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THE DEVELOPMENT OF COMPOSITE SABOTS FOR KINETIC ENERGY PROJECTILES

Bruce P. Burns[1], William H. Drysdale[2], Christopher P. R. Hoppel[2], and Travis A. Bogetti[2]

[1] U.S. Army Research Laboratory, ATTN: AMSRL-WM-T, Aberdeen Proving Ground, MD 21005-5066
[2] U.S. Army Research Laboratory, ATTN: AMSRL-WM-MB, Aberdeen Proving Ground, MD 21005-5069

Abstract

This paper describes the development of a composite sabot for armor-piercing, fin-stabilized, discarding-sabot (APFSDS) kinetic energy (KE) projectiles. A sabot is the package that carries the kinetic energy (KE) subprojectile while in the bore of the gun. As such, it has several functions: to support the long-rod penetrator during high axial acceleration, to seal the bore of the gun to the high-pressure propellant gas, and to separate from the penetrator after muzzle exit with minimal transverse disturbance on the penetrator motion. Since the sabot is discarded after muzzle exit, the sabot mass is parasitic, reducing the kinetic energy available to the penetrator from the launch phase. This consideration leads directly to the crucial requirement to minimize sabot weight. The efficiency of composite materials to reduce the weight of sabots was demonstrated during the Armament Enhancement Initiative (AEI) program. In the course of this program, two new kinetic energy 120-mm tank gun cartridges featuring different sabot and propelling charge technologies were type-classified. The first (the M829A1) was developed very rapidly using state-of-the-art aluminum sabot technology. The sabot for the later, higher performance cartridge (the M829A2), was manufactured with graphite fiber-reinforced epoxy material and represented a 35% sabot weight reduction.

The sabot for the M829A2 projectile represents a substantial stop in the development of composite materials. The sabot is one of the first high-performance, thick-section composite parts to be designed and manufactured in production. New analysis tools were developed to model the processing of the composite materials, the design loads on the structure, and the effects of defects in the thick-section parts. This has included the development of LAMPAT software, which allows ply-level analysis of thick-section, three-dimensional composite structures. In conjunction with LAMPAT, a new composite failure criterion was developed to account for the unique loading conditions within the sabot. Subscale experiments were developed and used to define strength allowables in locations where numerical models could not predict structural performance. Processing models was developed to minimize the effects of defects in the structures and reduce manufacturing cost. The results of this work led to the ability to rapidly design highly efficient sabots with minimal experimentation on full-scale structures.

1. INTRODUCTION

Kinetic energy (KE) ammunition is the primary method of defeating enemy main battle tanks in tank-to-tank encounters. This type of ammunition relies on kinetic energy achieved through high velocity and heavy, high-aspect-ratio rods to penetrate the heavy frontal armor of a main battle tank. It is through the use of the kinetic energy that the rod penetrates the hull and destroys the tank.

In KE ammunition, the sabot is the component that carries, by shear transfer along a grooved interface, a sub-caliber projectile (the subprojectile) during the roughly six milliseconds of in-bore time. It must support the subprojectile through axial accelerations of up to 75,000 g's, withstand pressure from the gun ballistics (breech pressures over 100,000 psi), and provide the "suspension" for the subprojectile by controlling transverse motion as the projectile accelerates down the gun tube. Upon muzzle exit, the sabot must discard with minimal disturbance to the flight of the projectile. Therefore, the sabot is responsible for the structural integrity of the projectile and provides the initial conditions for the flight of the projectile, influencing its accuracy.

The only part of the projectile that reaches the target is the subprojectile. The mass in other parts of the projectile (the sabot, obturator, and seals) is parasitic and limits the kinetic energy available for penetration. Since the penetration effectiveness of the subprojectile is proportional to the velocity on target, it is paramonnt that the sabot, seal, and obturator be as light as possible to maximize the kinetic energy of the subprojectile. This consideration leads directly to the crucial requirement of minimizing sabot weight to maximize the lethality of the round.

The efficiency of composite materials to reduce the weight of sabots was demonstrated during the Armament Enhancement Initiative (AEI) program [1] and [2]. In this program, two new 120-mm kinetic energy cartridges, the M829A1 and the M829A2 variants, were type-classified. The first variant was developed very rapidly using state-of-the-art aluminum sabot technology. The sabot for the second variant was manufactured with graphite fiber-reinforced epoxy material and represented a 30% sabot weight reduction from the first variant (about 2.25 lb). This weight reduction translated directly to increased muzzle velocity for the projectile (approximately 60 m/s) and increased armor penetration at the target.

2. STRUCTURAL DESIGN

As KE projectiles are accelerated forward, they can transfer on the order of 1.25 million pounds of force into the subprojectile. This force accelerates the projectile forward at accelerations on the order of 75,000 g's. This inertial loading will fracture the penetrator if it is not properly reinforced. Successful launches of monolithic, high density long-rod penetrators were originally accomplished with single ramp sabots which were either loaded from behind (so that the sabot and the subprojectile were loaded in compression) [3] or from the front (so that the sabot and sub-projectile were loaded in tension). [4] demonstrated that the most efficient method of carrying these loads was through the use of double-ramp sabots. In double-ramp sabots, the projectile is obturated (or sealed to the gun bore) from the center so that the back half is loaded in tension and front is loaded in compression as shown in Figure 1. The thickness of the aft ramp, saddle, and forward ramp regions in the sabot are inversely proportional to the axial elastic modulus of the sabot material. Therefore, increasing the axial elastic modulus and strength of the material allows for the thinner ramps and therefore lighter sabots.

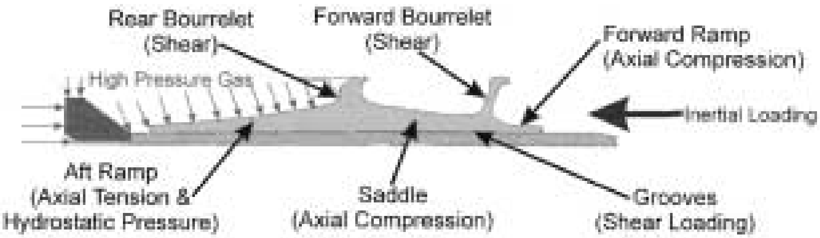

Figure 1. Axi-Symmetric view of a kinetic energy projectile. The major regions of the sabot and their loading requirements are indicated.

Materials Selection. The selection of the best material for the sabot can then be made on the basis of the highest ratio of strength and stiffness to density. Figure 2 is an Ashby [5] diagram comparing the specific stiffness (stiffness divided by density) to the specific strength (strength divided by density) for a series of engineering materials. Most monolithic metals (steel, aluminum, and titanium) have relatively equivalent specific engineering properties and fall in the center of the diagram. Fiber reinforced composite materials can have significantly higher specific properties in the direction of the fibers than conventional design materials. However, transverse to the fiber direction, the composites have relatively poor engineering properties. To efficiently design structures with composite materials for multi-axial loading, laminates are made with varying fiber orientation. This allows the strength to be tailored in the necessary directions. Structural design of sabots utilizing composite materials then requires an understanding of how composites carry load, how failure occurs in composite materials, how the architecture of these materials affects load transfer, and the important role of sabot geometry in ensuring efficient load distribution thronghout the sabot.

Analysis of Composite Material Structures. The heterogeneity of laminated composite structures and their inherent anisotropic properties make composites more difficult to analyze than traditional isotropic materials. The analysis of laminated composite structures is further complicated by the increased propensity for severe stress gradients to develop within anisotropic materials. Failure prediction of laminated composite structures must be based on the stress and strain states within the constituent lamina or plies. It is therefore necessary to compute, with reasonable accuracy, the ply-level stress and strain states throughout the laminated composite structure before any failure criterion is implemented, upon which design decisions may be based.

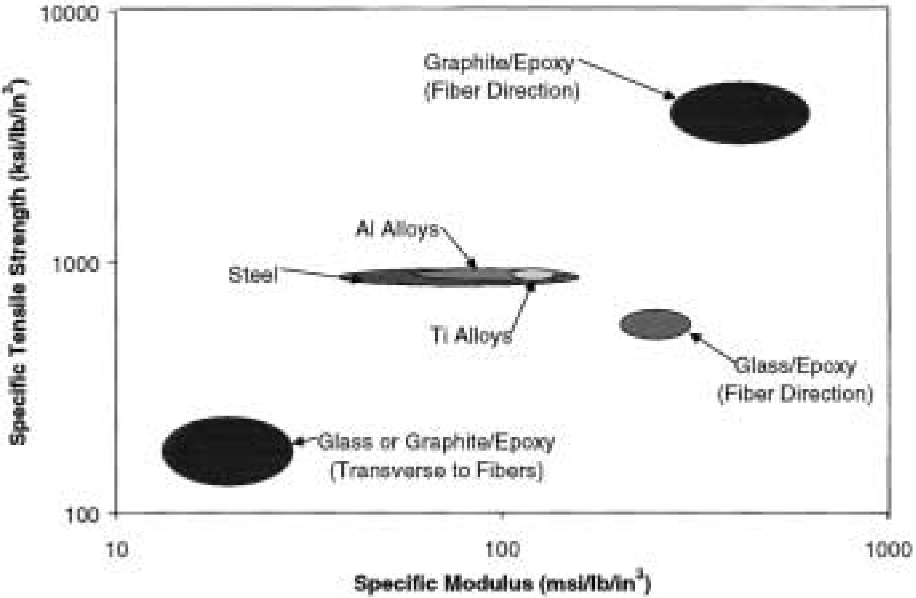

Figure 2. Diagram comparing the specific stiffness (stiffness divided by density) to the specific strength (strength divided by density) for some engineering materials [5].

Ply-by-ply stress and strain calculations may be pursued through two distinctly different approaches. One obvious approach is to treat the entire composite structure as a heterogeneous continuum, modeling each individual ply as a discrete material. Experience has shown that several finite elements through the thickness of a single ply are typically required to achieve accurate results. For thick multilayered composite structures (such as a sabot), this approach is not realistic due to computational limitations.

To circumvent the difficulties associated with the detailed ply-by-ply analysis, a “smearing-unsmearing” approach is used in the present analysis based on the numerical model presented by [6]. This approach has been developed in a computer code entitled LAMPAT 171. Using LAMPAT, representative sublaminate configurations in the sabot are first identified. Sets of equivalent or effective homogeneous properties for these representative sublaminate configurations are then computed. This step is referred to as the “smearing” of the properties. A typical structural analysis is then conducted, employing the effective thermo-mechanical properties as input, to obtain the average stress and strain distributions within the structure under the prescribed loading. At any local region in the sabot, the ply-by-ply stresses and strains can then be obtained by solving the laminated media problem with the average stress and/or strain values being applied as local boundary conditions onto the representative sublaminate configuration. This step is referred to as the “unsmearing” of the laminate stress and strains. Once the ply-by-ply stress and strain states are determined, an appropriate ply level failure criterion can be applied to assess failure. In the LAMPAT code, this procedure is used throughout the structure (i.e., for every element), ultimately providing structural performance or safety margin contour plots. This procedure is illustrated schematically in Figure 3.

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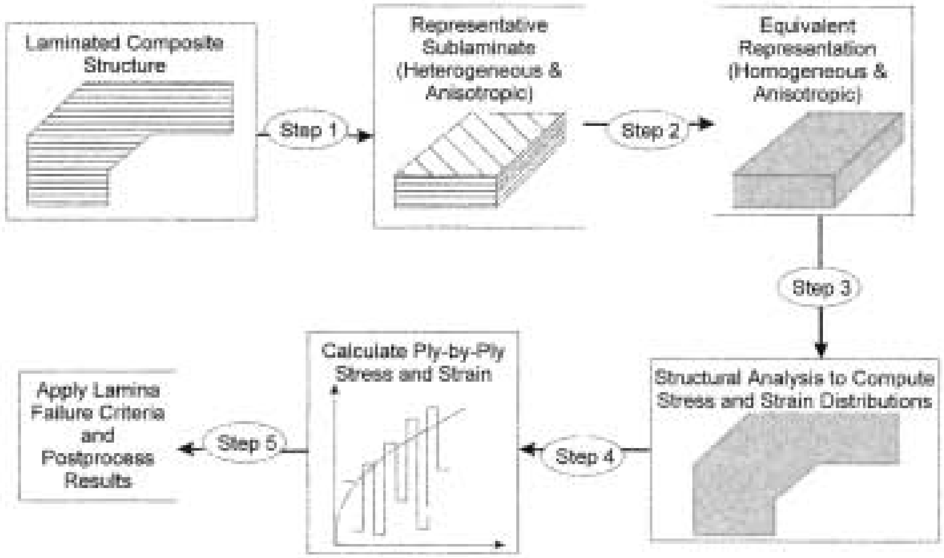

Figure 3. Smearing-unsmearing methodology for analysis of thick composite structures.

Failure Prediction. There are many ply-level failure criteria available for laminated composite materials. These are reviewed in several publications [8], [9], and [10]. The version that has been developed for design and analysis of composite sabots is a version of the maximmum stress failure criterion [8] modified to acconnt for the effects of hydrostatic pressure on the compressive strength [11].

In the maximum stress failure criterion, the six stress components for each ply in the sabot are compared to the operative failure allowables for those directions (in the three principal directions, composites have separate failure allowables in tension and compression). For sabot analysis, this failure criterion was modified to account for the effects of hydrostatic pressure on the compressive and shear strength allowables. The implementation of the failure criterion is described more completely in [12].

Material Architecture. One of the advantages of composite materials is that the properties can be tailored by changing the orientation of the material within the sabot to match the given loading conditions. The aft ramp of the sabot is loaded in axial tension while under high compressive stresses in the radial and circumferential directions; axial stiffness and tensile strength are important design parameters in this region. The aft bulkhead is loaded in shear under hydrostatic compression. The forward ramp or saddle is loaded in uniaxial compression, so this region requires high axial stiffness and uniaxial compressive strength. The forward bourrelet or scoop of the sabot requires high global shear strength to withstand the aerodynamic loads during sabot discard and radial compressive strength to withstand the loads associated with in-bore balloting of the round. The grooves of the sabot require high fracture toughness and shear strength to transmit loads between the sabot and the subprojectile [13].

3. VALIDATION

The complexities of the design of accelerating ballistics structures comprised of highly anisotropic laminated composite materials have been described. The technology developed initially focused on two classes of composite materials, nominally isotropic particle- and whisker-reinforced materials in a magnesium alloy matrix and graphite (carbon)-epoxy systems. The metal matrix solutions were not pursued once limitations to fracture toughness and the resulting implications on weight were rationalized. The polymer matrix solutions were quite successful and achieved program performance goals. A parallel producibility program was executed, so that once the technology was proven, production could be implemented rapidly. The approach used included a mix of analytical modeling and experiments such as the one shown in Figure 4, wherein the successful Launch of a full-size projectile system is shown. Subsequent designs, using the fully developed LAMPAT analysis methodologies provided further advances resulting in reduced sabot weight due to the selection of even better material architectures and subtle improvements in geometry.

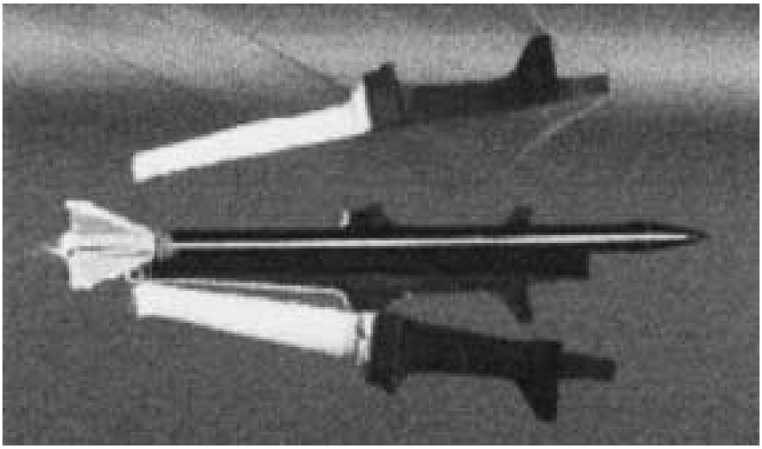

Figure 4. M829A2 projectile with the composite sabot separating from the sub-projectile.

4. CONCLUSIONS

The M829A2 cartridge was type-classified and entered full production with the worlds first and only known composite material sabot. From 1992 to 2000, it was one of the largest users of a composite material system in the United States Department of Defense, using roughly 400,000 lbs (180,000 kg) of graphite-epoxy prepreg annually. Product quality has been extraordinary, and affordable. A major improvement in performance was effected by a unique program that introduced new, high-performance materials into the ballistician’s toolkit, and the technology that emerged was successfully transitioned to high-performance ordnance applications.

5. ACKNOWLEDGEMENTS

The introduction of high-performance composite materials to perform a major structural function in a projectile required a very intense, cooperative effort that involved many organizations. Our salient partners included the Project Manager, Tank Main Armament Systems (who managed the program); the Armament Research, Development and Engineering Center; and the United States Industrial Base. The strong intellectual contributions of Richard M. Christensen, T.T. Chaio, and Frank Magness of the Lawrence Livermore National Laboratory are also acknowledged.

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