FIRE RESISTANT COMPOSITE MATERIALS FOR ENERGY ABSORPTION APPLICATIONS

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ABSTRACT

Oak Ridge National Laboratory is evaluating lightweight composite materials for use in ballistic and blast mitigation applications. Processing of advanced composite materials has been developed to combine energy absorbing fibers with fire resistant resin matrices. The most promising combinations include Zylon poly(p-phenylene-2,6-benzobisoxazole) (PBO) fiber in phenolic-based and cyanate ester resins. These composite materials are being evaluated in fire and smoke tests to demonstrate their ability to meet government agency fire testing requirements. The composites are also evaluated using a ballistic screening test to determine the material's ability to absorb mechanical energy at high strain rate. A summary of the processing experience, fire test and ballistic test results to-date is presented.

KEY WORDS: Energy Absorption, Fire Resistance, Organic Fiber

1. INTRODUCTION

The Oak Ridge National Laboratory (ORNL) is involved in the development of energy absorbing materials for use in ballistic and blast mitigation applications. Recent advances in organic fiber technology have made it possible to develop fiber-reinforced composite materials that offer the potential to defeat these threats, but at a fraction of the weight of conventional metal structures and shielding.

For applications that demand the use of fire resistant materials, care must be taken in selecting the constituents (fiber and resin) that comprise the composite. For example, the Spectra 1000 fiber from Allied Signal has been demonstrated by ORNL to have excellent capability to defeat ballistic threats. However, it is a polyethylene fiber and burns vigorously when subjected to flame.

The potential to improve poor fire performance by impregnating the fiber with an inherently fire resistant resin is limited by several factors. The first is that the optimum resin content for these energy absorbing composites tends to be relatively dry compared to more structural composites, minimizing the protection afforded by the resin. In some cases, the maximum

recommended processing temperature of the fiber might be lower than that required to cure the resin. (For example, the maximum recommended processing temperature for Spectra fiber is ~121°C, which eliminates inherently flame resistant resins such as cyanate esters and many phenolics from consideration.) External coverings placed over the surface of the composite as flame barriers can be penetrated by the fire around edges, joints and seams, particularly if the material that is being protected drips when heated. In addition, these barriers can sometimes compromise the energy absorbing capability of the composite by restricting the fiber deformation required to absorb energy.

Poly(p-phenylene-2,6-benzobisoxazole) (PBO) fiber, which is marketed under the trade name Zylon by Toyobo, is advertised as having exceptional thermal stability and nonflammability for an organic fiber. The heat release rate of PBO is extremely low, even near zero, while its char yield is very high. Fire and smoke test results on PBO fiber reinforced composites bear out the excellent fire resistance of PBO composite (1).

Mechanical and physical properties (Table 1) compared to other organic fibers suggest that PBO also has good potential as fiber reinforcement for ballistic/blast mitigation applications.

Table 1. Comparison of fiber properties

Property	PBO AS	Spectra 1000	Kevlar 29	Kevlar 49	Kevlar 129	S-glass
Tensile strength (GPa)	5.8	2.9	2.9	3.0	3.3	4.5
Tensile modulus (GPa)	180	113	70	112	96	85
Tensile elongation (%)	3.5	2.9	3.6	2.4	3.3	5.7
Density (g/cm^3)	1.54	0.97	1.44	1.44	1.44	2.48

In addition to the fiber, the resin matrix is a crucial constituent in determining the composite's fire performance as well as capacity to absorb energy. Conventional polymers used in energy absorbing application (epoxies and vinyl esters, for example) may be modified with halogenated functional groups or halogenated additives to improve fire performance. Such plastics are highly resistant to ignition, but once ignited, can produce toxic gases that are extremely irritating to humans as well as corrosive to adjacent structural and electronic components (2). For these reasons, it is preferable to incorporate resins with chemistries that are inherently fire-safe (without additives) for composite applications requiring fire resistance. Matrix materials demonstrated to have inherently good fire performance include phenolics (2) and some cyanate ester resins.

Studies (3,4,5) indicate that the dominant energy absorption mechanism for polymeric fiber-reinforced composite armor is fiber straining. Energy absorption can be influenced by the fiber-resin interface with lower adhesion between fiber and resin tending to promote increased delamination between plies. Composite systems that delaminate upon impact enable greater fiber

straining. The increased fiber loading coupled with some small amount of energy expended through delamination enhances ballistic performance.

Research (3) also indicates that the matrix resin also factors into the energy absorption capacity of the composite by preventing yarn slippage during penetration, thereby forcing the penetrator to engage and break more fibers. High modulus (stiffer) resins are more effective at maximizing load sharing between fibers (3).

Processing of advanced composite materials is being developed by ORNL to combine energy absorbing fibers with fire resistant resin matrices. The work presented here documents the results of a study in which laminates of PBO (Zylon) fabric were prepared with phenolic-based and cyanate ester resin systems. Laminates were produced with a range of weight percent resin contents and using several composite fabrication techniques. Specimens were evaluated with fire and smoke tests to demonstrate their ability to meet government agency fire testing requirements. These composites were also evaluated using a ballistic screening test to determine the material's ability to absorb mechanical energy at high strain rate. A summary of the processing experience, fire test and ballistic test results to-date is presented.

2. COMPOSITE MATERIALS AND PROCESSING

The PBO (Zylon) laminates evaluated as part of this study were laid up and cured at ORNL using a variety of composite manufacturing methods. Depending on the process conditions, these included curing under high pressure in a heated platen press, and vacuum bag curing in a convection oven.

The baseline (standard) manufacturing method is to consolidate these flat panels under high pressure in a heated platen press. To a large extent this is necessary to promote bonding and resin infiltration between adjacent plies because of some of the very low resin contents of these laminates. In this and related studies (6), 3.44 MPa (500 psi) consolidation pressure was adequate to produce quality laminates.

Process trials were also conducted using lower consolidation pressures (0.68-1.03 MPa) and pressure derived from vacuum bagging alone to determine if these composites are capable of being manufactured with alternate processing equipment, such as an autoclave or oven. This is important because an expanded fabrication envelope would permit more complex geometry composite hardware (boxes, cylinders, other three-dimensional parts) to be successfully and cost effectively manufactured in addition to panels. In sandwich structures, some secondary bonding operations might also be eliminated if the laminates could be co-cured and bonded with the other hardware at lower consolidation pressures.

The PBO laminates were prepared from Zylon fabric procured from Barrday Incorporated. This fabric consisted of a 500 denier yarn woven with a 122 x 122 yarns per 10 cm (31 x 31 yarns per inch) construction and with a nominal areal weight of 139 g/m^2.

The Zylon fabric was procured with two finishing treatments for these investigations – greige, and scoured and water-repellant treated. Greige refers to the as-woven condition, in which the oil

finishing agent applied to the fiber to minimize fiber abrasion/damage during weaving is not removed. The scoured and water-repellant finish is intended to minimize resin/fabric adhesion for increased delamination at impact, thereby increasing ballistic performance. However, the extracted yarn breaking strength data for these fabrics typically show that the scouring/finishing process lowers the fabric strength due to the increased handling damage from the scouring process.

The superior thermal performance of PBO fiber expands resin selection and processing options to include those resins with high(er) cure temperatures and inherently good fire/flame performance including cyanate ester and phenolic resins. Three matrix materials were selected for investigation because of their potential to meet government fire testing standards: (1) Polyvinyl butyral (PVB)/phenolic resin film procured from Barrday, Incorporated (2) EX-1551 cyanate ester resin manufactured by Bryte Technologies, Incorporated, and (3) RD98-228 cyanate ester resin manufactured by Vantico.

The PVB/phenolic resin consists of a nominal 50:50 weight percent blend of polyvinyl butyral elastomer and phenolic resin. It has been used successfully in previous ballistic threat application including with Kevlar fabric in Army helmets. It is relatively simple to process and has a short cure cycle (less than 1 h at 155°C). PBO laminates were prepared by interleaving the PVB/phenolic film between the plies of fabric, and with the quantity and location of the film determining the laminate's ultimate resin content and resin distribution characteristics. The low resin flow characteristics of the PVB/phenolic film basically determined that higher consolidation pressures were required to force the resin film to infiltrate and bond with the adjacent fabric plies. The better quality laminates were cured under 3.44 MPa in a heated platen press.

Bryte EX-1551 is a commercially available cyanate ester prepregging resin and was obtained as a B-staged film for these investigations. These PBO laminates were similarly prepared by interleaving the EX-1551 film between the plies of fabric. ORNL (7) experience has indicated that the cured properties of cyanate ester resins can be affected by the presence of moisture and/or air during the cure cycle. Therefore all PBO/EX-1551 laminates were bagged and cured under vacuum in either a heated platen press or oven. The EX-1551 cure cycle used in these trials was nominally 1 hour at 177°C and 2 hours post-cure at 215°C-225°C. The EX-1551 resin flow was adequate to achieve good consolidation in laminates cured with only vacuum bag pressure.

Vantico RD98-228 cyanate ester resin is not commercially available at this time but previous studies (8) have shown that it has exceptionally good fire/flame performance. The resin was obtained in dry powder form and PBO fabric infiltration was accomplished by dissolving the resin in acetone and immersing the fabric into the solution. The fabric plies were then dried in an air circulating oven at ~55°C to remove residual acetone. No catalyst was added to the resin and adequate cure was achieved with the application of heat alone. Laminate resin content was controlled by the ratio of resin-to-acetone in the solution, and by the number of times the fabric plies were immersed in the resin/solvent bath.

Curing was similar to the process used to prepare the PBO/EX-1551 laminates. All laminates were bagged and cured under vacuum conditions for either heated platen press or oven fabrications. Various cure cycles and temperature ramps were investigated during the course of this study, but all included a minimum of a 1 hour dwell at 160°C-177°C and 2 hours post-cure at 215°C-225°C. High resin content (greater than 20 weight percent) laminates were successfully consolidated with vacuum bag pressure alone. Lower resin content laminates required a minimum of 0.68 MPa to consolidate the laminate.

PBO/RD98-228 laminates were also prepared by melting the resin powder at ~85°C and then applying the liquid resin to the fabric with a roller. These laminates were not as successful because of the difficulty achieving uniform resin coverage over the fabric and at such low resin contents as required by this application. However, it is reasonable to assume that a commercial prepregger could prepare this resin into a film and apply it directly to the PBO fabric using conventional prepreg manufacturing equipment and techniques.

Preliminary results with the PBO/RD98-228 laminates were variable, indicating that further process optimization was required. Some of the laminates cured under high pressure in the platen press developed dark, black splotches at various locations in the laminate. Process investigations conducted during the course of these fabrications, and comparisons with laminates that were vacuum bag-cured in an oven suggest that the phenomena was related to inadequate venting of volatiles that remained trapped within the laminate during the cure cycle and inhibited the resin cure. Possible sources of volatiles are residual acetone from the dipping operation, residual solvent from the resin manufacturing process, and/or moisture. This problem was significantly reduced for laminates cured under high pressure by increasing the amount of breather cloth in the laminate stack to enhance the evacuation pathway during cure.

3. FIRE AND SMOKE TESTING

Six-ply thick laminates were prepared from Zylon fabric and PVB-phenolic and cyanate ester resin systems. Laminates were fabricated with both “low” (11-15 weight percent) resin contents typical of energy absorbing composites, and higher (22-28 weight percent) resin contents that might be found in more structural composites.

Details of the fire and smoke tests conducted as part of these investigations are described in the FAA Aviation Aircraft Materials Fire Test Handbook (9). For the 60-second vertical Bunsen burner tests, a flame with a minimum temperature of 845°C impinges on both sides of the specimen. The heat release rate test subjects specimens to a radiant heat flux density of 3.5 W/cm^2. For the smoke test the radiant heat flux density is 2.5 W/cm^2.

3.1 Vertical Bunsen Burner Test Table 2 shows that all of the PBO laminates successfully passed the 60 second vertical Bunsen burner test. Burn lengths were very low (2 cm or less). Discoloration is attributed primarily to resin charring or decomposition, rather than from the PBO fiber.

3.2 Heat Release Rate Test Table 3 summarizes the heat release rate data for all of the laminates. All samples passed with the exception of the high resin content (28.2 weight percent)

PBO/PVB-phenolic composite. The high heat release rate is attributed to the decomposition/burning of the polyvinyl butyral rubber resin constituent.

Table 2. PBO composite vertical Bunsen burner (60 second) tests

	Flame Out Time (min: s)	Burn Length (cm.)	Drip Flame Time (min: s)	Number of specimens	Comments
Pass criteria for 60 s burn test	<0:15	<15.2	<0:3		
PBO/PVB-phenolic film					
12.5 weight percent resin	0	<1.3	0	1	Pass
28.2 weight percent resin	3.3	4.2	0	3	Pass
PBO/EX-1551 cyanate ester resin					
12.1 weight percent resin	0	0	0	3	Pass
22.5 weight percent resin	0	<0.8	0	3	Pass
PBO/RD98-228 cyanate ester resin					
11 weight percent resin	0	1.9	0	3	Pass
28.2 weight percent resin	0	<0.5	0	3	Pass

Table 3. PBO composite heat release rate tests

	Average Total Heat Released* (kW min/m^2)	Heat Release Peak (kW/m^2)	Comments
Pass criteria	<65	<65	
PBO/PVB-phenolic film			
12.5 weight percent resin	46.8	40.1	Pass
28.2 weight percent resin	101.0	72.1	Fail
PBO/EX-1551 cyanate ester resin			
12.1 weight percent resin	34.0	35.4	Pass
24.8 weight percent resin	57.9	45.7	Pass
PBO/RD98-228 cyanate ester resin			
11 weight percent resin	14.8	15.5	Pass
28.2 weight percent resin	17.8	16.9	Pass

Note: Data is average of three specimens
* 2 minute total

Table 4. PBO composite smoke tests

	Maximum Value* of Specific Optical Density, D_s (D_m)	Comments
Pass criteria	<200	
PBO/PVB-phenolic film		
12.5 weight percent resin	7.3	Pass
28.2 weight percent resin	11.8	Pass
PBO/EX-1551 cyanate ester resin		
12.1 weight percent resin	13.6	Pass
24.8 weight percent resin	43.4	Pass
PBO/RD98-228 cyanate ester resin		
11 weight percent resin	10.4	Pass
28.2 weight percent resin	4.7	Pass

* Average of three specimens

3.3 Smoke Test Table 4 summarizes the laminate smoke test data. All composites, including the high resin content specimens, passed this test with extremely high margins.

3.4 Summary of Fire Test Results Based primarily on the heat release data in Table 3, the fire performance of the PBO laminates may be summarized as follows:

Material	Fire Performance
PBO/PVB-phenolic	Good
PBO/EX-1551 cyanate ester	Better
PBO/RD98-228 cyanate ester	Best

Because of the susceptibility of the rubber constituent, fire performance of PBO/PVB-phenolic laminates is especially dependent on resin content.

4. BALLISTIC SCREENING TESTS

As a method of screening a material's ability to absorb energy in high-rate loading conditions, small (18-cm x 20-cm) composite material targets are fabricated at ORNL to evaluate the materials' capability to stop a lead shotgun slug in a ballistic test. The targets are clamped tightly between aluminum front and back plates that are bolted together. Serrations in the plate faces adjacent to the composite and the bolt torque hold the composite between the plates during impact. Nominal 10-cm diameter cut-outs in the front and back plates provide the entry and exit paths for the shotgun slug. Strike (initial) projectile velocity is measured with a chronograph placed directly in front of the target. A second chronograph at the back of the target records residual exit velocity. The kinetic energy (KE) absorbed by the target is calculated via

$$KE = \frac{1}{2}\, mv_1^2 - \frac{1}{2}\, mv_2^2$$

where m is the mass of the projectile and v_1 and v_2 are the entry and exit velocities, respectively.

The shotgun slugs included Remington RR12RS and the Federal P127LRS low recoil lead slugs, which had measured nominal strike energies of 1620 J and 1760 J in these tests. The nominal projectile mass for both slug types is 28 g.

The test methodology for evaluating a laminate's capability to stop a projectile was to adjust a target's thickness until it successfully stopped the 1620 J slug. Some additional testing was also performed to evaluate laminate performance with the higher energy rounds.

In order to determine how resin quantity and distribution affect the ability of a PBO composite to absorb energy in high-rate loading, laminates were prepared with several different resin contents and resin distributions through the laminate thickness:

- Uniform resin distribution of nominally 11-15 weight percent
- Uniform resin distribution of nominally 21-26 weight percent

- Uniform resin distribution of nominally 40 weight percent
- Non-uniform resin distribution. Resin-rich (nominally 25 weight percent) outer plies and resin-starved (less than 10 weight percent resin) inner plies

Tables 5 and 6 summarize the ballistic test data for selected PBO composite specimens evaluated as part of this study. The data show that the threshold thickness for defeating the shotgun slug threat was a minimum 9-ply thickness of the Zylon fabric, or an areal weight of ~1500 g/m^2. At 8-plies thickness (1320 g/m^2 areal weight), the probability of shotgun slug penetration through the entire target thickness increased. For low resin content laminates prepared with a uniform resin distribution, equivalent results were obtained with laminates prepared with the PVB-phenolic, EX-1551 cyanate ester and RD98-228 cyanate ester resins.

An interesting result of this study was that the target (number 1) prepared with 9 plies of dry Zylon fabric (i.e. no resin) yielded comparable results in defeating the shotgun slug threat as the laminates prepared with uniform, low resin contents. This suggests that in these studies, the resin's role was not as crucial as the fiber's in contributing to ballistic performance.

The specimens with the lower resin contents of nominally 11-15 weight percent performed best for the PBO laminates fabricated with the PVB-phenolic and cyanate ester resins. The laminates with higher resin contents (greater than 20 weight percent) were all penetrated by the shotgun slugs, presumably because the additional resin restricted deformation and straining of the PBO fiber under high rate loading. In fact, the 12-ply thick PBO/PVB-phenolic specimen (number 9) with 23.3 weight percent resin was holed while the 8-ply thick counterpart (number 2) with 12.5 weight percent resin stopped a round with the same strike energy.

Figure 1.a. shows a typical low resin content (15.7 weight percent) 11-ply thick PBO/PVB-phenolic target after testing. The impacting slug deforms the composite into a conical shape that projects roughly 6.4 cm beyond the back face (plane) of the laminate. Figure 1.b. illustrates a comparable higher resin content (23.3 weight percent) 12-ply thick target. Deformation is roughly 20 percent that of the low resin content laminate. These results indicate that for structural applications, the resin content is important and needs to be carefully controlled when fabricating PBO composites for energy absorption applications.

The results also indicate the importance of the resin content of the laminate's outer fabric plies in absorbing energy. Sample numbers 18 and 19 are 10-ply thick PBO/EX-1551 laminates fabricated with a variable resin distribution through the thickness. The outer plies on both faces of the laminate were fabricated to be resin-rich, with a nominal resin content of 25 weight percent. The inner plies (approximately two-thirds of the laminate thickness) were fabricated with a much lower resin content (less than 10 weight percent). The overall average resin content of the laminate is 11.9 weight percent.

Table 5. Ballistic test data for dry PBO fabric and PBO/PVB-phenolic laminates

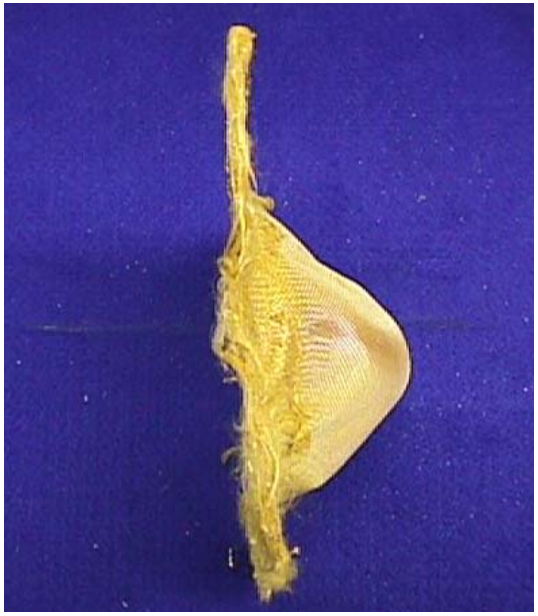
Specimen	Fabric Finish	Resin Content (weight percent)	Consolidation Pressure (MPa)	Number of Plies	Areal Weight (g/m^2)	Strike Velocity (m/s)	Energy Absorbed (J)	Holed	Number of Layers Perforated
				Dry PBO fabric (no resin)					
1	Greige	-	-	9	1250	365	1886	No	1/9
				PBO/PVB-phenolic resin					
2	Greige	12.5	3.44	8	1319	352	1752	No	0/8
3	Greige	12.5	3.44	8	1319	378	480	Yes	all 8
4	Greige	26.3	3.44	8	1564	346	157	Yes	all 8
5	Greige	41.1	3.44	8	1955	347	83	Yes	all 8
6	Greige	14.5	0.69*	9	1515	368	1920	No	2/9
7	Greige	12.5	1.04*	10	1662	371	1948	No	2/10
8	Greige	15.7	3.44	11	1857	358	1810	No	0/11
9	Greige	23.3	3.44	12	2248	353	283	Yes	all 12
10	Water repellant	13.5	3.44	8	1319	367	1908	No	2/8
11	Water repellant	16.2	3.44	9	1515	380	2043	No	2/9
12	Water repellant	14.4	3.44	11	1808	340	1632	No	0/11
13	Water repellant	14.4	3.44	11	1808	363	1870	No	5/11

* Poor laminate consolidation

Table 6. Ballistic test data for PBO/cyanate ester resin laminates

Specimen	Fabric Finish	Resin Content (weight percent)	Consolidation Pressure (MPa)	Number of Plies	Areal Weight (g/m^2)	Strike Velocity (m/s)	Energy Absorbed (J)	Holed	Number of Layers Perforated
				PBO/EX-1551 resin					
14	Greige	13.5	3.44	8	1319	335	No data	Yes	all 8
15	Greige	11.6	0.69	8	1319	363	1863	No	1-2/8
16	Greige	11.3	3.44	9	1466	369	1929	No	1-2/9
17	Greige	13.8	0.69	9	1515	388	2135	No	1-2/9
18	Greige	Resin distribution*	3.44	10	1613	347	1702	No	5/10
19	Greige	Resin distribution*	3.44	10	1613	368	1820	Yes	all 10
20	Water repellant	9.7	3.44	8	1271	340	1102	Yes	all 8
21	Water repellant	11.5	3.44	11	1808	375	1994	No	3-4/11
				PBO/RD98-228 resin					
22	Greige	12.6	3.44	8	1319	357	1802	No	1/8
23	Greige	13.5	3.44	11	1857	335	1589	No	2/11
24	Greige	21.2	3.44	11	2004	343	140	Yes	all 11
25	Greige	14.2	3.44	15	2541	363	1867	No	4/15
26	Water repellant	12.8	3.44	8	1319	361	1851	No	1/8
27	Water repellant	13.3	3.44	15	2492	365	1889	No	7/15

* Variable resin distribution with resin-rich (~25 weight percent) outer plies and resin-starved (<10 weight percent) inner plies. Average resin content: 11.9 weight percent



(a) PBO/PVB-phenolic target (11-plies thick) with uniform and low (15.7 weight percent) resin distribution.

(b) PBO/PVB-phenolic target (12-plies thick) with uniform and high (23.3 weight percent) resin distribution.

(c) PBO/EX-1551 target (10-plies thick) with variable resin distribution. Resin-rich outer plies (~25 weight percent) and resin-starved inner plies (<10 weight percent). Average resin content through laminate thickness is 11.9 weight percent.

Figure 1. Deformation of PBO laminate targets after ballistic impact from shotgun slug.

Even though the majority of the laminate thickness was fabricated with the lower resin content, the specimens' ballistic performance were lower than those of laminates prepared with a uniformly low resin content. The 459 m/s slug penetrated half of the 10-ply laminate's thickness. The entire laminate thickness was penetrated (holed) completely by the 487 m/s slug. Figure 1.c. illustrates the target that was completely penetrated. Deformation through the back of the target is roughly half that of the PBO/PVB-phenolic target fabricated with the uniformly low (15.7 weight percent) resin content (Figure 1.a.)

These results indicate that the optimum resin content for PBO composites is a uniform resin distribution that is on the order of 11-15 weight percent. Restriction of even only the fibers in the outer surface plies can be detrimental to the ballistic performance of the remainder of the laminate. The data suggest that care should be taken in applying external coatings and coverings to these composites (such as for wear resistance, cosmetic purposes, etc.) to ensure that these outer materials do not similarly restrain fiber deformation, thereby limiting the capacity of the composite to absorb energy.

The laminates prepared with the Zylon fabric treated with a water repellant finish were slightly more flexible than their greige counterparts, suggesting reduced fiber-resin adhesion. When tapped sharply with a coin, the laminates prepared with the water repellant treated fabric were also better at damping (muffling) the sound than the greige fabric laminates, again suggesting a weaker fiber-resin interface. However, under high rate ballistic loading, the laminates with the water repellant-treated fabric were equivalent to laminates made with fabric left in the greige condition. Based on the equivalent ballistic results, and the fact that the scouring process required to remove the finishing oils from the greige yarn can degrade fiber tensile strength, it is reasonable to select the greige treatment for these energy absorption applications.

The laminates consolidated with 0.69-1.04 MPa yielded equivalent ballistic results to the laminates prepared with the baseline 3.44 MPa consolidation pressure. This is not surprising in light of the other data that show that dry fabric and laminates prepared with a weakened fiber-resin interface also performed well in these ballistic tests. The PBO/PVB-phenolic laminates (numbers 6 and 7) were poorly consolidated at these low pressures primarily due to the low flow characteristics of the resin film. The higher flow of the EX-1551 resin during cure provided better resin penetration through the laminate and a more structural composite (numbers 15 and 17). In both cases, ballistic performance was not affected.

These results indicate that high consolidation pressures are not necessary to enhance ballistic performance for PBO fiber composites. However, depending on the flow characteristics of the matrix resin, high consolidation pressures may be necessary to compensate for the lower resin contents of these laminates, and to promote inter-ply bonding so that the composite holds together and can be handled in its end application.

5. CONCLUSIONS

Processing of advanced composite materials has been developed to combine energy absorbing fibers with fire resistant resin matrices. The most promising combinations include Zylon (PBO) fiber in a phenolic-based or a cyanate ester resin. PBO composites prepared with a low resin

content (11-15 weight percent) of PVB-phenolic, EX-1551 cyanate ester and RD98-228 cyanate ester resin passed a stringent series of fire tests that include Bunsen burner, heat release rate and smoke tests. At higher resin contents (22-28 weight percent), the PVB-phenolic resin laminates fail the heat release rate test but laminates prepared with EX-1551 and RD98-228 cyanate ester resin continue passing all fire tests.

PBO composites prepared with the fire resistant resin matrices are effective at absorbing energy as evaluated with a series of shotgun slug ballistic screening tests. The results of this testing indicate that the resin content and distribution is more important to ballistic performance than the resin's chemistry or properties. These results indicate that the optimum resin content for PBO composites is a uniform resin distribution that is on the order of 11-15 weight percent. With these resin contents, the threshold thickness for defeating the shotgun slug threat was a minimum 9-ply thickness of the Zylon fabric, or an areal weight of ~1500 g/m^2, and the energy absorbed was on the order of 1800-2000 J.

The laminates prepared with higher resin contents (greater than 20 weight percent) or resin-rich outer plies were all penetrated by the shotgun slugs, presumably because the additional resin restricted deformation and straining of the PBO fiber under high rate loading. These results indicate that for structural applications, the resin content is important and needs to be carefully controlled when fabricating PBO composites for energy absorption applications.

Although the laminates prepared with fabric that had been treated with a water repellant finish gave indications of having reduced fiber-resin adhesion, both the water repellant and greige treated fabrics yielded equivalent ballistic test results. This suggests that it is reasonable to select the greige treatment for these energy absorption applications, particularly in light of the fact that the scouring process required to remove the finishing oils from the greige yarn can degrade fiber tensile strength.

The laminates consolidated with both low and high consolidation pressures yielded equivalent ballistic results. The results indicate that high consolidation pressures are not necessary to enhance ballistic performance for PBO fiber composites. However, depending on the flow characteristics of the matrix resin, high consolidation pressures may be necessary to compensate for the lower resin contents of these laminates, and to promote inter-ply bonding so that the composite holds together and can be handled in its end application.

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