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EFFECT OF FIBER-REINFORCED PLASTIC STRENGTH PROPERTIES ON THE BALLISTIC PERFORMANCE OF CERAMIC COMPOSITE ARMOR

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and
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November 1998

Final Report
October 1997 - August 1998

Approved for Public Release; Distribution Unlimited

U.S. ARMY SOLDIER AND BIOLOGICAL CHEMICAL COMMAND
SOLDIER SYSTEMS CENTER
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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 1998	FINAL Oct. 1997 – Aug. 1998

4. TITLE AND SUBTITLE
EFFECT OF FIBER-REINFORCED PLASTIC STRENGTH PROPERTIES ON THE BALLISTIC PERFORMANCE OF CERAMIC COMPOSITE ARMOR

5. FUNDING NUMBERS
C 8B11D

6. AUTHOR(S)
James F. Mackiewicz and Gary Proulx

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Soldier and Biological Chemical Command
Soldier Systems Center
ATTN: SBCCOM-IB
Natick, MA 01760- 5019

8. PERFORMING ORGANIZATION REPORT NUMBER
NATICK/TR-99/006

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release; Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report provides detailed results of an investigation of the effect of Fiber-Reinforced Plastic (FRP) strength properties on ceramic composite armor ballistic performance. FRP laminates ranging from 5.3% - 19.5% resin content produced a range of weak to relatively strong panels in term of flexural strength, shear strength and elastic modulus. The low resin and corresponding low strength laminates yielded the most efficient armor systems when tested in conjunction with Aluminum Oxide (Al_2O_3) frontal ceramic component versus the 7.62 mm M80 Ball and .30 cal Armor Piercing projectiles. Although the 5.3% resin laminates possess very low flexural and shear strengths, the data indicates they have sufficient strength to provide adequate support to the ceramic component. High ballistic performance is more dependent on delamination, deformation and tensile elongation of the FRP material and is not dependent on ceramic component support as once believed.

14. SUBJECT TERMS

LIGHTWEIGHT ARMOR	FIBER-REINFORCED PLASTICS	SMALL ARMS
CERAMIC ARMOR	CERAMIC COMPOSITE ARMOR	V50 BALLISTIC LIMIT
COMPOSITE ARMOR	BALLISTIC PROTECTION	LAMINATES

15. NUMBER OF PAGES 25

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

TABLE OF CONTENTS

LIST OF FIGURES	iv
LIST OF TABLES	v
PREFACE	vi
INTRODUCTION	1
PROCEDURE	2
FIBER-REINFORCED PLASTIC (FRP) TEST PANELS	3
MECHANICAL TEST PROPERTIES OF FRP PANELS	5
V_{50} BALLISTIC LIMIT TEST RESULTS	6
CORRELATION AND ANALYSIS OF TEST DATA	12
CONCLUSIONS	16
RECOMMENDATIONS	17

LIST OF FIGURES

Figure	Page
1. Ceramic Frontal Component Break-up After Ballistic Impact	7
2. Cross Section of Delaminated Fiber-Reinforced Plastic	8
3. Rear Surface of Fiber-Reinforced Plastic Surface After Ballistic Impact	8
4. Effects of FRP Resin Content on Ballistic Performance vs. M80 Ball Projectile	9
5. Effects of FRP Resin Content on Ballistic Performance vs. .30 cal APM2	10
6. Comparison of Projectile Ballistic Performance as Function of FRP Resin Content	11
7. Flexural and Shear as Function of FRP Resin Content	14
8. Effect of FRP Flexural and Shear Strength on M80 Ball Ballistic Performance	15
9. Effect of FRP Flexural and Shear Strength on .30 APM2 Ballistic Performance	15

LIST OF TABLES

Table	Page
1. Characteristics of Aramid Fiber-Reinforced Plastic Armor Test Panels	3
2. Fiber-Reinforced Plastic Mechanical Test Properties	5
3. V_{50} Ballistic Limit Test Data	6

PREFACE

Support for this effort was provided by Major Peter Wajda of the U.S. Army Special Projects Support Activity (SPSA), Ft. Belvoir, VA. Without the continuing support and guidance provided by SPSA, innovative efforts for the advancement of armor technology would be less likely to meet the rapid needs of U.S. combat troops.

The authors wish to express their gratitude to Mr. Thomas Carson of the U.S. Army Aberdeen Test Center (ATC) for providing expedient testing and assisting in the technical evaluation of this report. We would also like to express our sincere appreciation to Joseph J. Prifti (U.S. Army Research Laboratory, Ret.) for his technical expertise and assistance in writing this report.

EFFECT OF FIBER-REINFORCED PLASTIC STRENGTH PROPERTIES ON THE BALLISTIC PERFORMANCE OF CERAMIC COMPOSITE ARMOR

INTRODUCTION

Research in light armor development for the defeat of small arms projectiles (5.45 mm - .50 cal Ball and AP) has predominately focused on the ceramic facing component. Incremental improvements in system performance have been realized over the past ten years through this methodology. The development of new high strength, low density, high modulus (without reductions in elongation) fiber and laminate materials such as Kevlar KM2, Protera, PBO, Spectrashield and Gold Flex have contributed greatly to reducing light armor weight by 20% - 35%. Advancements in polymer research and optimization of these new materials (non-compatible/thermoset-theromplastic resins and fiber orientation) combined with new design concepts which increase the synergism of both armor components will also greatly contribute to further weight reductions. This report addresses one of the major contributing factors to extending light armor technology, the effects of mechanical properties via resin content in Fiber-Reinforced Plastic (FRP) materials.

One of the most basic investigations for understanding and enhancing ceramic composite armor technology has yet to be quantified. This report investigates one of the basic concepts for understanding and improving light armor design by providing a quantitative and methodological analysis of the effects of Fiber-Reinforced Plastic (FRP) mechanical properties on the ballistic performance of ceramic composite armor systems.

The results derived from this investigation are not intended to be an optimization of any armor design. The intent is to provide an engineering tool for improving ballistic performance by adjusting the resin content and corresponding mechanical properties of the backing component laminate. By investigating the laminate resin content, it is envisioned that one may be able to ballistically optimize any type of FRP armor component based on the laminates mechanical properties. This investigation focuses on improving and understanding ballistic performance without regard for multihit, multithreat, structural integrity or durability.

Subsequent work in this area will focus on filling in additional laminate armor design gaps that exist for ceramic composite systems, including fabric weight and weave, resin system employed and effects of using different ceramic components. Eventually, an engineering database will be developed that can be used as a tool for designing ceramic composite armor systems that will provide for specific user requirements including multihit, reduced weight and threat type.

The recommendations section of this report outlines some additional experiments that should be performed in support of these types of investigations. Currently some of these experiments are already being performed and plans for additional testing are being presented to potential sponsors.

PROCEDURE

Seventy-two laminate panels, eighteen each fabricated with four variations in resin content (5.3%, 12.5%, 18% and 19.5% by weight) and corresponding ply counts (13, 13, 14 and 15 plies) of aramid fiber, were fabricated by Gentex Corp. The laminate panels were ordered, as best as possible, to achieve a constant areal density while compensating the lower resin content laminates with increasing ply count to account for the reduced laminate weight.

During the planning process the decision was made to maintain a constant laminate areal density so that a one-to-one comparison could be made. This action necessitated an increase in ply count as the resin content was reduced. While other types of experiments to evaluate FRP mechanical property effects on ceramic composite armor performance could have been employed, these were considered the most practical based on time, funding and future planned experiments.

The original contract solicitation for laminates specified Kevlar 29, 3000 denier, but Gentex was able to provide a lower cost proposal based on using the Twaron fiber which has properties very similar to conventional Kevlar 29. Since this was not a significant departure from the original test matrix, the contract was awarded to Gentex. The decision to use an aramid fiber was based on an extensive database on ceramic composite armor systems fabricated with conventional Kevlar 29 KRP but the actual fiber material used was not deemed as a critical factor for this investigation. Spectra, nylon, S-2 glass or polyester fabrics could have been used as a basis of comparison. Future experiments will investigate the effects of mechanical properties on various fiber materials.

FIBER-REINFORCED PLASTIC (FRP) TEST PANELS

All test panels were fabricated in nominal 12 in. x 12 in. sizes and had nominal areal densities of 1.5 pounds per foot square. The areal density chosen for the FRP was based on a significant database developed by the Army. This data shows that optimal armor performance can be achieved when employing FRP backing materials in the 1.5 - 2.0 lb./ft^2 areal density range. The resin system employed for these experiments consisted of the conventional 50% phenolic and 50% polyvinyl butyral resin developed for ballistic nylon fabrics in the 1950s and extended to Kevlar in the 1970's.

The fabric used to fabricate the aramid laminates employed standard Twaron Type 1000 yarn, 3000 denier, 17 x 17 plain weave and weight of 14.0 ounces per square yard. For each group of panels a mechanical property analysis (flexural and shear) was performed. All laminate test panels were hot-press molded in accordance with MIL-L-62474. Characteristics of the laminate test panels are provided in Table 1. In order to determine if the variations in resin content and mechanical properties are penetrator dependent both soft lead ball and hardened steel core armor piercing projectile V_{50} ballistic limit experiments were performed.

Table 1. Characteristics of Aramid Fiber-Reinforced Plastic Armor Test Panels

Panel Designation	Average Areal Density (lb./sq.-ft)	Average Thickness (in.)	Ply Count	Resin Content (%)
1A - 18A	1.54	0.255	13	19.5
1B - 18B	1.50	0.253	13	18.0
1C - 18C	1.49	0.276	14	12.5
1D - 18D	1.47	0.299	15	5.3

The ceramic facing component employed for these experiments was Coors Aluminum Oxide (Al_2O_3) AD94. Two thickness were procured to best tayilor tests against both 7.62 mm M80 lead ball (0.30 in. thick) and .30 cal AP M2 harden steel armor piercing (0.33 in. thick) projectiles. All ceramics were nominally 6 in. x 6 in. cell sizes. Ceramic tiles of this size were used to eliminate any detrimental effects associated with using smaller tiles (i.e. incrementally smaller tiles have been shown to lower ballistic performance). Aluminum Oxide AD 94 tiles were used as a cost saving measure relative to Boron Carbide and Silicon Carbide materials.

V_{50} ballistic limit tests were performed by the U.S. Army Aberdeen Test Center (ATC). Tests were performed against both ball and armor piercing projectiles for each group of laminate panels. For each test panel the ceramic was adhered to the FRP backing component with compliant polysulfide rubber sealing compound (class A-2, MIL-S-8802D) and allowed to cure for at least 24 hours. The ceramic tile was adhered approximately at the center of the laminate test panel. One shot was taken on each test ceramic composite test panel with the impact location at approximately the center of the ceramic tile. The test sample was clamped on all four sides to a steel supporting frame so as not to dislodge during ballistic impact.

MECHANICAL TEST PROPERTIES OF FRP PANELS

Mechanical property measurements of the aramid FRP laminates were determined in accordance with ASTM standard D 790 - 96a for flexural strength and tangent modulus of elasticity and ASTM standard D 3518 for in-plane shear. These tests were performed as baseline characterization and comparison tools for the FRP components. These test procedures have historically been used to evaluate the integrity of structural/armor FRP materials employed for vehicles and aircraft. These baseline static tests combined with the V_{50} ballistic limit measurements on the aramid-reinforced plastic armor components will provide the basis for evaluating the FRPs for structural integrity and resistance to penetration.

Table 2. Fiber-Reinforced Plastic Mechanical Test Properties

Panel Designation	Tangent Modulus of Elasticity (psi E+05)	Three Point Flexural Strength (psi)	In-plane Shear (psi)
A Series (19.5% resin)	3.92	8215	3585
B Series (18% resin)	2.74	6462	3316
C Series (12.5% resin)	1.56	4024	2247
D Series (5.3% resin)	0.25	1011	686

Results derived from these tests as outlined in Table 2 clearly show the degradation in strength properties as the resin content is incrementally decreased. A significant observation of the data is the dramatic decrease in both modulus and flexural strength as the resin content is lowered minimally from 19.5% to 18% while the in-plane shear remains relatively high. This observation will be more significant with the correlation of ballistic data. The remaining data follows a relatively linear decrease in mechanical properties, as would be expected. The appreciably low values for both flexural and in-plane shear at the 5.3% resin level indicates that a "critical minimum" for resin content is being approached.

V_{50} BALLISTIC LIMIT TEST RESULTS

Results of the ballistic limit tests summarized and presented in Table 3. Ballistic testing was performed in accordance with MIL-S-662 using four partials and four completes in the V_{50} determination. Percent increases in performance were based on an arbitrary number so that this report could be disseminated in the public domain.

Table 3. V_{50} Ballistic Limit Test Data

Panel Designations	Ply Count	7.62 mm M80 Ball V_{50} Ballistic Limit (Increase)	.30 cal AP M2 V_{50} Ballistic Limit (Increase)
A Series (19.5% resin)	13	+29%	+22%
B Series (18% resin)	13	+31%	+9%
C Series (12.5% resin)	14	+42%	+11%
D Series (5.3% resin)	15	+49%	+21%

[1] *Frontal Component: Al_2O_3 (AD94), 0.30 in. and 0.33 in. thick for 7.62 mm M80 Ball and .30 cal APM2 Tests Respectively.*

Thicker ceramic tiles (10%) were employed for the armor piercing tests to ensure that the test data would be representative to actual armor configurations. This obviously means that the ceramic component will be a larger percentage of the overall armor weight and thus will contribute more to the defeat of the steel core penetrator. The thinner tiles employed for the M80 tests similarly means that the FRP laminate will contribute more to the defeat of the soft lead core penetrator. Figures 1 - 3 show a typical armor sample after ballistic testing. The high degree of delamination, as shown in Figures 2 and 3, is a result of the low (5.3%) FRP resin content.

The M80 ball test results as shown in Table 3 and Figure 4 and follows a linear relationship for ballistic performance versus resin content. The data show that by simply adjusting the resin content and corresponding ply count it is possible to increase ballistic performance by over 20% ft/sec. The linear behavior was expected until the resin content was lowered to approximately 12%. Below this point it was believed that ballistic performance would drop dramatically. This assumption was based upon previous testing and modeling of ceramic composite armor systems. Evidentially, this is not always the case and exemplifies the rational for performing these types of experiments

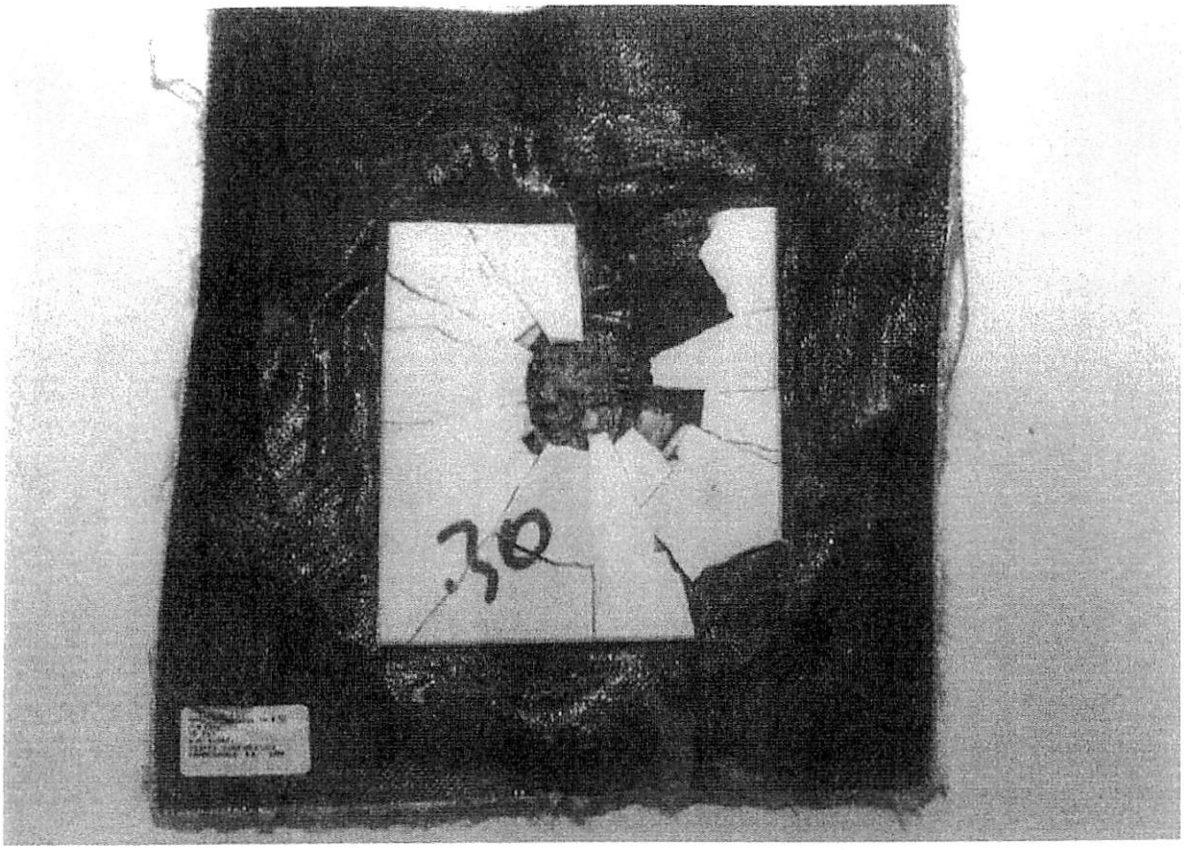

Figure 1. Ceramic Frontal Component Break-up After Ballistic Impact

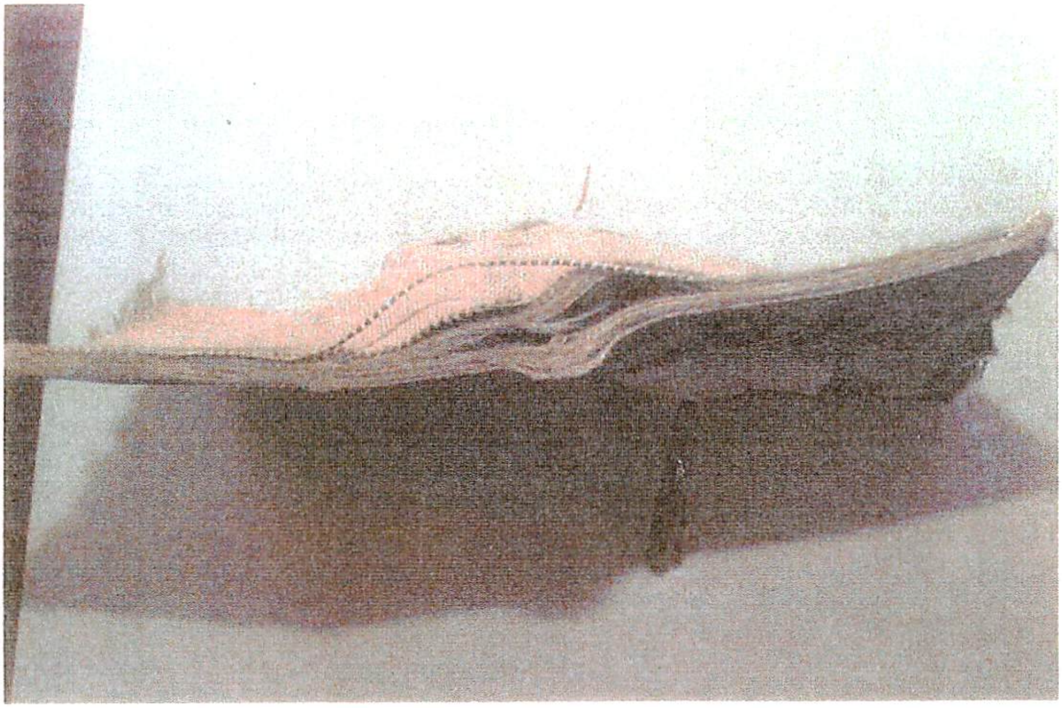

Figure 2. Cross Section of Delaminated Fiber-Reinforced Plastic

Figure 3. Rear Surface of Fiber-Reinforced Plastic Surface After Ballistic Impact

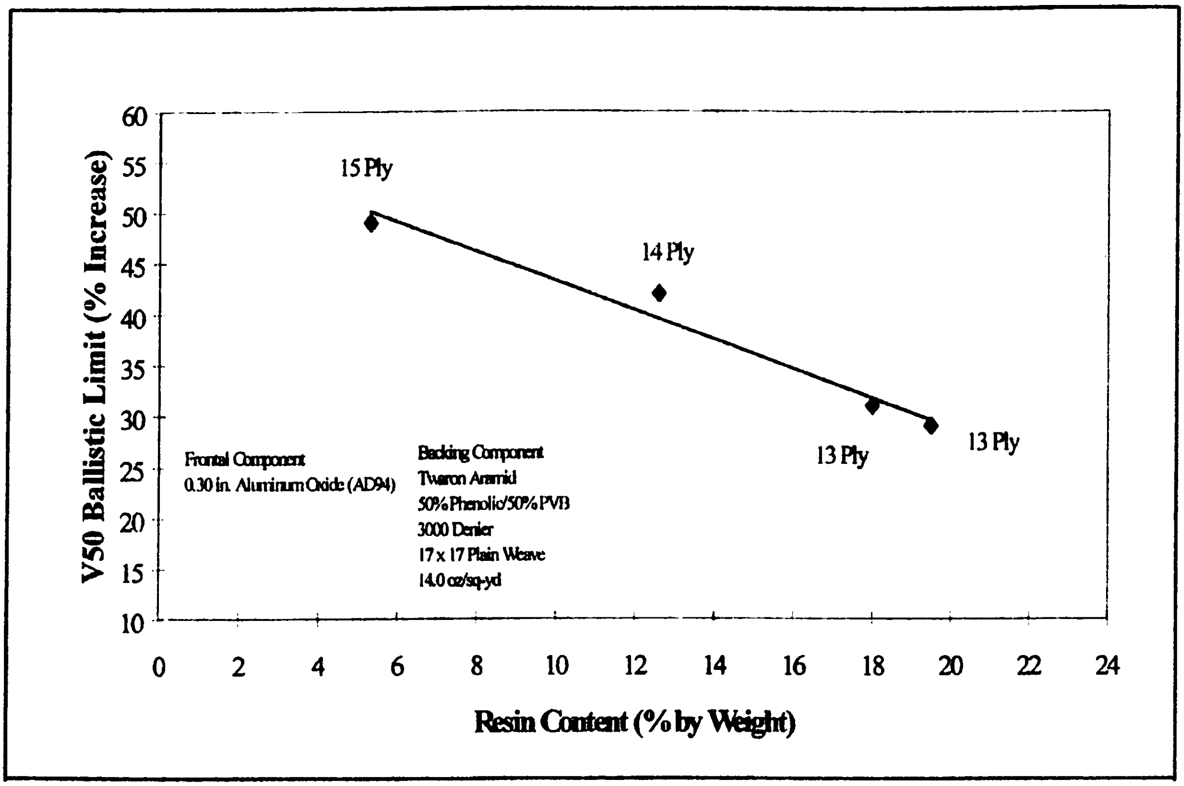

Figure 4. Effects of FRP Resin Content on Ballistic Performance vs. M80 Ball Projectile

Armor piercing M2 ballistic test results as shown in Table 3 and Figure 5 and 6 provide for a more complex analysis than that offered by the M80 ball data. Figure 5 shows two high points, one provided by the highest resin content or strongest laminate and one at the lowest resin content or weakest laminate. This reversal in performance trends at first appears to be a phenomena indicative of shatter gap. A shatter-gap occurs when the projectile core is shattered and thereby defeated by the armor when impacted at relatively high velocities (V_{high}) but at lower velocities (V_{low}), the projectile defeats the armor because the projectile does not impact with sufficient energy to fracture. The shatter-gap phenomena usually occurs when high hardness (HRc 55 -65) steel core penetrators impact high hardness armors. Upon further evaluation including examination of the residual penetrator, shatter gap was ruled out as a possible rational for the trend reversal. Shatter-gap only occurs when two V_{50} measurements can be made (V_{50} high and V_{50} low) from the same test samples. This is not the case since the two test samples have different resin and ply counts. Thus, the conclusion for the APM2 test data indicates that there are two high V_{50} values, one at the weakest (5.3%) and one at the highest (19.5%) strength laminates. The high values provided by the 19.5% resin content laminates was expected based on a significant amount of work previously performed. The high value provided by the 5.3% resin content or weakest laminates was unexpected. Given the soft lead M80 ball core, which readily deforms upon impact with the ceramic tile, it is easier to explain the high V_{50} value of the weakest laminate. Unfortunately, it is much more difficult to explain against the hardened AP penetrator. With the limited data provided by these experiments one can make the assumption that the increased delamination capability of the weaker laminates off-sets any detrimental effect caused as a result of under supporting the ceramic tiles which provided the high V_{50} values with the higher strength laminates.

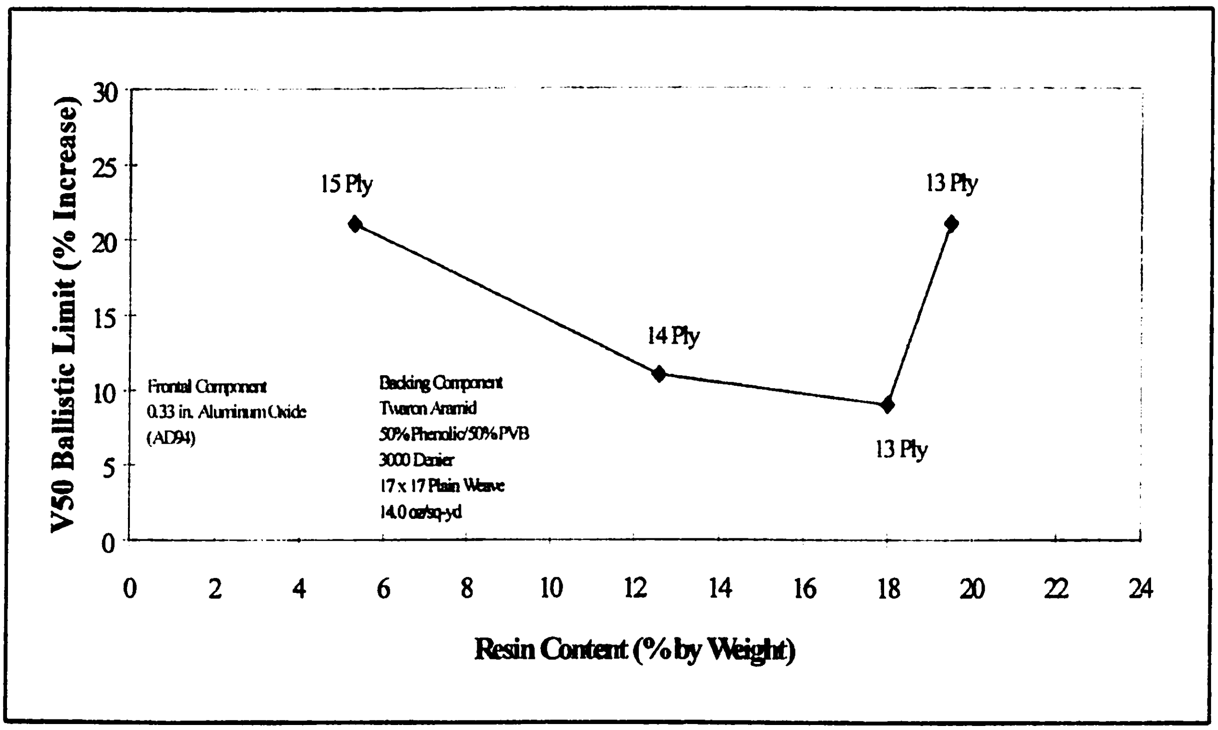

Figure 5. Effects of FRP Resin Content on Ballistic Performance vs. .30 cal APM2

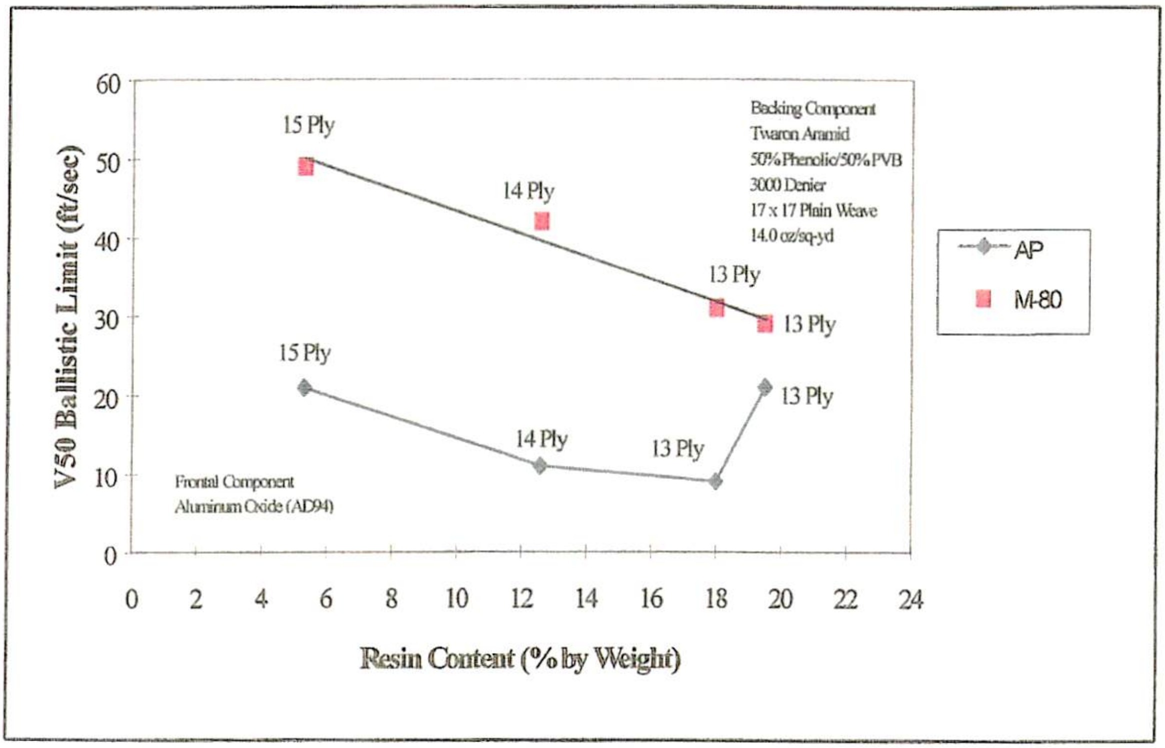

Figure 6. Comparison of Projectile Ballistic Performance as Function of FRP Resin Content

CORRELATION AND ANALYSIS OF TEST DATA

The analysis of the mechanical strength properties is being limited to the flexural and in-plane shear measurement determined in Table 2. Modulus of elasticity measurement were determined by using the equation $E_B = L^3m/4bd^3$ presented in ASTM D790-96a. It was determined during the initial analysis that the modulus of elasticity to ballistic performance trends closely followed the linear path as determined for the flexural strength analysis. Since the flexural strength values were quantitative measurements and in an effort to limit duplicative analysis the evaluation focused on flexural and in-plane shear strengths.

Ballistic limit performance values (V_{50} BL) for the ceramic (aluminum oxide AD94) composite (aramid FRP) armor as a function of FRP resin content are outlined in Table 3. Figure 4 reveals a relatively linear relationship (inversely proportional) of performance as a function of resin content versus the 7.62 mm M80 Ball projectile. This is considered reasonable since the lower resin content laminates (5.3% and 12.5% by weight) have more aramid fabric plies (15 and 14) than the higher resin content laminates (13 plies). More importantly, the individual plies are more ballistically efficient for the lower percent resin laminates since they can delaminate more readily and through deformation and tensile elongation are able to absorb more kinetic energy. The weak bond strength for the low resin content laminates is reflected by the in-plane shear values presented in Table 2 (only 686 psi for the 5.2% resin laminates). Also for the same number of plies (13) the ballistic performance of the (19.5%) laminates is less than the 18% FRP because of their higher bonding strength and in-plane shear. It is important to note that the M80 Ball projectile has a soft lead core penetrator (weighting 114 grains) which is readily deformed upon impact at relatively low stress levels. Therefore, the frontal ceramic component does not have to maintain it's integrity for a long duration thereby tolerating less support by the backing FRP component. This observation is reinforced by the low flexural strength (1011 psi) exhibited by the high performing 5.3% resin laminates.

The effect of FRP resin content on ballistic performance against the .30 caliber Armor Piercing M2 projectile also yields an inverse linear relationship as given in Table 3 and shown in Figure 5. Figure 6 reveals that the incremental decrease in performance (or slope of the performance curves) are similar versus both the .30 cal APM2 and M80 Ball projectiles. However, for the highest FRP resin content (19.5%) and strength laminates (Figure 9) the ballistic performance is dramatically increased to the level achieved by the lowest resin percent laminates (5.3%). Previous studies have confirmed the importance of the frontal ceramic component in breaking-up the hardened steel penetrator (HRc 65) within the APM2 projectile. Therefore, it is reasonable that the high strength laminates would provide greater support to the ceramic thereby delaying ceramic failure and thus achieve the higher stress levels required for efficient break-up of the steel penetrator. The surprising result is high performance levels provided by the lowest resin content (lowest strength) laminates. It appears that the frontal ceramic may not require the degree of support previously hypothesized. Apparently, the ceramic is maintained integral long enough to achieve the required time interval to break the tip of the penetrator and the remaining ceramic erodes an additional portion of the penetrator. The residual but blunted portion of the penetrator is defeated by the delaminated multiple pies of low resin

FRP backing. Thus, optimal performance is not a singular solution versus the AP projectile. Maximum performance can be obtained at the lowest and highest resin contents thereby indicating a trade-off between back-up rigidity for ceramic support and delamination for greater energy absorption.

The mechanical properties generated in Table 2 lend support to the analysis described above. The lowest resin content FRP laminates (5.3%) posses extremely low strengths (686 psi shear, 1011 psi flexural and 0.25 x 10^5 modulus) yet provide the best performance. Laminates with only 686 psi shear can be readily delaminated at relatively low loading rates (induced by shock waves and ceramic-projectile ram) and thereby maximize their energy absorption capability. Conversely, the poorer performing higher resin laminates posses relatively high strength (over 3000 psi) thereby providing greater resistance to delamination. With a flexural strength in the 1000 psi range for the low resin FRPs only marginal support for the ceramic can be expected, however, enough support is apparently provided to achieve the high performance.

As expected the flexural and shear strengths increase with increasing resin content as illustrated in Figure 7. Furthermore, both flexural and shear strengths increase linearly for resin contents from 5.3% to 18% by weight. At the highest resin content (19.5%) a more dramatic increase in flexural strength (8215 psi) is observed. Increases in modulus of elasticity with increasing resin content follow a similar nearly linear relationship as shown in Figure 8. Figures 7 and 8 also reveal, through a modest linear extrapolation, that "theoretical zero strength" would be obtained for a 2.5% resin laminate. Therefore, it's reasonable to conclude that the 5.3% resin laminates are at or very nearly approaching the lowest feasible resin content. Again the higher modulus values for the high resin laminates are indicative of relatively rigid materials. It is important to note that the mechanical property values were determined for conventional low strain rate or static conditions.

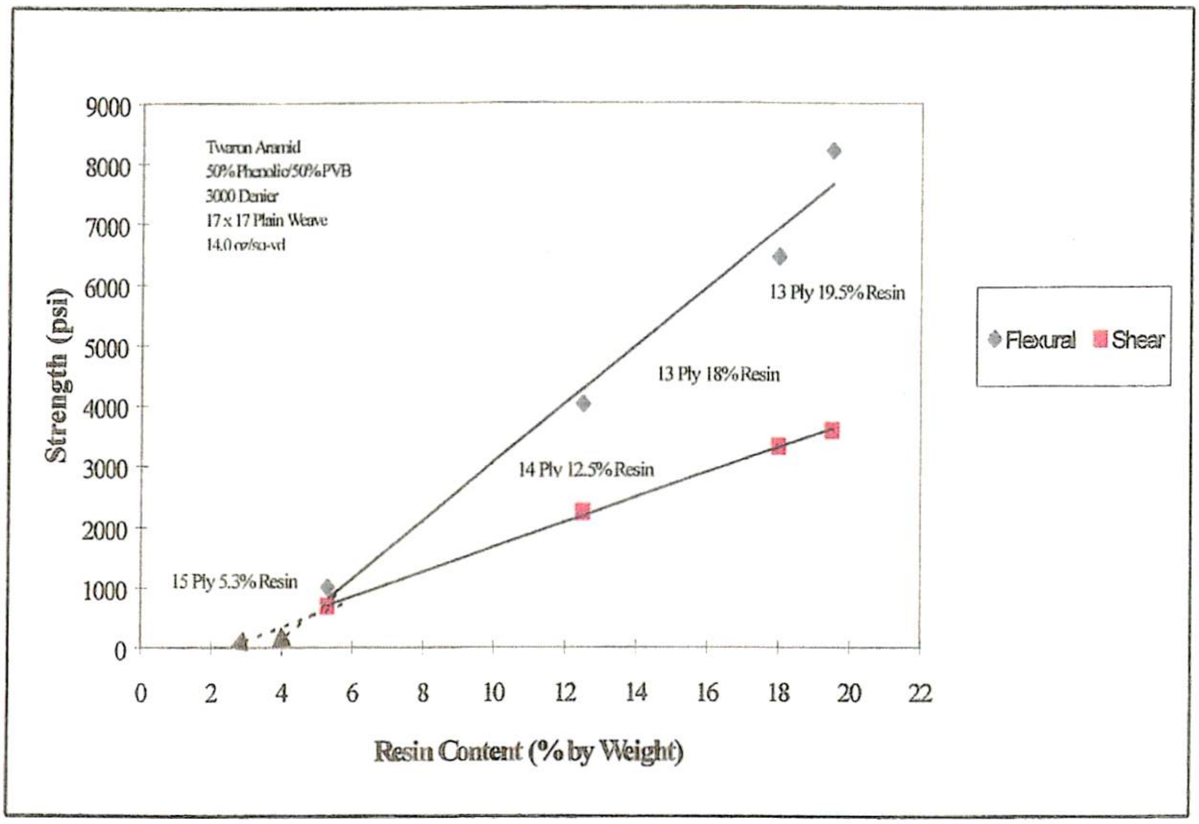

Figure 7. Flexural and Shear as Function of FRP Resin Content

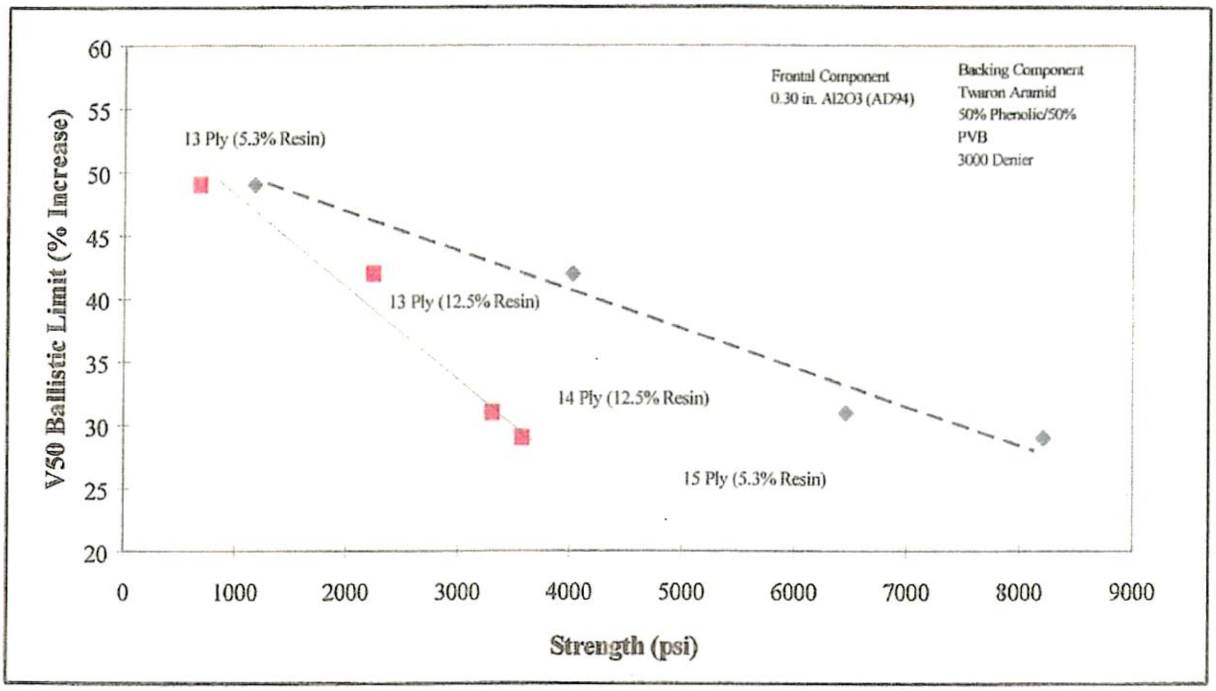

Figure 8. Effect of FRP Flexural and Shear Strength on M80 Ball Ballistic Performance

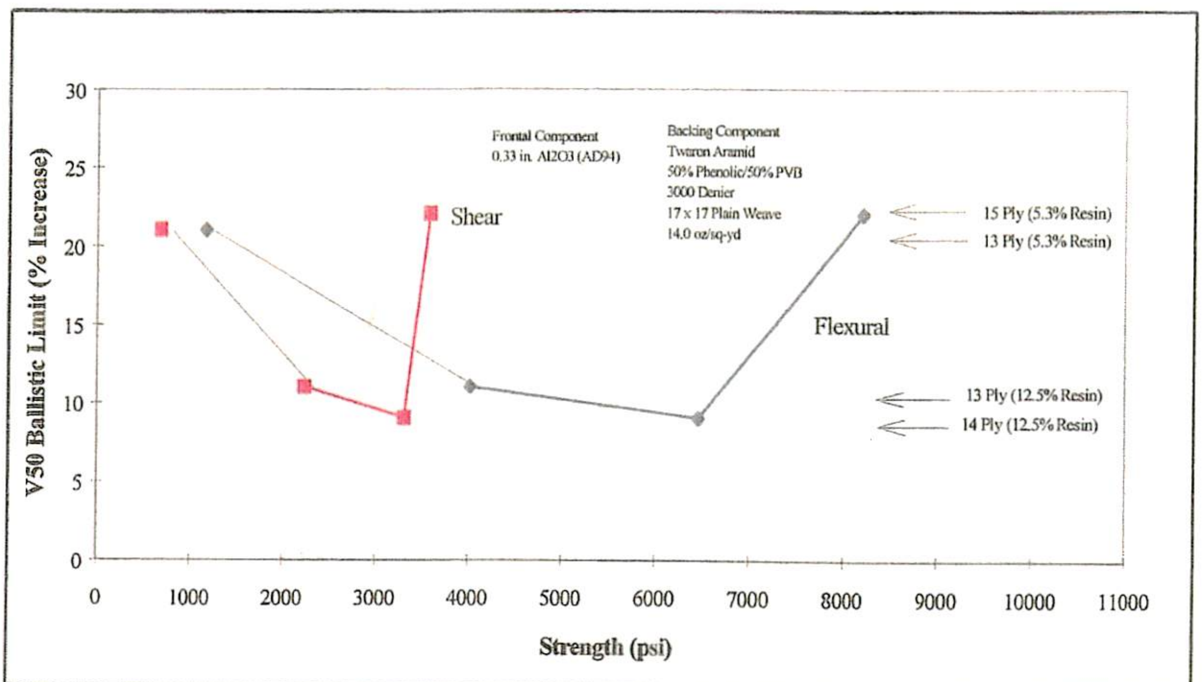

Figure 9. Effect of FRP Flexural and Shear Strength on .30 APM2 Ballistic Performance

CONCLUSIONS

1. Resin content and corresponding strength of the FRP backing component play an important role in the ballistic performance of ceramic composite armor when tested against both soft and hard core penetrators.

2. Low resin content FRP laminates (with corresponding low strengths) provide the highest ballistic performance against both 7.62 mm M80 Ball projectiles. The reduction in ballistic performance (V_{50} BL) is basically linear with increasing resin content laminates, higher strength for the resin content ranges investigated (5.3% to 19.5%).

3. Tests versus the .30 cal APM2 projectile show that the low resin content laminates again provide higher ballistic performance for resin contents ranging from 5.3% to 18% laminates. However, at the highest (19.5%) resin content a dramatic reversal occurs with ballistic performance being equivalent to or slightly higher than the low resin (5.3%) FRPs.

4. Strength properties (flexural, shear and modulus) increase with increasing FRP resin content. The 5.3% resin laminates are substantially weaker than the higher resin content laminates, as expected.

5. Although quite weak, the 5.3% laminates posses enough strength to adequately support the frontal ceramic component required to maintain it's effectiveness upon impact. The low resin/low strength FRPs delaminate quite readily during the ballistic event thereby absorbing greater kinetic energy through deformation and fiber tensile elongation.

6. Based on data generated for this and other investigations one can conclude that fragmentation protection values may be used for assessing laminate performance contribution for ceramic composite armor systems. The high V_{50} values demonstrated by the weakest or lowest resin content 5.3% laminates shows that similar V_{50} measurements against Fragment-Simulating Projectiles (FSPs) can be used as an evaluation tool during experimental screening phases of development.

7. Composite laminates can be structurally tailored by a number of methods including variations in resin content. It now appears that laminates can be similarly tailored to increase ceramic composite armor performance. Ceramic composite armor performance versus specific threat types can be enhanced through laminate backing optimization. One means of performance optimization can be achieved through laminate mechanical properties.

This document reports research undertaken at the U.S. Army Soldier and Biological Chemical Command, Soldier Systems Center, and has been assigned No. NATICK/TR-97/006 in a series of reports approved for publication.

RECOMMENDATIONS

1. Variable resin content FRP laminates employed in ceramic composite armor configurations will be further investigated. The dynamic behavior of both ceramic and laminate components will be analyzed using multiflash x-ray radiography to determine:

a. Level of ceramic support required and provided by variable resin content laminates.
b. Time sequence of armor/penetrator interaction during the ballistic event.
c. Delamination/deformation processes employed by the variable FRP laminates.

2. Quantify fabric weave effects (200, 400, 1000, 1500 and 3000 denier) for laminates on ceramic composite armor performance in a manner similar to that provided in this report.

3. Investigate the potential of gradient FRP backing components by marrying both low and high strength laminate sections strategically placed to maximize ballistic performance.

4. Verify that the low to high resin content FRP backing laminates, when coupled with high performance ceramics (B_4C and S_iC), exhibit similar behavior patterns as demonstrated with the frontal Al_2O_3 ceramic components employed for these experiments.