-70%) >Reduced Signature (IR, Radar, Acoustic) >Higher Fatigue Resistance
HMMWV	Life Cycle Cost	>Parts Consolidation >Corrosion Resistance >Enhanced Damage Tolerance/Repairability

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Appendix. Specifications and Assembly Procedure for Armor Kit Manufacturing

The following specification and assembly of the door, serves as a guide for the manufacturer’s assembly procedure. The assembly of the ShieldStrand® composite armor kit follows the procedure for first cutting the ShieldStrand® composite panel, then machining contact and fastener points into the panel, and then inserting and adhering fasteners into the panel.

CUTTING COMPOSITE PANEL

Figure 11. Composite Door Fabrication

Molded ShieldStrand® panels can be cut using water jet cutters and wet saws (Figure 12). All wet and dry blades should be solid carbide or carbide coated as shown in Table 5. Wet machining of composites will require either separation or isolation of cuttings from normal cooling flow. Dry machining of composites will produce significant amounts of dust and it is recommended using dust mitigation systems such as vacuums. A large disc wet saw is used for the straight cuts. CNC milling is used for all complex cuts. Water jet cutting is also used for all cuts and requires the use of garnet abrasive. The suggested procedure for cutting is as follows:

1. From a blank panel, complete cut outs on base panel per a CAD drawing or direct programming.
2. Make a cut along the angle highlighted on the CAD drawing.
3. Make all radius cuts along the four corners.
4. Cut out window panel with radius cuts in each corner.

Figure 13. Composite Machining

MACHINING CONTACT AND FASTENER POINTS

Machining contact and fastener points can be done by CNC and standard drill presses and routers. All tooling should be solid carbide or carbide coated and examples are listed in Table 5. Wet machining of composites will require either separation or isolation of cuttings from normal cooling flow. Dry machining of composites will produce significant amounts of dust and it is recommended that dust mitigation systems such as vacuums be used. The suggested procedure for the hardware contact areas is to remove a surface seal contact strip around the outside of the door. The machining steps for inserts and bolt-through points are as follows:

1. For assembly of the prototype, all holes were made with a drill press with a vacuum hose to collect cuttings. (Figure 13)
2. Some of the holes produced using the wet jet cutters were slightly oval. However, this did not effect the insertion or adhesion of the metal fasteners.
3. A section of the door required two through-bolts in close proximity as shown in the CAD detail. If these bolts were fastened into the composite with traditional liners, there would be potential damage of

the panel. A special steel reinforced fastener was devised from welding two bolts to a single connector plate. A relief for this connector plate was milled into the composite as illustrated in Figure 14.

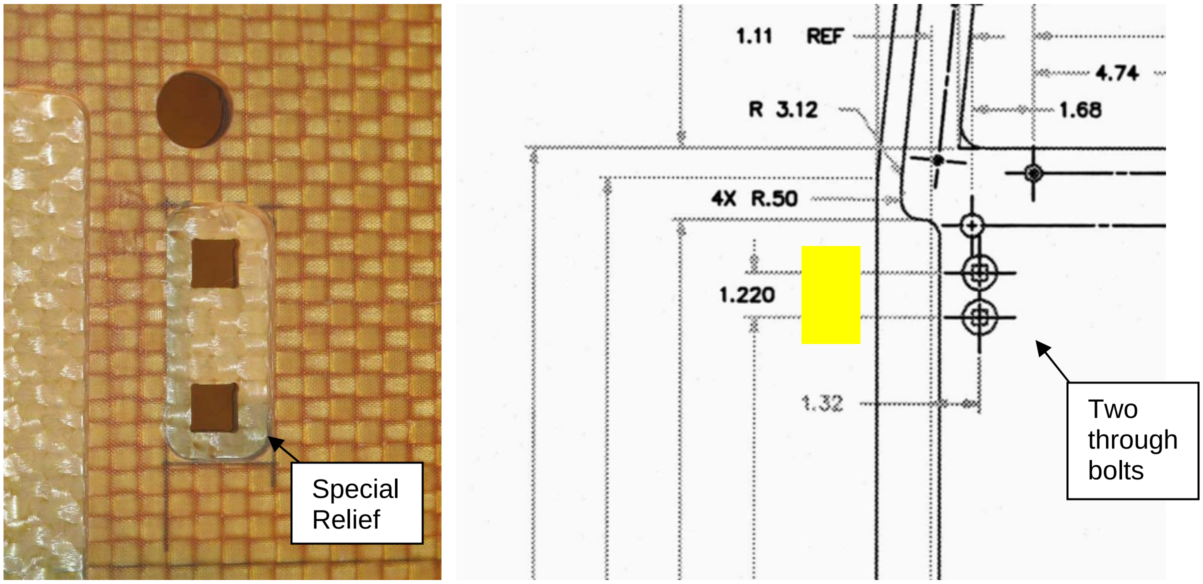

Figure 14. Special Fastener Details for Bearing Strength

INSERTING AND ADHERING FASTENERS

Threaded fasteners identified in Table 5 were pressed into the composite armor to allow bolting of the liner to the steel door. Prior to insertion, either the hole in the panel or the outside of the fasteners are coated with epoxy to adhere the fastener to the armor liner. The fasteners are inserted manually with a hammer or pressed at less than 100 psi (Figure 15). Table 5 lists all fasteners and hardware required with a part number and a typical vendor source for the door kit example. Similar concepts, tooling and hardware could be used for other add-on exterior mounted armor kits.

Figure 15. Insertion of Fasteners

Table 5. Tooling and Hardware for Armor Kit Requirements

Tooling and Hardware for ShieldStrand® Door Panel					
Tooling					
Item	**Type**	**Qty.**	**P/N**	**Typical Source**	
Solid Carbide Burr 1/2" dia. / end cut	double cut	6	200413	Tri-Chem	TRI-CHEM CORPORATION-MADISON HEIGHTS, MI P: 800.456.6255 X 275
#6 Carbide Drill-CSK	82 deg.	3	1042266	MSC	MSC INDUSTRIAL SUPPLY - mscdirect.com 800.645.7270
				Hannibal	Hannibal Carbide - Hannibal, MO P: 573.221.2775 distributor -Dayton Tool & Supply
Carbide Countersink	1/2" x 82 deg.	6	58316	Hannibal	
Carbide Countersink	7/8" x 82 deg.	6	58328	Hannibal	
Carbide Countersink	11.00mm .4331	1	514110	Hannibal	
Short Pilot	1/4" x 5/32"	1	50308	Hannibal	
Hardware					
Item	**Type**	**Qty.**	**P/N**	**Source**	
Threaded insert ,zinc plate steel, int. thread 1/4" x 20 15/32" long	Zinc plated steel	18	97191A230	McMaster	McMasterCarr 1.330.995.5500 Note: To fit 1/2" armor with maximum thread engagement cut to 5/16" long and chamfer outside leading edge for insertion.
Adhesive					
Item	**Type**	**Qty.**	**P/N**	**Source**	
Dexter Hysol EA 9430	Ultra-Hi Strength Epoxy	1	EA9430 kit	Rudolph	Rudolph Brothers P: 614.833.0707 F: 800.600.9508