A Study on the Ballistic Performance of Composites

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Summary: The mechanical behaviour and ballistic performance of carbon, glass (E and S type), aramid and polyethylene fabric reinforced composites with different epoxy resins were studied. The specimens – produced by hand lay-up method – were characterized by low velocity (Charpy and drop-weight tests) and high velocity (two different calibre ballistic) impact tests. The energy absorption capacity of the composites was found to be strongly affected by the material properties of the reinforcing fiber, by the type of fabric structure and by the elasticity of resin.

Keywords: composites; impact resistance; thermoset; structure-property relations

Introduction

Polymer matrix composites are used in increasing volume in high performance applications [1, 2]. One of the most important applications is the protection from ballistic impact. Such materials can absorb a significant part of the kinetic energy of the projectile and are also characterized by high specific strength and specific stiffness. In recent years textile composites have been used in composites for protective applications because of their higher energy absorption capability - due to their thickness, stiffness and strength properties.

Several definitions of ballistic impacts are used in the literature [3]. An impact event is considered to be a low velocity impact if the contact period of impactor is longer than the time period of the lowest vibrational mode. In low velocity impact regime, the support conditions are crucial as the stress waves generated outward from the impact point have time to reach the edges of the structural element, resulting in a full-vibrational response. For common epoxy composites, the transition to a stress wave-dominated impact occurs at impact velocities between 10 and 20 m/s. Drop-weight testers generally induce low-velocity impacts [4]. In high velocity or ballistic impact, the response of the structural element is governed by the 'local' behaviour of the material in the neighborhood of the impacted zone, the impact response of the element being generally independent of its support conditions. The contact period of the impactor is much smaller than the time period of lowest vibrational mode of the structure. The ballistic performance of a composite means the capacity of energy absorption of structures during a high-velocity impact. The ballistic performance is often used as ballistic limit in practice. For a given target-projectile combination, the ballistic limit is defined as the lowest initial velocity of the projectile that will result in complete penetration. At the ballistic limit the residual velocity of the projectile is zero [5]. Several factors affect ballistic performance of fiber reinforced composites: material properties of reinforcement; fabric structure; mechanical properties of matrix; interaction of multiple plies – number and order of layers; projectile geometry; projectile velocity.

Interaction of yarns and projectile at impact are reported in studies. Numerical studies by Roylance [6] have shown that the majority of the kinetic energy of the projectile is transferred to the principal

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yarns (yarns that are in direct contact with the projectile) as strain and kinetic energy, whereas, the contribution of the orthogonal yarns to energy absorption is small. Clearly, fibers possessing high tensile strengths and high failure strains can absorb considerable amounts of energy. In the study of Lee et al. [7] correlation was found between the number of yarns broken and the level of impact energy absorbed. Roylance and Wang [8] have shown that materials possessing high modulus and low density disperse the strain wave more rapidly from the impact point, which distributes the energy over a wider area and prevents large strain development from developing at the impact point. Although tensile strength, modulus, and strain-to-failure of yarn play significant roles in ballistic performance, but the effect of these properties cannot be tested individually (Laible [9]).

It has been observed that loosely woven fabrics and fabrics with unbalanced weaves result in weaker ballistic performance [10]. Weave patterns typically used for ballistic applications are plain and basket weaves. The density of the weaves, known as the ''cover factor'' is determined from the width and pitch of the warp and weft yarns and gives an indication of the percentage of gross area covered by the fabric. Chitrangad [11] notes that fabrics should possess cover factors from 0.6 to 0.95 to be effective when utilized in ballistic applications. Larsson's [12] studies have proved that stitching of multiple fabric plies can increase the ballistic impact damage tolerances of a carbon fiber – brittle epoxy laminate. This property of the stitched laminate was found to be much better than that of a prepreg laminate; and the compression strength after ballistic impact test increased by about 50%.

The impact property and damage tolerance of composite laminates with different laminate constitutions depends on ductile behaviour of the matrix. Morii et al. [13] studied glass fiber reinforced matrix hybrid composites with drop-weight tests and found that the impact energy absorption was almost constant when the conventional resin was placed at the impact surface layer, while it increased exponentially with the increasing fraction of the flexible resin if the flexible resin was placed at the impact face.

Based on experimental results it was found that the thickness of composites affects significantly the energy absorption capacity during ballistic impact [14, 15, 16, 17]. Several studies report on the behaviour of multiple plies fabric and composite structures at high velocity impact, mainly from the aspect of failure mechanism. Larsson et al. [18] investigated hybrid composites containing carbon and polyethylene (Dyneema type SK 66) fibers in rigid and flexible epoxy matrices. It was shown that the best ballistic protection was obtained with laminates consisting of two types of fibers separated so that the carbon fiber reinforced part was at the front of the laminates. It is noticeable that for laminates with carbon fibers at the front surface the results for laminates of 50%- 50 % carbon and polyethylene fibers are the same as for laminates with 100% polyethylene fibers. They have interpreted these results as a consequence of the rigidity of the epoxy matrix, since this does not allow fibers or laminate at the back surface to move relative to each other during penetration so that they store energy by tensioning, which is a dominant mechanism for energy absorption in an efficient fiber composite for ballistic protection.

Several studies deal with the effect of the shape of the projectile. Ulven et al. [19] investigated ballistic performance of carbon fiber/epoxy composites against hemispherical, conical, and flat projectiles, and FSP (fragment simulating projectile). The largest amount of energy was absorbed in the panel from the impact of the conical projectile, followed by the flat, hemispherical projectile, compared to FSP (in case of 6.5 mm composite thickness). The significant difference in the amount of absorbed energy can be explained by the different failure mechanisms. In case of thinner composite panels the differences are significantly lower

– although the tendency remained the same – since the thinner sheets bend at impact.

Shim et al. [20] has described the differences between low- and high-velocity impacts. With low impact velocities the yarns do not fail during the initial stress wave; therefore, the transverse deflection of the fabric has time to propagate up to the edges of the panel, which allows the fabric to absorb more energy. Panels struck by a low-velocity projectile are characterized by extensive creasing and stretching, which may contribute to energy dissipation. With a high-velocity impact the damage is localized and the yarns fail before significant transverse deflection can develop.

Based on the results found in the scientific literature our aims in this study were to produce composites by using different fabric structures as reinforcement and epoxy resins of different elasticity, and to investigate their fracture and ballistic properties.

Experimental

Materials

Based on our earlier experience and literature data carbon fabric (Hexcel, USA), E-glass fabric (S.G. Vetrotex, France), S-glass fabric (BGF Industries, USA), aramid (Havel composites, Czech Republic) and polyethylene fabric (Cramer Fabrics, USA) were selected as reinforcements for sample preparation. Two types of rigid epoxy resin Eporezit AH 16 + Hardener T54 (P + M Kft. Hungary), and XB 3517 + Hardener XB 3419 (Hunstman GmbH, Germany) and two types of flexible epoxy resin Eporezit AH 16 + Hardener T58 (P + M Kft. Hungary), Polypox E492 (UPPC AG, Germany) were used. The elasticity of Polypox resin can be adjusted by a third epoxy component in a wide range. Materials used in sample preparation are listed in Table 1 and 2, for reinforcing fabrics and matrix resins, respectively.

Sample Preparation

Epoxy matrix laminates were prepared by hand lay-up method, followed by compression molding at a pressure of 20 bar, followed by a thermal curing process. Our goal was to prepare composite sheets of similar fiber content and thickness, so we changed the number of fabric layers in sheets according to the weight per unit area of reinforcing fabrics. The measured fibers content are shown in Table 3.

In order to investigate the effect of reinforcing fabric structure fabrics with identical fiber thickness, weight per unit area, and density but with different weaving patterns were selected. Two different carbon fabrics fulfilled the above-mentioned criteria. Composite sheets were prepared using 5, 10, 15, 20 carbon fabric layers. Samples were marked as A_n_B, where A means the type of reinforcing fabric, n the number of layers, B the type of matrix. Table 3. shows the main characteristics of samples.

Table 1.
Properties of reinforcing fabrics

Properties	Carbon fabric (43192) (warp/weft)	Carbon fabric (43194) (warp/weft)	E-glass fabric (warp/weft)	S-glass fabric (warp/weft)	Aramide fabric (warp/weft)	Dyneema (polyethylene) fabric (warp/weft)
Type of fiber	3K-HR	3K-HR	E-glass	SCG	Type2200	SK65
Linear density (tex)	110/110	110/110	310/620	33/33	121/121	880/880
Setting per 10mm	4.8/4.8	4.8/4.8	10/5	28.7/25.5	6.7/6.7	9/9
Weave	plain	twill 2/2	plain	8 HS atlas	twill 2/2	twill 2/2
Weight per unit area (g/m^2)	193	193	300	190	170	160
Marking	Cp	Ct	E	S	AR	DY

Table 2.
Properties of matrix components used for sample preparation

Matrix marking	Composites component		Comments
	Resin	Hardener	
M1	Eporezit AH16	T54	rigid
M2	Eporezit AH16	T58	flexible
M3	XB 3517 (Huntsmann)	XB 3419	rigid
M4	Polypox E492 (UPPC)	Polypox H 030	flexible
M5	Polypox E492 Polypox E403*	Polypox H 030	flexible
M6	Polypox E492 Polypox E403*	Polypox H 030	flexible
M7	Polypox E492 Polypox E403*	Polypox H 030	flexible

* -with this liquid epoxy resin elasticity may be adjusted

Test Methods

The experiment with velocity of 10–20 m/s [3] is considered as dynamic, low velocity test. Charpy tests and drop weight tests were conducted in this category. Charpy tests were performed on a Zwick 5113 pendulum impact tester. During Charpy test the impact was flat wise using unnotched samples with a 5.4 J hammer that conforms the EN-ISO 179-1 standard. The studied samples suffered only partial breakage, hence the specific impact strength values (a_{cU}) can be used only for comparison of the different composite samples. The samples' size used for drop-weight tests was 70 mm $\times$ 70 mm, the spear shape was hemispherical with diameter of 20 mm. The tests were carried out according to the ISO 6603 standard, on a Ceast Fractovis 6785 drop-weight tester. The impacting weight was 18.62 kg with 10 m/s velocity. The testing instrument can record diagrams of time/force and displacement/force, which show the maximal contact force and maximal absorbed energy during impact. The total absorbed energy can be calculated from the diagram. As the force measurement limit of the testing machine is 10 kN, in many cases the applicable load was not high enough. In these cases the comparison of the recorded diagrams and their extrapolated results indicates the energy absorption capacity (E_{tot}).

The ballistic tests were performed on the shooting-range of the Technology Agency of the Hungarian Defense Ministry, using two projectile types with different bores. During the first test small-bore projectile (22LR) was used (weight 2.6 g, hemisphe-

Table 3.
Characteristics of samples

Laminate	n	Areal weight (kg/m^2)	Thickness h (mm)	Fiber fraction percentage by volume
E_7_M1	7	2.69	1.36	60.5
E_7_M2	7	2.92	1.56	55.0
E_7_M3	7	2.77	1.42	58.3
E_7_M4	7	3.01	1.74	55.3
E_7_M5	7	2.84	1.53	53.9
E_7_M6	7	2.77	1.47	55.9
E_7_M7	7	3.11	1.75	55.1
AR_7_M1	7	1.96	1.5	55.1
DY_6_M1	6	1.64	1.55	63.9
Cp_5_M1	5	1.28	0.9	59.6
Cp_10_M1	10	2.53	1.6	67.0
Cp_15_M1	15	3.84	2.4	67.0
Cp_20_M1	20	5.16	3.5	61.3
Ct_5_M1	5	1.28	0.98	54.9
Ct_10_M1	10	2.40	1.6	67.0
Ct_15_M1	15	3.73	2.55	63.1
Ct_20_M1	20	5.06	3.4	61.2
S_10_M1	10	2.63	1.48	57.0

rical shape, lead projectile, velocity 360 ± 10 m/s, according to the EN 1522:1998 standard FB1 bullet-proof class). The shooting distance was 10 m. During the second test a big bore projectile (357 Magnum) was used (weight 10.2 g, conic shape, lead core, metal coat projectile, velocity 430 ± 10 m/s, according to the EN 1522:1998 standard FB3 bullet-proof class). The shooting distance was 5 m. Samples of dimension 150 mm $\times$ 150 mm were used. The sample was mounted on a simply supported holder, sandwiched between two rigid metal frames. Striking and residual velocity were measured by sensors. Neglecting the projectile-air frictions energy, and the kinetic energy of the broken parts of composites, the value of absorbed energy is given by the difference of the projectile's kinetic energy before and after the impact (E_p) [3].

Results and Discussion

Effect of Material Properties of Fibers

The results of low velocity tests in case of samples with identical resin and different reinforced structures are shown in Fig. 1.

The best energy absorption was obtained for glass reinforced composites. Among the glass reinforced composites the ones with E-glass samples had high specific impact strength, which indicates rigid behaviour, therefore these samples had low energy absorption capacity during drop weight tests. The low energy absorption capacity of carbon fabric composites is also consequence of rigid behaviour of carbon fibers. The different weaving patterns result difference in energy absorption of composite sheets, basket weaving seems to be advantageous. Composites reinforced by aramid and Dyneema fibers are frequently used for ballistic protection purposes, therefore we expected better results with these samples. The tensile strength values of aramid and Dyneema fibers are comparable with that of E-glass fibers, but they exhibit lower density and higher elongation at break. As the matrix of the samples studied was a rigid epoxy resin, the flexible nature of the fibers did not manifest. Samples exhibited only partial failure during the Charpy test, the samples bent after the cracking of the matrix and the hammer drove through the damaged specimens between the supports. The adhesion between the Dyneema (polyethylene)

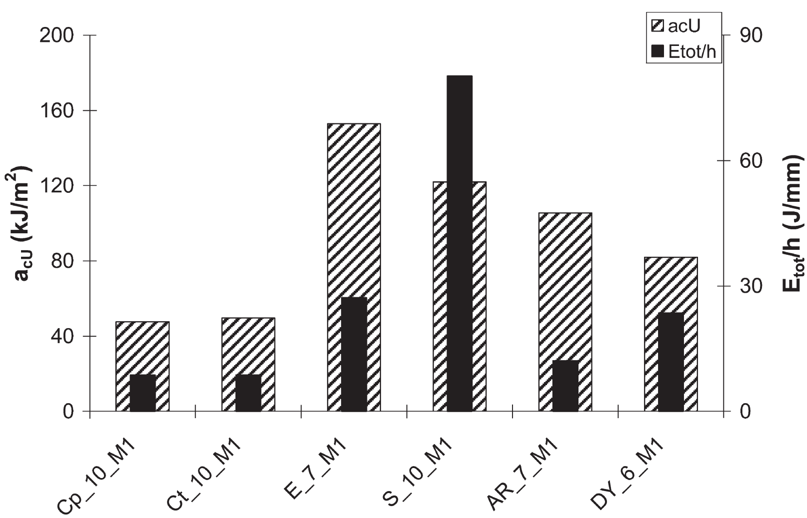

Figure 1.
Specific impact strength and specific energy absorption capacity in case of samples with identical resin and different reinforcing fabrics.

fibers and the epoxy resin is weak, therefore the specific impact strength of the Dyneema reinforced samples is lower than that of aramid reinforced sample. In the drop-weight test the energy absorption of the Dyneema reinforced composite was higher than that of the aramid reinforced sample. It seems probable that – due to the higher elongation at break of the Dyneema fibers and due to the lower fiber-matrix adhesion – the reinforcing fiber underwent a higher deformation while being pulled out from the matrix before perforation, therefore the absorbed energy was also higher.

The results of small-bore tests can be seen in Fig. 2.

Similarly to low velocity impact tests carbon fabric reinforced composites showed low energy absorption capacity due to the rigidity of carbon fibers. Highest energy absorption capacities were performed by glass reinforced composites. Aramid and Dyneema reinforced composites also exhibited good energy absorption. The energy absorption of the Dyneema reinforced composite was lower than that of the aramid reinforced composite. As in this case the impact velocity is orders of magnitude higher than in the case of the drop-weight test. The differences in fiber-matrix adhesion and in fiber properties (elongation, etc), probably influenced the energy absorption. Similarly to drop weight tests, in the case of small bore ballistic tests S-glass reinforced samples showed higher energy absorption, than the E-glass samples. However this difference cannot be seen in case of large bore ballistic tests (see Fig. 3).

This behaviour can be attributed to the different reinforcing structures and different projectile geometries.

Effect of Fabric Structure

The weaving structure of the reinforcing fabric influences the energy absorbing capacity of the composite. To study this effect samples reinforced by carbon fabrics with different weaving structures were studied by drop weight test. Carbon fabrics were made of yarns of identical diameter, with identical fiber density, the fabrics had basket and plain weave. Samples with different ply numbers were prepared. The results are shown in Fig. 4.

Basket weave carbon fabric reinforced samples have 10% higher energy absorption in than plain weave fabric reinforced samples. This difference in energy absorption could be observed in all samples of different ply numbers. Therefore the weave structure of the reinforcement influences the energy absorption ability of the composite independently of the thickness of the

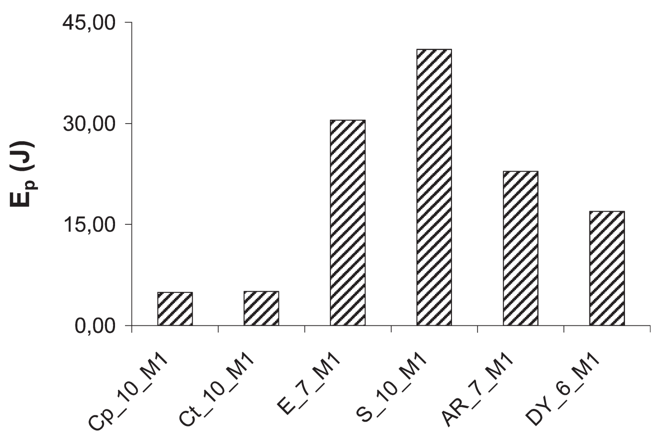

Figure 2.
Absorbed energy in small bore ballistic tests in case of samples with identical resin and different reinforcing fabrics.

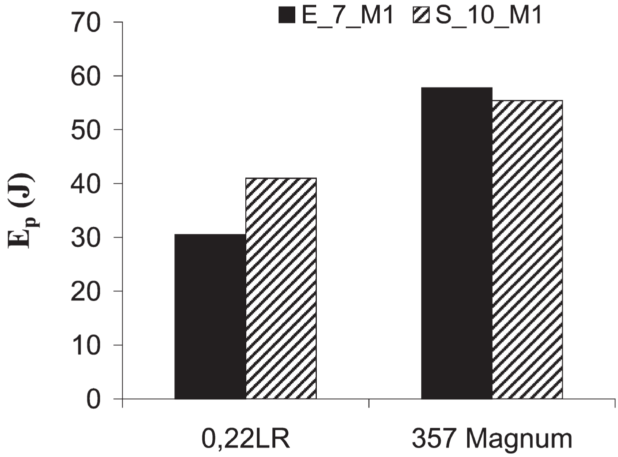

Figure 3.
Absorbed energy in ballistic tests using two projectile types with different bores.

composite. These results are in accordance with the literature data [21]. As shown by Fig. 4. the specific energy absorption ability of the composites increases with the number of the plies, therefore the efficiency of the layers also increases.

Effect of Mechanical Properties of the Matrix

The results of low velocity test in case of samples with different resins and identical E-glass reinforced structures are shown in Fig. 5.

It is clearly seen that the samples with rigid matrix have higher specific impact strength, than composites with flexible matrix. However, during drop weight test the composites with flexible matrix show higher energy absorption (see Fig. 5.a). This behaviour can be explained by the different damage and energy absorbing mechanisms, justified by the displacement/force diagram (see Fig. 5. b that shows the characteristic

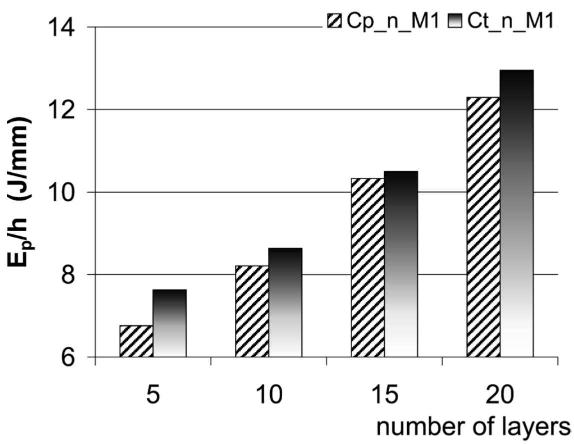

Figure 4.
Effect of reinforcing fabric structure on the specific energy absorption capacity of composites, measured by drop-weight test.

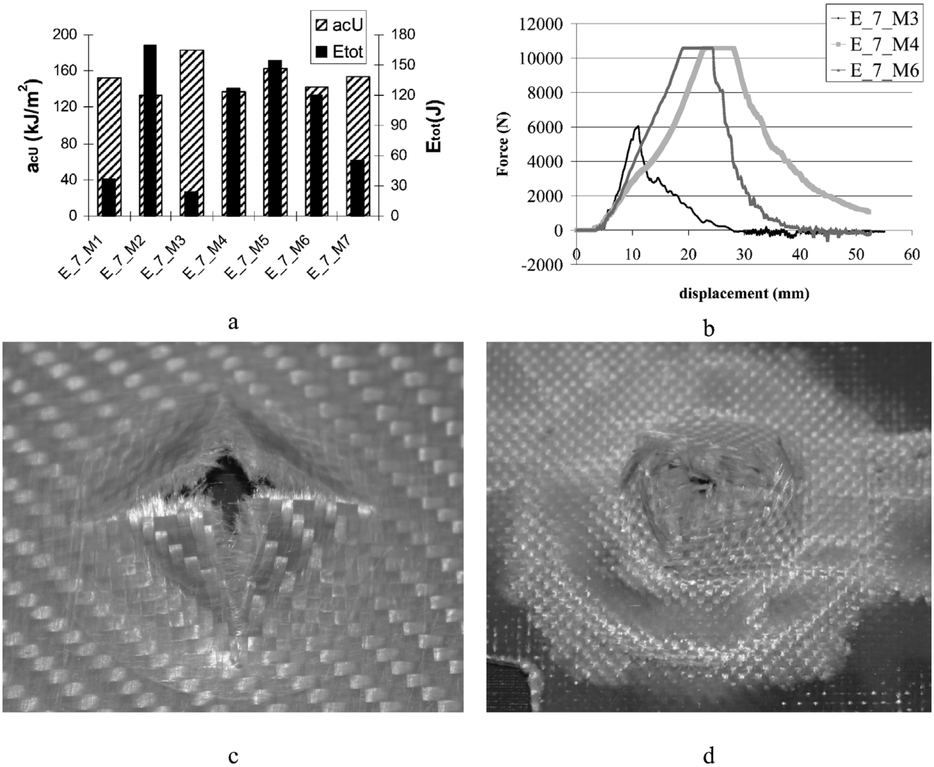

Figure 5.
a) Specific impact strength and energy absorption in drop-weight impact test, b) characteristic displacement/force drop-weight diagram in case of samples with different resin and identical reinforced structures, c) damage zone of a rigid matrix composite after a drop weight test, d) damage zone of a flexible matrix composite after a drop weight test.

displacement-force curves) and the image of the samples after drop weight impact test (see Fig. 5. c, d). In case of samples with rigid matrix the diameter of damaged zone of the front surface is equal to the spear size. On the back face broken fibers and matrix cracking can be seen. The matrix cracking is parallel to the warp and weft directions. In case of samples with flexible matrix composites the damaged zone is extensive, it is bounded by the fixing rings. On the back face the sample is bulged, the fibers are pulled out, the broken fibers can be seen along a circle. Before perforation the rigid matrix composites show no deformation, while the flexible matrix composites suffer extensive deformation. This difference can be seen on the initial slope of the displacement/force diagram.

The results of the ballistic impacts – similarly to drop weight tests – show that the flexible matrix composites have higher energy absorption values (see Fig. 6.).

The order of composites based on energy absorption is not the same in case of drop weight and ballistic tests. If ranking is performed based on the degree of energy absorption, one can see that in the drop-weight test the energy absorption of samples with flexible matrices is the highest (in decreasing order M2, M5, M4, M6, M7), followed by two rigid matrix composites. In the case of the shooting test, ranking the samples based on the energy absorption one can see that the two highest energy

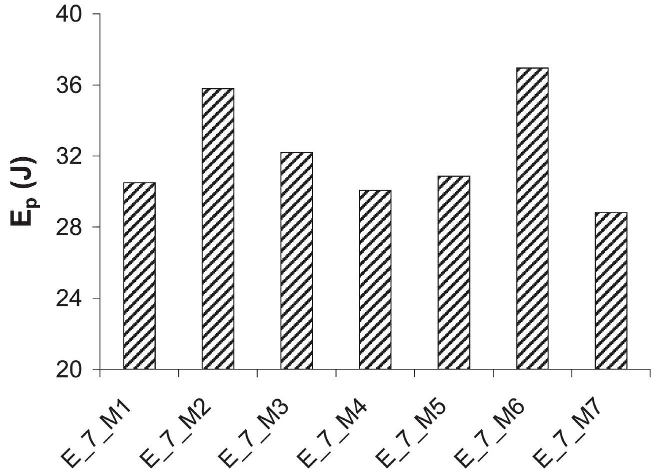

Figure 6.
Absorption energy in ballistic test, in case of samples with different resin and identical reinforced structures.

absorption values are in fact exhibited by two flexible matrix composites (in decreasing order M6 and M2). This is followed, however, by a rigid matrix composite (M3), then follow the rest of the composites with comparable absorption values (M5, M1, M4 and M7). Therefore the degree of flexibility of the matrix also influences the energy absorbing ability of the composite.

The differences between the drop-weight and ballistic tests can be explained by the differences in the test velocities. This means that by studying one of them we cannot draw conclusion for the other one.

Conclusions

The mechanical behaviour and ballistic performance of carbon, glass (E and S type), aramide and polyethylene fabric reinforced composites with different epoxy resins were studied. The specimens were qualified by low velocity (Charpy and drop weight test) and high velocity (two different bores ballistic) impact test. It was demonstrated that the elasticity of matrix greatly affects the energy absorption capacity of composites structures. Composites with rigid epoxy matrix reduce ballistic performance in comparison with composites with flexible epoxy matrix. It has been shown that the basket wave fabric structure reinforced samples have 10% higher energy absorption capacity in all cases than plain weave fabric reinforced samples. It has been demonstrated that with increasing the number of plies the specific energy absorption ability of the composites increases, i.e. the efficiency of the individual layers also increases. It was established that glass, aramide and Dyneema (polyethylene) reinforcing composites structures show high ballistic performance. To clarify the order of effectivity among investigated reinforcing structures further big bore tests are required.

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