Ballistic Performance of 21 Layered Hybrid Composites

Cenk YANEN[1], Murat Yavuz SOLMAZ[2]

***Abstract*—** This paper experimentally investigates usability of multilayered hybrid composite as personal body armor material which is an important parameter in ballistic fabric energy. This study four hybrid composites material with different thickness and number of layers have been produced by using 3 different types of fabric. Then ballistic tests have been performed by using Beretta gun and 9 mm FMJ bullet according to the National Institute of Justice 0101.06 standards. In the ballistic tests, the speed of bullets and the depth of penetration occurring on the test samples have been measured and the damages have been assessed. The results show that unidirectional hybrid composites show a superior ballistic performance as compared to the other hybrid composites.

***Keywords*—** Hybrid composite, Ballistic performance, Armor material.

I. Introduction

Currently high-strength polymer fabrics are widely used for protective systems due to their mechanical properties and impact resistance [1]. High performance polymer fibers such as aramid fibers, carbon fibers and glass fibers have remarkable properties such as lightness, flexibility, high Young's modulus and good impact resistance, which make them attractive candidates for the manufacturing of modern protective equipment [2].

The effect of hybridization of glass-carbon fabric was reported by Pandya et al. [3]. They studied the ballistic impact behavior of symmetric hybrid composites made using plain weave E-glass fabric and 8H satin weaved T300 carbon fabric with epoxy resin. It was found that the placing of E-glass layers in the exterior and carbon layers in the interior provides higher ballistic limit velocity than placing carbon layers in the exterior and E-glass layers in the interior.

Nayak et al. [4] investigated the ballistic impact responses of plain woven aramid/epoxy composites with thicknesses from 10 to 25 mm. They concluded that the ballistic limit shows linear change with the laminate thicknesses. Furthermore, delamination fiber breakage and pull out constituted the mechanisms of penetration and major energy absorption. Based on Zhang et al. [5], a bi-linear relationship was found between the ballistic limit velocity and sample thickness. The increase in thickness of UHMWPE composites demonstrated a two-stage penetration process; shear plugging during the initial penetration followed by the formation of a transition plane and bulging of a separated rear panel [6]. Wambua et al. [7] reported increase of ballistic impact velocity (V50) for increasing composite thickness. V50 refers to the ballistic impact velocity for which there is a 50% chance of penetration and 50% of non-perforation of the composites.

The effect of hybrid composites was studied experimentally by Randjbaran et al. [8] to investigate the effects of stacking sequence layers of hybrid composite materials on ballistic energy absorption [9].

In a ballistic back face signature test, the NIJ standard for personal protection [10] requires that a projectile to be stopped and the penetration depth of depression (indentation) into a clay witness (backing the armor) should not exceed 1.73 in. (~44 mm). Deeper penetrations are associated with lethal trauma inflicted to the wearer. Therefore, the smaller the indentation, the better the armor ballistic performance should be.

One of the most well-known polymeric fibers for protective systems is aramid fiber with the commercial name Kevlar [11]. Fabrics made with this aramid fiber have high strength, high modulus and good tenacity, which are desirable properties for ballistic applications; however, they are relatively expensive and the design of protective equipment with these fabrics should include studies to reduce the amount of required fabric layers without compromising the effectiveness of the armor.

The aim of this study is to produce layered hybrid composites for personal body armor and to ensure high ballistic resistance and lightness. In this study, 21 layered hybrid composite test samples have been produced and ballistic tests have been performed according to NIJ 0101.06 standard and the results have been investigated. The ballistic tests have been performed by using Beretta Gun and 9 mm FMJ bullet from 5 m distance. In this study we have focused on if the test samples have been succesful according to mentioned NIJ 0101.06 standard. Materials and experimental procedures are described in Section 2. Results and discussion are presented in Section 3, followed by conclusions in Section 4.

II. Methods

A. Materials

In this study four hybrid layered composite test samples have been produced. Four configurations were tested: (i) [Glass(45°)7 /Aramid (plain)7 /Carbon(45°)7], (ii) [Glass(0°)7 /Aramid (plain)7 /Carbon(0°)7], (iii) [Glass(plain)7 /Aramid (plain)7 /Carbon(plain)7] and (iiii) [Glass(twill)7 /Aramid

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(plain)7 /Carbon(twill)7]. For all configurations, plain-woven aramid was used. . The properties of these fabrics are given in Table I.

TABLE I
THE FIBER FABRIC USED IN SAMPLE PRODUCTION

Fabric Name	Fabric Type	Density [gr/m^2]
Carbon Fiber	Unidirectional 0°	300
Carbon Fiber	Unidirectional 45°	400
Glass Fiber	Unidirectional 0°	300
Glass Fiber	Unidirectional 45°	460
Aramid Fiber	Plain Woven	410
Carbon Fiber	Plain Woven	200
Carbon Fiber	Twill Woven	245
Glass Fiber	Plain Woven	200
Glass Fiber	Twill Woven	282

B. Fabrication of Composite Laminates and Sample Configuration

Hybrid laminated composites of 200 mm x 200 mm size was used for the ballistic testing. The hand-lay-up method was used to fabricate laminated hybrid composites. Aramid, Carbon and Glass fabrics were hand laid-up with the epoxy matrix by mixing epoxy resin (Hexion MGS L326) and hardener (Hexion H265) in the ratio of 4:1. Two thick mild steel plates were used as a mold (200 mm x 200 mm) in the fabrication process [12]. The composites were cured by applying compression pressure using at 20 bar pressure. The test samples have been cured by increasing the temperature gradually from 20 C° to 110 C° in 4 hours. The schematic of test sample is given in Fig. 1 [13].

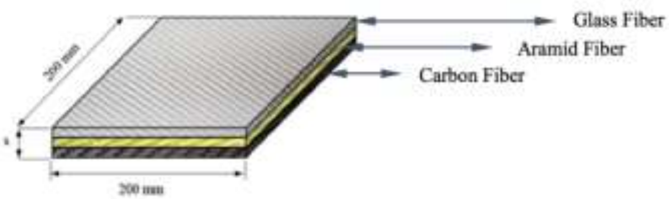

Fig 1. The schematic of the structure of [Glass/Aramid/Carbon] layered hybrid polyester resin matrix

The properties of layered hybrid composite produced in Firat University Mechanical Laboratory are given in Table II.

TABLE II
PROPERTIES OF LAYERED HYBRID COMPOSITE

Name	Material	Number of layers	Weight [gr]	Density [gr/cm^3]
B5	[Glass (45°)/Aramid (plain)/Carbon (45°)]	21	554	1.54
B6	[Glass (0°)/Aramid (plain)/Carbon (0°)]	21	468	1.63
B7	[Glass (plain)/Aramid (plain)/Carbon (plain)]	21	372	1.55
B8	[Glass (twill)/Aramid (plain)/Carbon (twill)]	21	432	1.54

C. Ballistic Testing

All samples were tested according to the National Institute of Justice 0101.06 standard. According to NIJ 0101.06 Level II-A standard, in the shots from 5 m by using 9 mm FMJ bullet, the bullet speed has to be 373 ± 9.1 m/s. The velocity of the projectile was measured with a Chrony F1 Master chronograph located between the barrel and the composite test samples. A steel frame with a 200 x 200 mm2 window was built to hold the sample without back support. A full metal jacket bullet with a diameter of 15.7 mm and a mass od 8 g was used. According to NIJ 0101.06 standard, to consider the test sample successful, the bullet used in the test have to stay in the test sample and the depth of penetration have to be maximum 44 mm. For the depth of penetration above 44 mm, the test sample is considered to be unsuccessful even if it is not perforation. The depth of this penetration, measured with a caliper (Fig. 3) is associated with the ballistic performance of the target. The ballistic tests have been performed by the same person to make sure that carrying out the tests in the same condition. The experimental setup is shown in Fig. 2. The kinetic energy of the bullet for mass (m) and the impact velocity (V), Ek is:

$$E_k = \frac{1}{2} m V^2$$

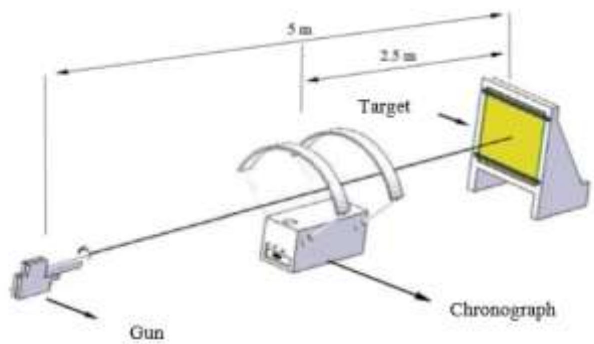

Fig 2. Schematic view of the ballistic test system

III. RESULTS

The ballistic impact experiment was conducted using 9 mm FMJ projectile. Each sample was impacted according to NIJ 0101.06. The striking velocities of the projectile were measured using chronograph. The photos of the 21 layered test samples after the ballistic tests are shown in Fig. 3-6.

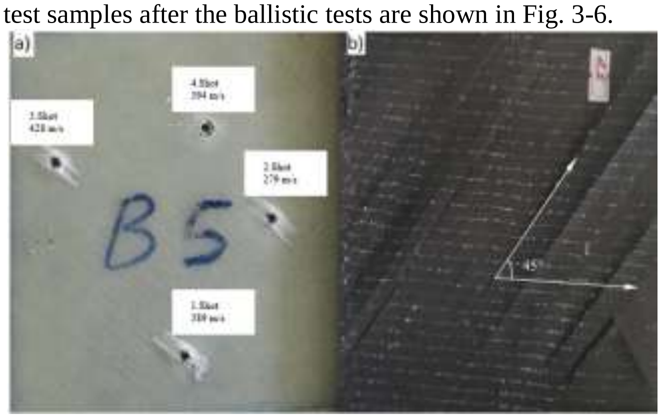

Fig 3. [Glass(45°)$_7$/Aramid (plain)$_7$ /Carbon(45°)$_7$] test sample a) front view b) rear view

Four shots were performed to 21 layered plates. Test results photos of B5 sample is given in the Fig. 3. Bullet velocity and kinetic energy values that calculated with these velocities is defined by chronograph between center point of target and weapon given in Table III.

TABLE III
BALLISTIC TEST RESULT OF B5 SAMPLE

Sample Sequence: [Glass(45°)$_7$/Aramid (plain)$_7$ /Carbon(45°)$_7$]				
Shot Number	Bullet Velocity (m/s)	Kinetic Energy (Nm)	Depth of Penetration (mm)	Evaluation
1	389	606,00	8,00	No Perforation
2	279	312,28	5,70	No Perforation
3	428	729,40	10,60	No Perforation
4	394	621,28	9,35	No Perforation
Average	372	567,24	8,41	

None of shots to first of 21 layered sample caused perforation and sample verified as successful. Average of 4 shot to sample B5 is 372 m/s and corresponding depth of penetration value is 8,41 mm. This sample verified as successful according to NIJ level II-A. In this sample carbon fiber fabric functioned as support plate cause fiber damage at directions ±45° because of it is 45° and hard structured.

Second sample that ballistic test of it performed is [Glass(0°)7 /Aramid (plain)7 /Carbon(0°)7] sequenced B6. Ballistic test results of B6 sample is given in Fig. 4. Bullet velocity, kinetic energy and their assessment is given in Table IV.

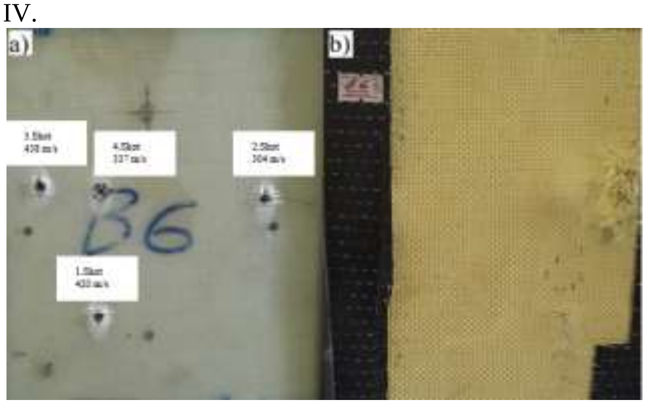

Fig 4. [Glass(0°)7/Aramid (plain)7 /Carbon(0°)7] test sample a) front view b) rear view

TABLE IV
BALLISTIC TEST RESULT OF B6 SAMPLE

Sample Sequence: [Glass(0°)$_7$/Aramid (plain)$_7$ /Carbon(0°)$_7$]				
Shot Number	Bullet Velocity (m/s)	Kinetic Energy (Nm)	Depth of Penetration (mm)	Evaluation
1	420	705,65	7,30	No Perforation
2	304	369,39	5,80	No Perforation
3	337	455,39	6,80	No Perforation
4	438	768,44	-	Perforation
Average	354	510,14	6,63	

Fourth shot have 438 m/s one of 4 shots performed to sample B6 caused perforation. At back face carbon fiber plate with effect of crash rupture happened. Except shot number 4 other shots average depth of penetration value is 6,63 mm corresponding to average 354 m/s bullet velocity. Shot number 4 perforation happened, fiber plates and leave the system by rupturing.

Ballistic test results of [Glass(plain)7/Aramid(plain)7/ Carbon(plain)7] sequenced B7 sample is given in Fig. 5. Bullet velocity, kinetic energy and their assessment is given in Table V.

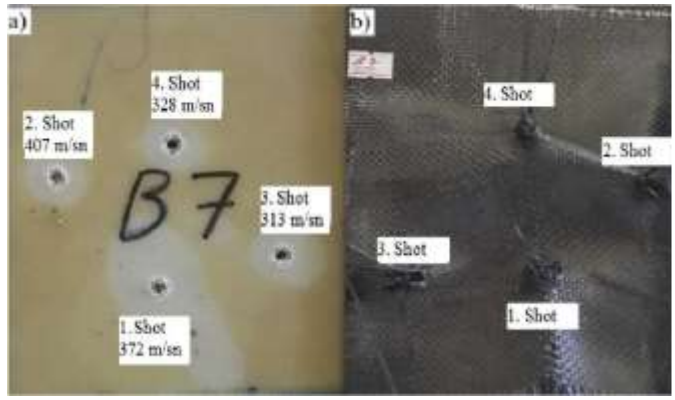

Fig 5. [Glass(plain)$_7$/Aramid (plain)$_7$ /Carbon(plain)$_7$] test sample a) front view b) rear view

TABLE V
BALLISTIC TEST RESULT OF B7 SAMPLE

Sample Sequence: [Glass(plain)$_7$/Aramid (plain)$_7$ /Carbon(plain)$_7$]				
Shot Number	Bullet Velocity (m/s)	Kinetic Energy (Nm)	Depth of Penetration (mm)	Evaluation
1	372	554,01	-	Perforation
2	407	663,29	-	Perforation
3	313	391,19	-	Perforation
4	328	429,44	-	Perforation
Average	355	509,48	-	

The bullet speeds of shots to B7 test sample have been between 313 m/s and 407 m/s. All of these shots have resulted with perforation and the samples have been unsuccessful.

Test results photos of B5 sample is given in the Fig. 6. Bullet velocity and kinetic energy values that calculated with these velocities is defined by chronograph between center point of target and weapon given in Table VI.

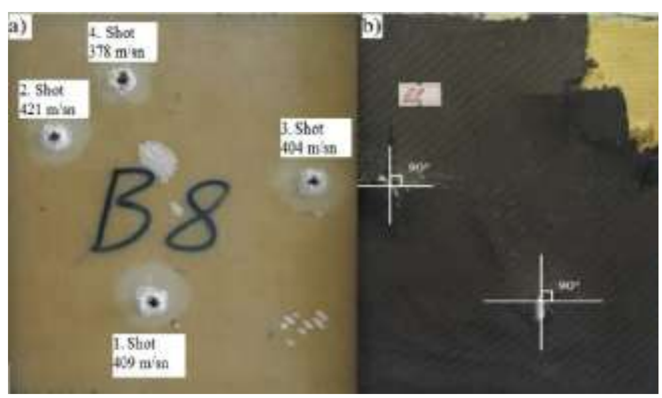

Fig 6. [Glass(twill)$_7$/Aramid (plain)$_7$ /Carbon(twill)$_7$] test sample a) front view b) rear view

TABLE VI
BALLISTIC TEST RESULT OF B8 SAMPLE

Sample Sequence: [Glass(twill)$_7$/Aramid (plain)$_7$ /Carbon(twill)$_7$]				
Shot Number	Bullet Velocity (m/s)	Kinetic Energy (Nm)	Depth of Penetration (mm)	Evaluation
1	409	668,26	-	Perforation
2	421	707,70	-	Perforation
3	404	652,41	10,0	No Perforation
4	378	572,31	7,5	No Perforation
Average	391	612,36	8,75	

Perforation has been occurred in the Shot-1 and Shot-2 of 4 shots to B8 test sample with speed of 409 m/s and 421 m/s respectively. In the shots no puncture has occurred due to the carbon fiber fabric in the rear of the test sample is in twill type, fiber damage has been occurred in both horizontal and vertical directions. Carbon fiber plate has ruptured with Shot-2. In the Shot-1 damage has been occurred in fiber fabric due to twill weaving type and also, perforation has been observed. The average bullet speed has been 391 m/s and the average depth of penetration has been 8.75 mm of all shots accept Shot-1 and Shot-2 in which perforation has been occurred.

IV. CONCLUSIONS

In this study, test samples have been produced to investigate the usability of layered hybrid composites as personal armor material. Ballistic tests of these samples have been performed with the reference of NIJ.0101-06 standard and the results of the tests have been investigated. The structural configuration of the test sample and the evaluations of the ballistic test results are given in Table VII.

TABLE VII
THE BALLISTIC TEST RESULTS

Name	Material	Number of layers	Mass [gr]	Evaluation
B5	[Glass (45°)/Aramid (plain)/Carbon (45°)]	21	554	II-A
B6	[Glass (0°)/Aramid (plain)/Carbon (0°)]	21	468	Puncture
B7	[Glass (plain)/Aramid (plain)/Carbon (plain)]	21	372	Puncture
B8	[Glass (twill)/Aramid (plain)/Carbon (twill)]	21	432	Puncture

In the ballistic tests conducted with the B5 sample, the value of BFS was observed to be 5.70 mm at 279 m / s and 10.60 mm at 427 m / s, which is the lowest projectile speed. The increase in the amount of depression versus the increase of 417.12 joules in the projectile kinetic energy has been 4.90 mm.

The first three shots with speeds of 304 m/s, 337 m/s and 420 m/s made to the B6 sample resulted in no damage to the material and the fourth shot at 438 m / s resulted in perforation and the sample failed.

All shots having speeds of 313 m / sec, 328 m / sec, 372 m / sec and 407 m / sec made to the B7 sample were perforated and the sample failed.

The first two shots with speeds of 409 m / s and 421 m / s made to the B8 sample resulted in perforation. No damage was found on the sample in the other shots having speeds of 404 m / s and 378 m / s. However, this ball has been considered unsuccessful in terms of ballistic protection due to the perforation of the first two throws.

B5 with [Carbon (45°)7/Aramid(plain)7/ Glass(45°)7] lineup has been observed to be the only successful test samples in the ballistic tests.

By considering the results of all test, 45° unidirectional fabrics have been determined to have better ballistic resistance from 0° unidirectional fabrics.

When woven fabrics are examined among themselves, it has been determined that the ballistic strength of fabrics with twill weaving structure is better than fabrics with plain weaving structure.

When the unidirectional fabrics are examined, it has been determined that ballistic use is more suitable for fabrics having a 0 ° angle depending on the structural characteristics of the unidirectional fabrics having an angle of 45 °.

In all experiments, it was determined that the unidirectional fabrics with an angle of 45 ° were more successful than the ones with plain fabric type.

The damage types have been investigated after the ballistic tests and damage of fiber and separation of layers have been observed to be the most common damage types.

Behind the protection property, another important factor in the design of armor material is lightness property. The successful test samples of the ballistic tests in this study can be recommended to study to reach an optimum weight and thickness with better ballistic resistance by reducing the number of layers for new armors.

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