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LAMINATES FOR BALLISTIC PROTECTION

Roy C. Laible, et al

Army Natick Laboratories
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Kevlar 29 and fiberglass laminates were ballistically evaluated with 9 mm projectiles to determine their ability to protect against severe hand gun threats.

The Kevlar laminates exhibit an advantage over the glass laminates, providing complete protection against 9 mm projectiles up to 395 m/sec at an areal density of 7.3 kg/m^2. The glass laminates allowed some complete penetrations even at a higher areal density.

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ABSTRACT (cont'd)

The mechanical properties of the Kevlar and glass laminates have been compared in an attempt to determine the mechanism by which they stop or slow down missiles. The Kevlar laminates do exhibit considerably higher static tensile strengths along with slightly higher elongations to break than do the glass laminates. This ability of the Kevlar to absorb more energy may be one of the important factors in providing the improved ballistic protection.

The comparative resistance of the glass and Kevlar laminates to cyclic bending was compared to determine mechanical weaknesses of the laminates which might lead to failure through use and handling prior to exposure to any ballistic impact. The Kevlar laminates do plastically deform but survive many more high load cyclic deformations than do the glass laminates which tend to catastrophically fail under similar conditions of test.

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INTRODUCTION

Most of the published work on composites of glass and Kevlar has the stated application of providing structural components for airplanes, boats and other consumer goods. These composites generally possess relatively low fiber fractions (60% weight percentage) and utilize resins and coupling agents designed to provide good adhesion and stress transfer. (1)

On the other hand, the glass laminates usually used for ballistic protective applications utilize woven roving fabric treated with starch - oil size and a high volume fraction of fiber (75% by weight). These factors decrease the adhesion and tend to give lower shear resistance and poorer stress transfer. In fact, delamination under the stress of ballistic impact may be an advantage leading to increased energy absorption. The development of Kevlar 29, an aromatic polyamide fiber, has, for the first time, introduced a wholly organic fibrous reinforcement with a modulus and heat resistance competitive with glass and a tensile strength superior to glass. The properties of the Kevlar 29 itself have been outlined previously. (2, 3)

The present paper describes work conducted to prepare laminates of glass and Kevlar 29 and to determine their ability to provide protection against a severe hand gun threat, the 9 mm pistol ball. In addition, the mechanical properties of the glass and Kevlar composites prepared for the above use are compared in an attempt to determine reasons for their ability to stop and slow down missiles as well as weaknesses which might lead to mechanical failure prior to missile impact.

EXPERIMENTAL

A. Materials

1. Fabrics

a. Kevlar 29 Fabric

The Kevlar fabrics used were a 0.17 kg/m^2 (5 oz/yd^2) 8 Harness Satin prepared from 44 tex (400 denier) yarn in a 28 x 28 count and a 0.44 kg/m^2 (13 oz/yd^2) 2 x 2 basket weave prepared from 167 tex (1500 denier) yarn in a 35 x 35 count.

b. Glass-Woven-Roving

The glass-woven-roving was a 0.78 kg/m^2 (23 oz/yd^2) starch oil sized fabric (J. P. Stevens #1157) prepared from E glass.

2. Pre-preg

a. The Kevlar 29 fabric was impregnated with an acid cure thermosetting resin system consisting of the following major components:

(1) Polyvinyl butyral (PVB)

(2) Trimethylol phenol

(3) Phenol formaldehyde

The 0.17 kg/m^2 fabric was coated to obtain 30-34% resin pickup (final weight) while the heavier weight Kevlar fabric 0.44 kg/m^2 was coated to 20-24% pickup.

Components	Parts by Weight	% Solids of Total Solids
PVB 18-20% hydroxyl	868.0 (25% solid in EtOH)	47.2
Phenol formaldehyde	100.0 (57% solids)	12.4
Trimethylol phenol	267.0 (60% solids)	34.8
Phthalic anhydride	85.6	5.6
Methanol	51.2	-

b. The glass fabric was impregnated with an unsaturated polyester resin modified with diallyl phthalate using a high temperature catalyst system. The fabric was coated to obtain 23-25% resin pickup (final weight).

B. Preparation of Laminates

Flat laminates of Kevlar were molded by placing the appropriate number of plies of pre-preg to obtain the desired areal density between two sheets of a glass scrim Teflon coated release agent. This sandwich was placed between the platens of a 889 kN (100 ton) Wabash molding press at a nominal pressure of 6.9 MPa (1000 psi) and a temperature of 171°C for a total of seven minutes. After one or two minutes the pressure was released to permit the structure to degas and then was reapplied. The time of degassing varied with the amount of volatiles in the pre-preg which is related to the pre-preg age and treatment. Insufficient degassing can be detected by blistering of the final laminate. Laminates were removed hot from the press and allowed to cool to room temperature.

Flat laminates of glass were molded in a similar manner but at a much lower pressure of 0.85 MPa (125 psi) and a temperature of 138°C. Cycle interruption was not necessary in the case of the glass laminates because volatiles are not produced.

C. Ballistic Testing

All ballistic testing was conducted at the Biophysics Laboratory, Edgewood Arsenal, MD, using 8.0 g (124 grain) full metal jacket 9 mm projectile. The projectiles were fired from a 9 mm Mann barrel using hand loaded cartridges. Velocities from 335-396 m/sec (1100-1300 ft/sec) were obtained.

D. Physical Testing

1. Bending modulus was measured in accordance with Method I of ASTM D790-71, "Flexural Properties of Plastics."

2. Tensile properties were measured in accordance with ASTM D638-72, "Tensile Properties of Plastics."

3. Interlaminar shear was measured in accordance with ASTM D2733-70, "Interlaminar Shear Strength of Structural Reinforced Plastics at Elevated Temperatures." Testing was conducted at 23 ± 2°C and 50 ± 2% relative humidity.

RESULTS AND DISCUSSION

A. Ballistic Performance

The Kevlar 29 and glass-woven-roving laminates were subjected to ballistic impact with the 9 mm projectile. At the heavier areal density of 10.7 kg/m^2 (35 oz/ft^2) the Kevlar laminates had no complete penetrations even at an impact velocity up to 375 m/sec (1230 ft/sec). The glass-woven-roving at this same areal density had defeated the projectile four times and had one complete penetration (Table I).

TABLE I

Comparison of Ballistic Performance of Glass and Kevlar 29 Laminates (10.7 kg/m^2) Against the 9 mm Projectile

Material	Number of Impacts	Velocity Range (m/sec)	Results
Kevlar 29	10	357-375 (1172-1230 ft/sec)	10 - No Penetrations
Glass WR	5	352-359 (1155-1178 ft/sec)	4 - No Penetrations 1 - Penetration (359 m/sec)

The laminates were also fired at a reduced areal density 8.2 kg/m^2 (27 oz/ft^2). A total of nine impacts on the Kevlar laminate produced no complete penetrations. In the case of the glass-woven-roving laminate, four out of five impacts resulted in complete penetrations. Those results showed that at least for this threat, Kevlar possesses an advantage over glass.

TABLE II

Comparison of Ballistic Performance of Glass and Kevlar 29 Laminates (8.2 kg/m^2) Against the 9 mm Projectile

Material	Number of Impacts	Velocity Range (m/sec)	Results
Kevlar 29	9	358-364 (1176-1196 ft/sec)	9 - No Penetrations
Glass WR	5	352-367 (1155-1204 ft/sec)	1 - No Penetrations (352 m/sec) 4 - Penetrations

An additional advantage of the Kevlar laminates can be seen in Figures 1 and 2 which show the back surfaces of the laminates after ballistic impact. The glass laminate shows considerably more back surface deformation and delamination than does the Kevlar.

The Kevlar laminate was prepared from a lightweight (0.17 kg/m^2) relatively high cost fabric. The ballistic experiments were repeated using the heavier weight Kevlar fabric (0.44 kg/m^2) prepared from less expensive 167 tex yarn. Even a lower total weight of this material (7.3 kg/m^2) laminate)) was able to stop all 9 mm projectiles fired at even higher velocities up to 395 m/sec.

B. Mechanical Properties

The relative low cost of the glass-woven-roving ($2/kg) compared to Kevlar 29 ($15/kg) makes it imperative that glass and Kevlar 29 be compared structurally before any decision is made on the use of either in applications such as helmets for police or military use. The first test selected was that of the bending moment. Utilizing a 100 mm span length on 25.4 mm wide strips tested at 2.54 mm/min, the following results were obtained (Table III):

TABLE III

Comparison of the Bending Moment Properties of Laminates of Glass and Kevlar 29

Material	Areal Density (kg/m^2)	Max Fiber Stress (MPa)	Bending Modulus (GPa)	Max Load (N)
Glass	6.1	165.4	19.3	293
Kevlar 29	6.1	95.8	7.58	377
Glass	11.6	185.3	20.7	387
Kevlar	11.6	110.2	9.6	1289

For both bending modulus and maximum fiber stress, the glass appears to be favored. However, the actual load at yield is higher for the Kevlar 29 than for the glass. This is especially true for the Kevlar at the heavier areal density (11.6 kg/m^2). The areal densities were selected to bracket those used for the ballistic tests.

It was noted in the bending tests just described that while the Kevlar yields without visible failure, the glass shows the initial signs of fracture. For this reason it was decided to investigate the effects of repeated cycling upon the resultant properties of the two competitive materials. Repeated bending tests were conducted on the Kevlar and glass laminates using an areal density of 11.6 kg/m^2 and a maximum load of 892N (200 lbs). The Kevlar laminates survived 1000 cycles but exhibited some plastic deformation while the glass laminates after only 100 cycles were delaminated and fractured to a degree that they retained essentially zero bending modulus and low tensile strength. Pictures of typical specimens are given in Figures 3 and 4.

Both composites with their very low resin content would be expected to exhibit relatively low interlaminar shear values compared to those composites prepared for structural applications. The measurement of interlaminar shear is another useful indicator of the relative structural integrity of the glass and Kevlar laminates. Such tests were conducted on both laminates at an areal density of 11.6 kg/m^2 utilizing a crosshead speed of 0.25 mm/min and typical 25.4 mm wide specimens with a 12.7 mm distance between saw cuts. The interlaminar shear values averaged 10.1 MPa (1470 psi) for the glass laminates and 29.2 MPa (4240 psi) for the Kevlar laminates. These values suggest that the Kevlar laminates should possess greater structural integrity during tough handling than would glass.

The last comparison conducted was that of tensile strength. Type II ASTM tensile specimens of Kevlar and glass laminates, prepared in several areal densities, were subjected to tensile tests with the following results:

TABLE IV

Tensile Strength Data on Various Kevlar and Glass Laminates

Material	Number of Plies	Areal Density (kg/m^2)	Elongation-to-Break (%)	Tensile Strength (MPa)
Kevlar	5	3.0	-	531
Kevlar	10	6.1	-	420
Kevlar	14	8.2	3.9	427
Glass	6	8.2	3.0	289
Kevlar	20	11.6	-	438
Glass	9	11.6	-	262

Elongation-to-break values are given in Table IV only for those tests in which an extensometer was used to measure elongation to failure. In these two cases the laminates are those used for the ballistic tests. Furthermore, the larger elongation-to-break (3.9%) exhibited by the Kevlar combined with the higher tensile strength 427 MPa (62,000 psi) results in higher work to rupture values. These higher work to rupture values may in turn be responsible for the ballistic advantage of Kevlar laminates over that of glass laminates. Tensile tests conducted at a strain rate one decade faster raise the tensile values for the glass laminates 5 - 10% with a much smaller improvement shown by the Kevlar. This may account for the fact that the glass laminates are somewhat competitive with Kevlar ballistically despite the rather large difference in static tensile strengths. Although the mechanical properties (tensile strength, interlaminar shear and behavior under repeated bending) all seem to favor the Kevlar laminates, actual field tests of the proposed items (helmets, vest inserts) would be required to determine the actual ability of the materials to maintain their integrity under service conditions.

CONCLUSIONS

1. Both glass and Kevlar laminates possess a potential for providing protection against small arms fire.

2. Using the highly penetrating 9 mm projectile at velocities as high as 375 m/sec (1230 ft/sec), the Kevlar laminates possess an advantage over glass with no projectiles penetrating the laminate even at the lowest areal density tested (7.5 kg/m^2). Even the less costly, heavier denier Kevlar yarn produces a suitable fabric for the laminate.

3. Backside damage and delamination from ballistic impact is less for the Kevlar laminates than for the glass.

4. The results of the tensile tests show that Kevlar 29 laminates would be expected to sustain higher energy impacts than glass laminates because of the higher tensile strengths and elongations-to-break exhibited by the former material.

5. The other mechanical tests conducted (interlaminar shear, bending, cyclic bending) appear to favor Kevlar. Actual user tests will be necessary to determine the advantage of Kevlar in resistance to mechanical abuse.

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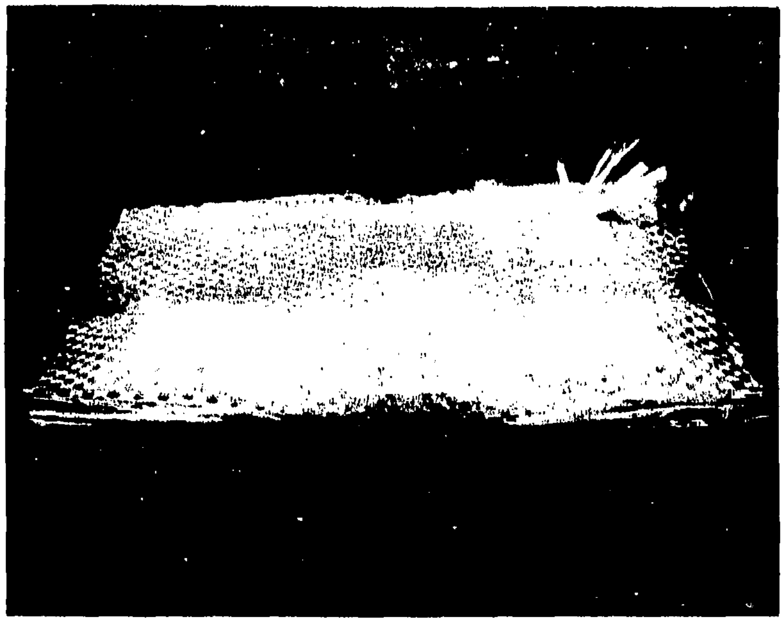

FIG. 1 Back Surface of Glass Laminate After Multiple Impacts with 9 mm Projectile

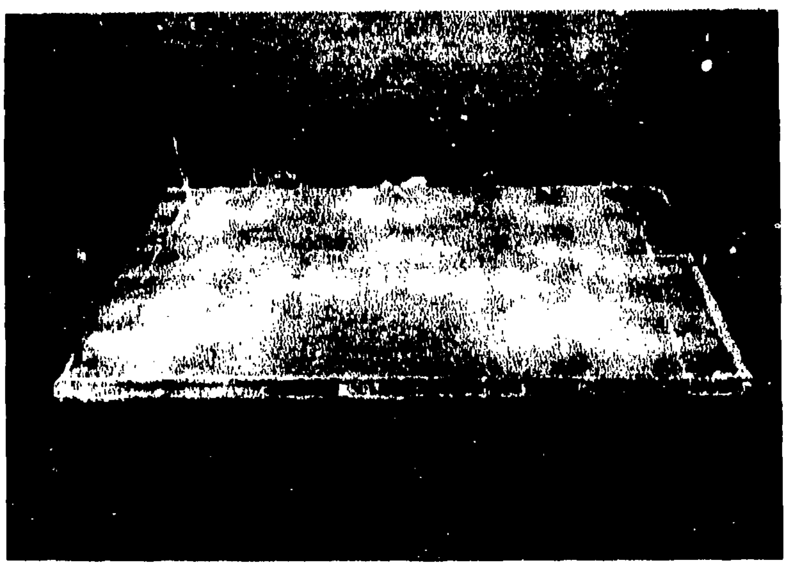

FIG. 2 Back Surface of Kevlar Laminate After Multiple Impacts with 9 mm Projectile

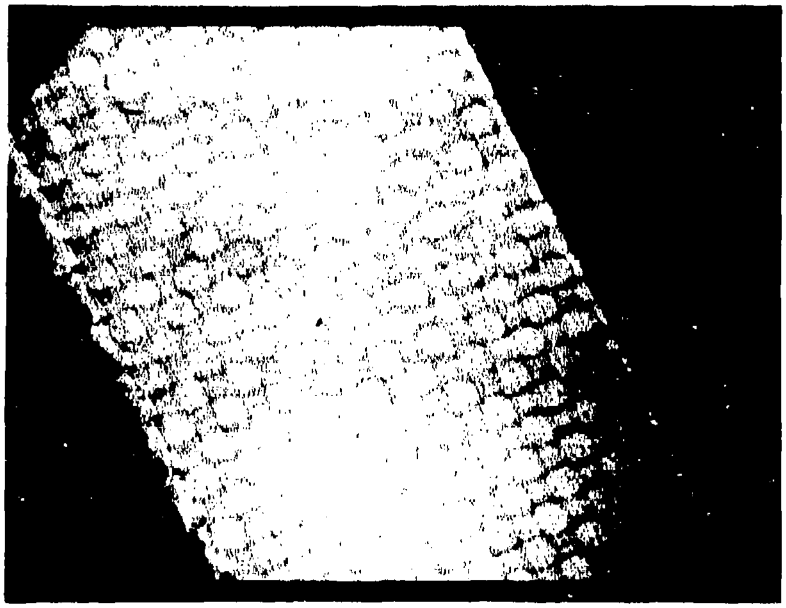

FIG. 3 Top Surface of Kevlar Laminate After 1000 Cycles at A Maximum Load of 90 kg

FIG. 4 Top Surface of Glass Laminate After 11 Cycles at A Maximum Load of 61 kg