THE SYNERGISTIC ROLES OF HIGH STRENGTH GLASS COMPOSITE AND ALUMINA CERAMIC FACING IN LIGHTWEIGHT COMPOSITE ARMOR AGAINST ARMOR PIERCING PROJECTILES

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SUMMARY

The mechanisms for defeating an armor piercing projectile threat using ceramic-faced fiberglass composite armor will be discussed. Composite materials display an exceptional energy absorption capacity when compared on the basis of weight with monolithic systems. However, the penetrating capabilities of modern armor-piercing projectiles are known to overwhelm fabric-based composite armor, necessitating the addition of a hard material to face the armor. The resulting system can be viewed as macro-composite in which each component of system has a role in defeating the threat. In this paper, the mechanisms and roles of an *S-2 Glass*® fiberglass composite and alumina tiles of a ceramic-faced composite armor system in defeating an armor-piercing round are identified and discussed. A predictive model for the ballistic protection behavior of a ceramic-faced fiberglass composite armor system is presented and validated with experimental data.

1. INTRODUCTION

In order to provide light, rapidly deployable vehicles for the support of ground troops, armored vehicle designers are increasingly turning to composite materials for improved strength and stiffness to weight ratios. Composite materials are also becoming popular as lightweight armor. One popular vehicle using this approach is the M1114 High Mobility Multi-Purpose Wheeled Vehicles (HMMWV or Humvee). The composite used to armor the Humvee is called HJ1. It is a patented, licensed system that complies with MIL-L-64154. It is comprised of high-strength *S-2 Glass* fibers and phenolic resin, laminated into hard armor panels that offers superior protection against fragmented ballistic threats when compared to monolithic systems on an equivalent weight basis. However, all fiber-based composite armors have difficulty protecting against modern armor-piercing threats.

Armor piercing ammunition is designed to penetrate the hardened armor of modern military vehicles. It is typically comprised of a sharp, hardened steel or tungsten carbide penetrator covered with a guilding metal jacket that adds mass and allows the projectile to conform to a rifled barrel and spin for accuracy. When an AP round hits armor, the guilding is rapidly deformed and drops away, leaving the sharpened penetrator traveling with a high velocity to bore its way through the armor. This mechanism is quite effective against fiber-based composite armors due to the inability of the armor to blunt the hardened tip. One common design to defeat this threat is the addition of a hardened face on the armor. The hypothesis is that the hardened face will blunt the projectile and limit its ability to focus energy at a pointed tip. Ceramic plates have served this purpose quite well.

Designing an armor system to defeat a given threat level is a relatively straightforward task. Several trial areal densities (weight per unit area) in the expected range are tested against the threat at varying velocities. The velocity at which a given threat is found to penetrate a given areal density of armor 50% of the time is called a V50. A plot of areal density vs. V50 is constructed, and the areal density at which the V50 equals the expected impact velocity of the incoming threat is interpolated. Typically a linear relationship is assumed. Of course, the result must be verified with further testing, and finally a safety factor of the armor designer's choice is added such that the probability of the incoming threat penetrating the armor is exceptionally low.

However, for an armor consisting of a ceramic face and a composite backing, there is another variable in addition to areal density that must be considered. The ratio of ceramic areal density to composite areal density has been found to dramatically affect the performance of ceramic-faced composite armor. This factor is the focus of this paper, as it has not been studied in detail to date in an unclassified format.

2. LITERATURE REVIEW

The ballistic penetration of *S-2 Glass* fiber based composite panels has been studied frequently in the past 17 years. In 1986, Owens Corning began investigating the possibility of using these high strength fibers for ballistic applications. The *S-2 Glass* has a higher strength, modulus, and elongation than the more common E-glass fibers. Thus the energy absorbing potential of these fibers is much higher. In an early study, Hartman prepared and tested many *S-2 Glass* fiber composites at the University of Dayton Research Institute. He found that the total energy dissipation potential of these composite panels is the sum of the strain energy and kinetic energy, both of which increase in direct proportion to the areal density of the panels [1]. In a later study, Bless and Hartman found that for a broad range of fragment simulating projectiles (FSP's), a linear relationship existed between the V50 and the areal density divided by sample thickness [2]. They suggested that this meant that the resistance to penetration was proportional to the number of fibers intersected by the projectile.

Bless and Hartman also studied the differences in penetration mechanisms for blunt-faced and sharp projectiles using a novel x-ray photographic technique that allowed the projectile's path and speed to be measured throughout the impact [3]. Using these data, they found that the initial and intense impact shocks contributed significantly to the deceleration of blunt projectiles. The tested panels were also examined by cross-sectioning the composite across the penetration path of the projectile. The study found that energy loss was strongly affected by projectile nose shape. Blunt projectiles were less effective at penetrating because the fibers penetrated had to be cut twice and the material in front of the projectile had to be accelerated rearward. On the other hand, sharp-nosed projectiles tended to move the fibers laterally away from the advancing projectile, resulting in kinked fibers around the penetration cavities with little energy absorption. The primary reason why armor-piercing projectiles are so effective against all fiber-based composite armor is that neither the fiber nor matrix material of the composite is hard enough to cause deformation of the sharp, hardened penetrator nose.

For non-AP systems, such as .30 cal M80, a full metal jacketed (FMJ) round, the performance of 100% HJ1 systems has been investigated in the past. Figure 1 shows a plot of V50 as a function of areal density for the HJ1 composite against the .30 cal M80 FMJ round [4]. The HJ1 is quite effective at stopping the FMJ threat; however, it requires a facing to stop AP threats.

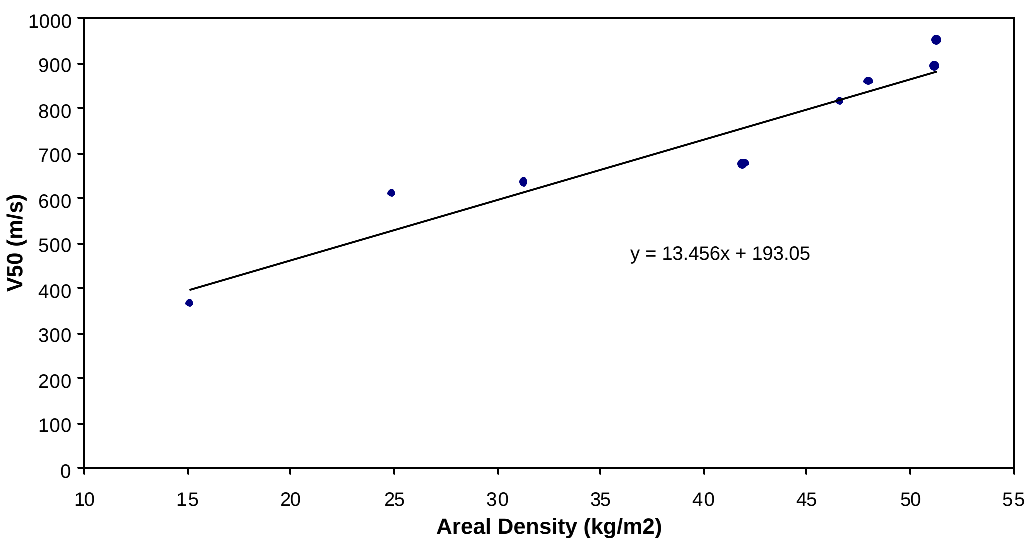

Figure 1. HJ1 Performance against an FMJ threat

One solution to stopping armor-piercing rounds that has been successfully implemented is to apply ceramic tiles to the composite. The components of this macro-composite system each have a specific role. Ceramic tiles are light, hard, and strong in compression. When a ceramic tile sustains a ballistic impact, the face of the tile experiences compressive forces, against which ceramics are extremely strong and typically will not fail. Erosion of the projectile tip occurs first, followed by failure of the ceramic in tension as the compressive shock wave reaches the back surface of the tile and is reflected as a tensile wave [5]. However, by the time the ceramic fails, it has absorbed some energy, but more importantly it has eroded the tip of the projectile so that it cannot easily push aside the fibers in the composite backing.

The composite backing material (HJ1) used in the above macro-composite solution serves a dual purpose; it carries the bulk of the load when the armor is used for structural applications in addition to ballistic protection. It also absorbs the kinetic energy of the armor-piercing projectile once its tip is blunted. The kinetic energy is absorbed through a combination of fiber strain and fracture, fiber pullout, and composite delamination. One adjustable parameter that is not fully understood in open literature to date is the influence of varying the ratio of composite backing to ceramic facing on the ballistic performance of the macro composite system. In this study, different HJ1 to ceramic ratios of a fixed areal density macro-composite were tested for ballistic performance.

3. EXPERIMENTAL

Various Al_2O_3 ceramic tiles were attached to different thickness HJ1 panels with an elastomeric adhesive. The tiles and composite were cleaned and lightly sanded to insure a good bond. The adhesive thickness was controlled to 0.5mm using wire spacers at the tile corners. The thickness of the components was selected such that the total areal density of each panel was 51kg/m^2. The glue was allowed to cure, and then the panels, and a sample of ceramic tile without composite backing, were tested for ballistic performance against a .30 caliber APM2 projectile. Each panel's construction and ballistic test performance are given in Table 1.

Panel	HJ1 (kg/m^2)	Alumina (kg/m^2)	Total (kg/m^2)	HJ1 Content (%)	V50 (m/s)
1	39	12	51	77	562
2	28	23	51	55	780
3	20.5	30.5	51	40	948
4	0	51	51	0	<550

TABLE 1. Summary of Ballistic Panel Data

The data point at 0% HJ1 is the slowest velocity possible with the ballistic set-up. The actual V50 for the ceramic alone is lower. When these results are plotted as ballistic performance against HJ1 content as in Figure 2 below, it becomes apparent that there is an inflection point between 0 and 40% HJ1 where ballistic performance is maximized. At HJ1 compositions above 40%, the results are quite linear, and decrease with increasing HJ1 content.

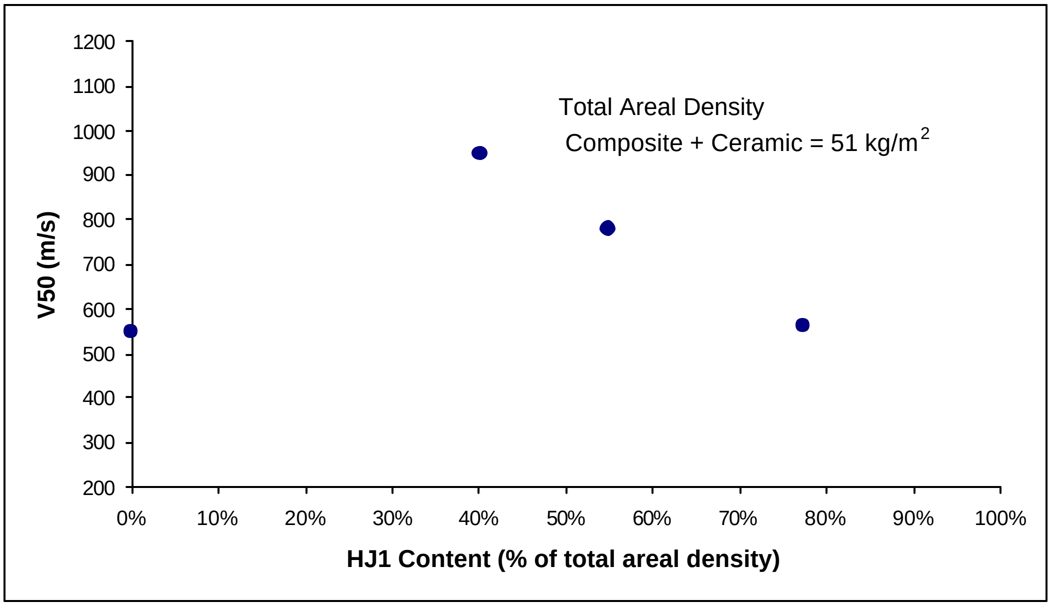

Figure 2. Ballistic Performance of Various Systems

The data above 40% HJ1 content can be analyzed using a rule-of-mixtures composite approach. The data can be found to fit Equation 1 below, which is similar to that typically used for strength and modulus of a unidirectional composite panel tested in the longitudinal direction. In this equation, Wf is weight fraction.

$$V50_{composite}=V50_{ceramic}Wf_{ceramic}+V50_{HJ1}Wf_{HJ1} \quad (1)$$

The data from Table 1 can be used to solve this equation above 40% HJ1. It can be shown that the V50 constant associated with the ceramic portion of the composite in this region is 1381m/s, and the V50 constant associated with the HJ1 portion is 299m/s. However, at low HJ1 composition ratios (below the inflection point) the relationship does not hold true.

4. CONCLUSION

The macro-composite armor solution comprised of Al_2O_3 ceramic tiles and HJ1 composite backing has a maximum .30 cal APM2 V50 of 948m/s at an areal density of 51kg/m^2. This compares well against traditional hard steel armor, which requires more than 3 times as much areal density to defeat the same threat [6]. For unfaced HJ1 of 51kg/m^2, the V50 for .30 cal APM2 is expected to be near 300m/s. However, for non-AP threats, such as the .30 cal M80, 51kg/m^2 of HJ1 produces a V50 of about 880m/s. This vast difference in results is evidence of how devastating the AP round is against composite armor, and a strong argument for the need of a ceramic facing to defeat armor piercing threats. However, a superior composite backing, such as HJ1, is required to absorb the kinetic energy and to provide structural performance after ballistic impact. The ceramic tile, on the other hand, shatters and offers little mechanical support after impact.

A similar effect has been observed for ceramic-faced HJ1 panels in defeating the STANAG level 5 (14.5mm B-32 API) and the .50 cal M2AP threats. In each of these cases, the combined stopping ability of the system of HJ1 backing and ceramic facing has yielded superior results to that of the individual components. The synergistic effect of the alumina and HJ1 components is evident. The results presented in this paper support the hypothesis that each component of the composite system has a particular role in defeating and AP threat. The proposed mechanism for stopping the AP round is that the ceramic blunts the penetrator upon impact, while the HJ1 composite panel absorbs the bulk of the projectile's energy through various mechanisms including fiber strain and fracture, fiber pullout, and delamination.

The ballistic performance of the macro-composite solution greatly depends upon the ratio of ceramic to HJ1 composite. The solution has its maximum performance somewhere between 0 and 40% by weight HJ1. In the range of >40% by weight HJ1, the ballistic performance of the macro composite system follows a rule-of-mixtures performance model, with the V50 constant of the ceramic at approximately 1380m/s and the V50 constant of the HJ1 at about 300m/s.

5. REFERENCES

[1] HARTMAN, D.R., Ballistic Impact Behavior of High-Strength Glass-Fiber Composites, 41st Annual Conference, Reinforced Plastics Institute, The Society of the Plastics Industry, Inc., January 1986, Session 16-D, pages 1-5

[2] BLESS, S.J. and HARTMAN, D., Ballistic Penetration of *S-2 Glass* Laminates, 21st SAMPE Technical Conference, September 1989, pages 852-866.

[3] BLESS, S.J., BEYAMI, M, and HARTMAN, D., Penetration Through Glass Reinforced Phenolic, 22nd SAMPE Technical Conference, November 1990, pages 293-303.

[4] Advanced Glassfiber Yarns Ballistics Training Manual, 2002.

[5] LANKFORD, J. AND GRAY, W., Composite Armor, in Concise Encyclopedia of Composite Materials, Edited by A. Kelly, Pergamon Press, 1989, pages 55-62.

[6] U.S. Military Department of Defense Specification MIL-A-12560H95, July 1991.