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Research Paper / Makale

The Effect of Hybridization on the Ballistic Impact Behavior of Nanostructured Hybrid Composite Plates

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Abstract: Hybrid composites are the material group largely preferred for use in space, aerospace and ballistic applications, where superior mechanical strength and low density are required. Hybrid composites are produced using high strength Kevlar and S-glass fiber as reinforcement material. Three different nano-particle, nano-clay, nano-calcite and nano-carbon, were used in order to increase the ballistic impact performance of hybrid composite plates. The nano-particles were added into the epoxy resin–hardener mixture in 0.5, 1, 1.5 and 2 (wt.%) ratios. The hybridization was performed by combining the plates produced with different matrix materials. After the tests, the deflection values on the back surface of the material were measured and the presence of perforation in the material was evaluated. As a result of the study, it has been observed that the ballistic properties are affected from the changing of the laminates stacking sequence and ballistic strength of the material can be increased by the addition of nano-particle. In hybrids composites produced by the addition of S-glass, ballistic strength was reduced, although the weight was reduced by 20%. It was found that nano-calcites adding hybrid composite plates at the front sites and nano-clay added plates at the back sites showed superior ballistic performance.

Keywords: Ballistic impact; hybrid composite, nano-clays, nano-calcites, nano-carbon, polymer–matrix composites.

Hibritleştirmenin Nano Takviyeli Hibrit Kompozit Plakaların Balistik Darbe Davranışlarına Etkisi

Öz: Hibrit kompozitler, özellikle yüksek mekanik dayanıma karşılık düşük yoğunluk istenen havacılık, uzay ve balistik uygulanmalarda çokça tercih edilen malzeme grubudur. Bu çalışmada, takviye malzemesi olarak, yüksek dayanımlı Kevlar ve S-cam fiber kullanılmıştır. Matris malzemesi olarak ise yüksek enerji emilimine sahip üç tip (nano-kalsit, nano-kil ve nano-karbon tüp) nano malzeme kullanılmıştır. Nano-parçacıklar epoksi sertleştirici karışımı içerisine 0,5, 1, 1,5 ve % 2 oranlarında katılmıştır. Bu şekilde farklı matris malzemeleriyle üretilen plakalar çeşitli sıralamalarla dizilerek hibritleştirme işlemi yapılmıştır. Balistik testler sonrasında malzeme arka yüzeyinde meydana gelen çökme değerleri ölçülmüş ve malzemede delinme olup olmama durumu değerlendirilmiştir. Çalışma sonucunda, malzemenin balistik dayanımının plakaların sıralamasının değiştirilmesinden etkilendiği, nano-parçacık takviyesinin ise balistik dayanımı arttığı görülmüştür. S-glass eklenerek üretilen hibrit kompozitlerde, ağırlık %20 oranında düşürülse de, balistik dayanım azalmıştır. Kalsit takviyeli plakaların ön yüzeyde, kil takviyeli tabakaların arka yüzeyde olduğu durumda en iyi balistik dayanım elde edilmiştir.

Anahtar Kelimeler: Balistik darbe; hibrit kompozit, nano kil, nano-kalsit, nano-karbon, polimer-matris kompozitler.

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1. Introductıon

Polymer matrix composites (PMC) have been widely used in navigation, transportation technology, aerospace and ballistic applications due to their low densities, excellent corrosion resistance, high strength values and thermal resistances. Considering all these areas where PMC are used, it is seen that they are exposed to a wide range of loads. Ballistic impact is the most critical one, among all loading types, affecting the lifetime of the material.

Hybridization of PMCs is the most common method for improving ballistic impact strength [1-4] therefore investigation of hybrid PMCs' ballistic-impact behaviors is importance. Impact resistance of hybrid composites depends on the fiber type, the thickness of the layers, the matrix material, stacking sequences of layers and the boundary conditions [2, 5-6]. Hybrid composite materials are divided into two groups as fiber hybrid composites and matrix hybrid composites [7]. Fiber hybrid composites are produced by combining different fiber types while matrix hybrid composites are produced by adding nano-particles or whiskers to the matrix to improve material properties [1, 7-9]. It is possible to find studies about fiber hybrid composites produced with varying combinations of fiber types and investigating their ballistic strength [1-3, 10-11]. In these studies, ballistic strength was found to be positively influenced by different stacking sequences types and fibers used in different ratios. However, studies investigating the ballistic strength of matrix hybrid composites with different types of matrix are quite limited. But nano-particle added composites have been carried out several investigations with regard to the increase of the mechanical and thermal properties of composites by adding low concentrations of nano-particles into polymers without jeopardizing density, toughness or the manufacturing process [12-18]. Investigations on the mechanical properties of nanostructural composites demonstrated that addition of nano-particles has some influence on the tensile strength and young modulus, elongation at break and fracture toughness.

The present study has focused on the ballistic performance of hybrid PMCs with nano-particles, commonly used in protective body armour due to its excellent impact resistance, high strength-to weight ratio. For this purpose, nano-clay, nano-calcite and nano-carbon were used which provide high energy absorption capacity. The results of the present paper are discussed in terms of damage and perforation.

2. Experimental Procedures

2.1 Matrix Preparation

In this study, three types of nano-particles epoxy mixture were prepared. The best combinations were found to include 0.5, 1 and 2 wt.% nano-clay, 1 and 2 wt.% nano-calcite and 0.5, 1, and 2 wt.% nano-carbon. Mixtures with different proportions were prepared to determine the ratios, in which nano-particles would show the best ballistic properties. The ratios of nano-particles were based on previous studies [11, 19-21]. In the production of nanostructured composites, it is difficult effective dispersion of the nano-particles in the polymer matrix. Some nano-particles such as nano-carbon have strong Van der Walls bonds and tend to agglomerate in an epoxy matrix. Agglomeration is not a problem in lower proportions of nano-particles, but higher amounts of nano-particles adhere to each other to form barriers that limit stress waves that occur during ballistic tests. As a result, they decrease the strength of the material causing disorder. Ultrasonic cavitation technique is one of the most efficient means to disperse nano-particles into a polymer. Hielscher UP400S ultrasonic processor was used to obtain a homogeneous mixture of epoxy resin and Eczacıbaşı Product nano-clay (Figure 1a). The mixture of epoxy resin and nano-clay was stirred at 25^{o}C for an hour with an ultrasonic device to carry out clay dispersion into polymer matrix. It was used a high speed shear mixer at a shear rate of 2500 rpm for 1 h for homogeneous mixture of epoxy resin. Then, sonication for 2 h was performed by using an ultra sonicator to further disperse the nano-clay. During the mixing process, the resin temperature was ensured at a certain temperature. After sonication, the epoxy/nano-clay mixture displayed a uniform distribution of particles. The process of dispersing nano-calcite and nano-carbon into epoxy resin and the mixing ratios of nano-calcite, nano-carbon, epoxy and hardener were similar as described earlier. The epoxy resin and hardener used in this study was provided with Fibermak, Turkey. The nano-clay and nano-calcite particles used in this study were organically modified montmorillonite minerals of type supplied by Eczacıbaşı Product and Afyon Adaçal Product, Turkey, respectively. Nano-carbon was supplied with Ege Nanotek Inc., İzmir, Turkey.

2.2 Target Preparation

The composite preparation and the target geometry constitute the target preparation processes. The target area was 300x300mm and two different fibers with different nano-particles concentrations in epoxy were used to construct the composite plate. The laminated samples had been fabricated using hand lay-up method. The composite plate consists of 20 layers with a total thickness of 2mm. Kevlar prepregs and S-glass were wetted by a thin layer of the epoxy/nano-clay, epoxy/nano-calcite and epoxy/nano-carbon, separately. Kevlar prepregs used in this study was supplied by Fibermak, Turkey.

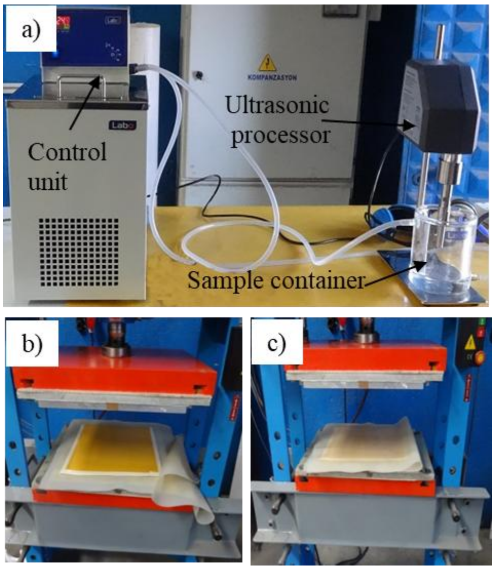

Figure 1. Fabrication procedure of composites plates, a) ultrasonic processor system, b-c) curing of nanostructured composite laminates.

Curing of the Kevlar/epoxy nano-clay and nano-calcite and nano-carbon plate was carried out for 150 minutes at 80°C followed by 150 minutes at 120°C. The first set of ballistic tests was pure epoxy composites. Kevlar fiber epoxy composite plates with 0% nano-particles concentration were first tested in order to set the basis for comparison when testing subsequent configurations. The hybrids PMCs were fabricated from Kevlar and S-Glass with different nano-particle concentrations in epoxy and to use them as targets in the ballistic impact tests. The ballistic tests were also carried out to show how the performance of Kevlar and S-glass composites can be increased by nano-clay, nano-calcite and nano-carbon and effect of stacking sequences of laminates.

2.3 Ballistic Tests

The ballistic impact tests were performed at the 8. Main Maintenance Center Command in Afyon, Turkey. The National Institute of Justice Standard NIJ 01.01.04 was used for the experimental setup. Ballistic test setup Schematic presentation of ballistic test procedure according to NIJ Standard was seen in Figure 2.

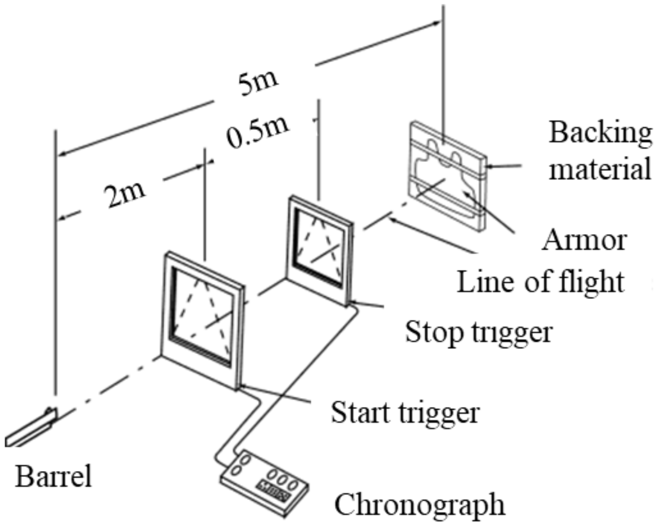

Figure 2. Schematic presentation of ballistic test setup.

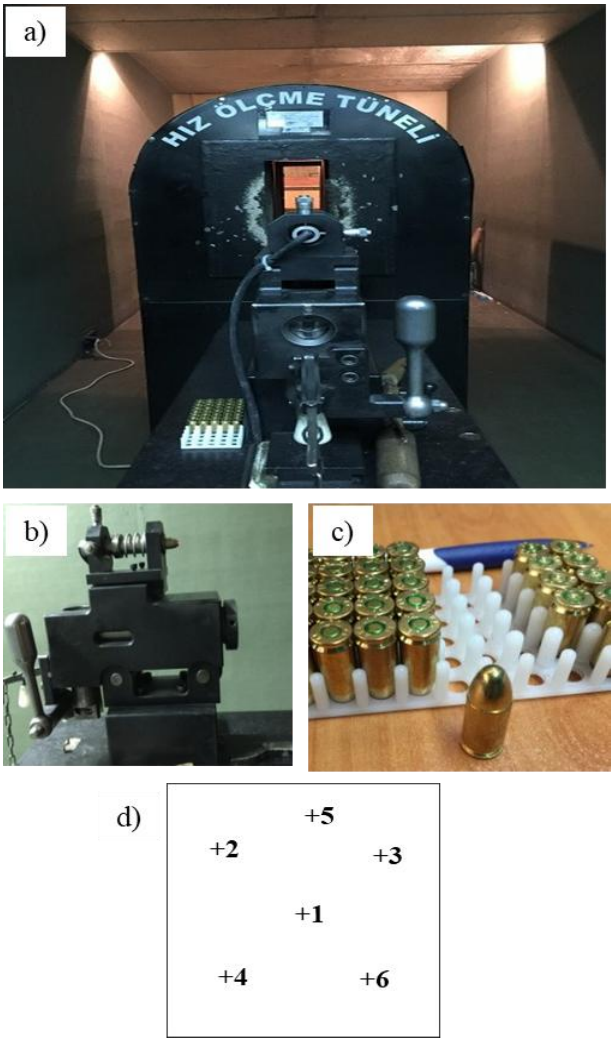

Figure 3. (a) Photograph of a typical ballistic impact test facility; (b) test weapon; (c) fragment projectiles, d) sketch of impact locations and firing order for specimen testing.

The test setup included three main parts: the barrel in which the bullet is placed, the chronograph tunnel, and the support representing the human body on which the test specimen is fixed (Figure 3). During tests, the bullet fired from the barrel hits the fixed specimen after passing through the velocity tunnel. The velocity of the bullet is measured by velocity sensors placed in the chronograph tunnel. When the bullet hits the target plate, it causes some amount of deflection at the back of the plate. The ballistic strength information of the material is obtained by measuring the deflection amount.

3. Results and Discussion

3.1 Ballistic Test Results

In the present part of study, the effects of nano-particle reinforcement and hybridization process on the damage mechanisms and ballistic resistance of composite material would be examined and usability of nanostructural composite material in ballistic applications would be analyzed. Previous studies demonstrated that by adding this type of hard micro-nano inorganic particles into the matrix, Young's modulus and material toughness could be increased [22-25]. Ballistic test results for produced hybrid composites are given in Figure 4.

The highest deflection depth was 29 mm on C control samples (Figure 4). Furthermore, no perforation was observed in none of the impact points in samples H1, H2, H3, H15, H16 and H18 among 19 hybrid composites produced. Produced hybrid combinations were separated into 6 groups based on reinforcing material, nano particle rates and number of composite layers (Table 1). Kevlar was used as reinforcement material in all except for the 2nd Group which was stated to contain S-glass in the table. The nano-particle content in the table is given sequentially from front to back in terms of the ballistic test direction.

In Group 1, the effects of stacking sequences of composite plates containing nano-clay and nano-calcite on ballistic resistance were analyzed. It was found that ballistic resistance of the H2 hybrid composite sample with calcite on the front surface and containing 1% nano-particles was higher (Figure 4). Material resistance of this type of nanostructural composites is dependent on the tension conducted between the matrix and the nano-particle. In nanostructural composites, with the addition of rigid particles such as calcite with a strong bond structure, stress transfer from the matrix to the nano-particle is facilitated and resistance of the material (Young's modulus) and fracture toughness [23-25]. As a result, deflection values were measured lower in H2 coded sample compared to the H1 sample. The H3 sample with 2% calcite rate demonstrated a ballistic resistance increase as well. Higher energy absorption was obtained in H2 sample when compared to H1 and H3 sample at the same velocity values.

In the 2nd Group, it was attempted to lighten the material with S-glass fiber reinforcement in addition hybrid PMCs. With low density and high resistant S-glass reinforcement, the material weight decreased by approximately 200 g and perforations were observed at all deflections. On the other hand, in 3rd Group samples H7, H8 and H9 where three nano-particle reinforcements at the rate of 1 wt.% were applied in different sequences, ballistic resistance did not differ significantly based on the sequence of hybrid structure. In all three samples, it was observed that as the nano-particle content increased, the material became more brittle and the ballistic resistance decreased. The effects of nano-carbon rates of 0.5, 1, and 2% on ballistic resistance are shown in 4nd Group H10, H11, and H12 samples. In all samples in this group, perforations were observed and ballistic resistance of the material did not significantly increase with increasing nano-carbon rate. The effect of the increase in nano-clay in the front layer on ballistic resistance was analyzed in the samples in Group 5.

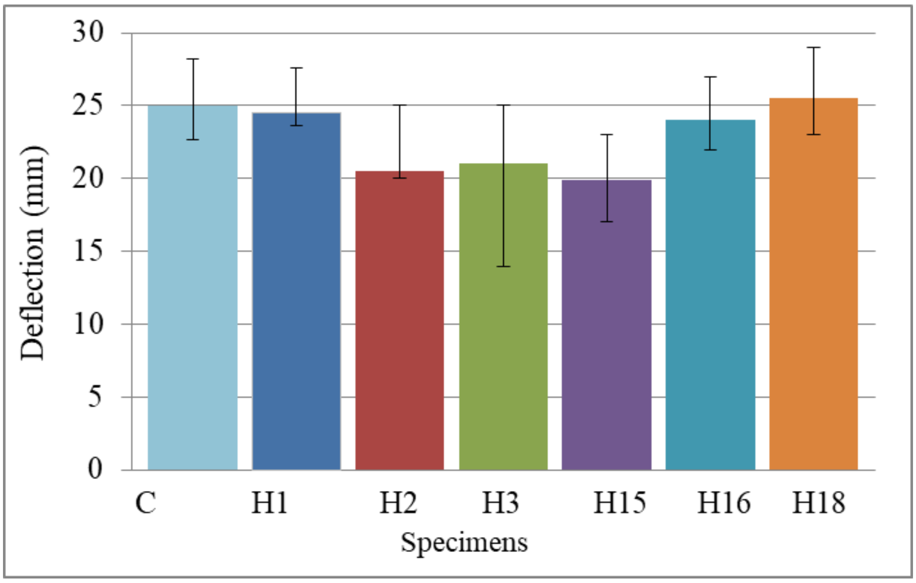

Figure 4. Deflection values of hybrid and non-hybrid PMCs.

In samples H13 and H14, it was observed that sample became more brittle with an increase of 0.5 wt.% of nano-clay, energy absorption decreased and the number of perforation points increased on the material. In samples where the effects of 1.5 wt.% nano-clay reinforcement in the front layer and nano-carbon rate were compared, it was observed that as the nano-carbon rate increased, energy absorption of the hybrid material increased. In Group 6, nano-clay reinforcement in the front layer was increased to 2 wt.%. In that case, a significant increase was observed in material ballistic resistance. Ballistic resistance increased in proportion with the nano-particle rate in H18 samples and 1 wt % nano-carbon reinforcement rates.

As the nano-carbon rate reached 2 wt %, ballistic resistance decreased and perforations were observed on the material. An increase in ballistic resistance was observed along with the increase in nano-clay rate in the front layer in samples H15, H16 and H18.

As shown in Figure 4, with the nano-particle reinforcement, the deflection in all sample groups decreased compared to the control sample. It is possible to say that the ballistic strength increases with the nano-particle added to the matrix in all samples. It showed a tendency to aggregate only with increasing amount of nano-particles in the H18 sample. As a result of this situation, even if no perforating was observed in the H18 sample, the deflection values were found to be higher. In all sample groups, the lowest deflection was measured in H15 sample. However, there was no significant increase in deflection amount. In H2 sample where nano-calcite reinforced plate was at the front, delaminated areas did not overlap and impact induced damage was not reinforced. In this case, ballistic resistance of the sample increased when compared to H1 sample. In H3 sample, where nano-calcite rate was increased to 2 wt.%, parallel to this case, the deformation area on the front and back surfaces and deflection amount on the back surface decreased (Figure 5).

Table 1. Hybrid PMCs ballistic test results.

Target characteristics	Group	Codes	Weight [g]	Damaged
Kevlar		C	988.3	-
			999	-
			1012.4	-
Clay 1% + Calcite 1%		H1	1014	-
Calcite 1% + Clay 1%	1	H2	998.4	-
Calcite 2% + Clay 1%		H3	1004.6	-
Clay 1% + S-Glass + Calcite 1%		**H4**	**844.1**	**Perforated**
Clay 1% + S-Glass + Calcite 2%	**2**	**H5**	**848.1**	**Perforated**
Calcite 2% + S-Glass + Clay 1%		**H6**	**847.9**	**Perforated**
Clay 1% + Carbon 1% + Calcite 1%		H7	1036.3	Perforated
Carbon 1% + Calcite 1% + Clay 1%	3	H8	1048.7	Perforated
Clay 1% + Calcite 1% + Carbon 1%		H9	1016.3	Perforated
Calcite 1% + Carbon 0.5% + Clay 1%		H10	1002.1	Perforated
Calcite 1% + Carbon 1% + Clay 1%	4	H11	1027.4	Perforated
Calcite 1% + Carbon 2% + Clay1%		H12	1019.5	Perforated
Clay 1% + Carbon 0.5% + Calcite 1%		H13	1020.4	Perforated
Clay 1.5% + Carbon 0.5% + Calcite 1%	5	H14	1032.3	Perforated
Clay 1.5% + Carbon 1% + Calcite 1%		H15	1019.1	-
Clay 1.5% + Carbon 2% + Calcite 1%		H16	1032.2	-
Clay 2% + Carbon 0.5% + Calcite 1%		H17	1023.7	Perforated
Clay 2% + Carbon 1% + Calcite 1%	6	H18	1051.6	-
Clay 2% + Carbon 2% + Calcite1%		H19	1014.5	Perforated

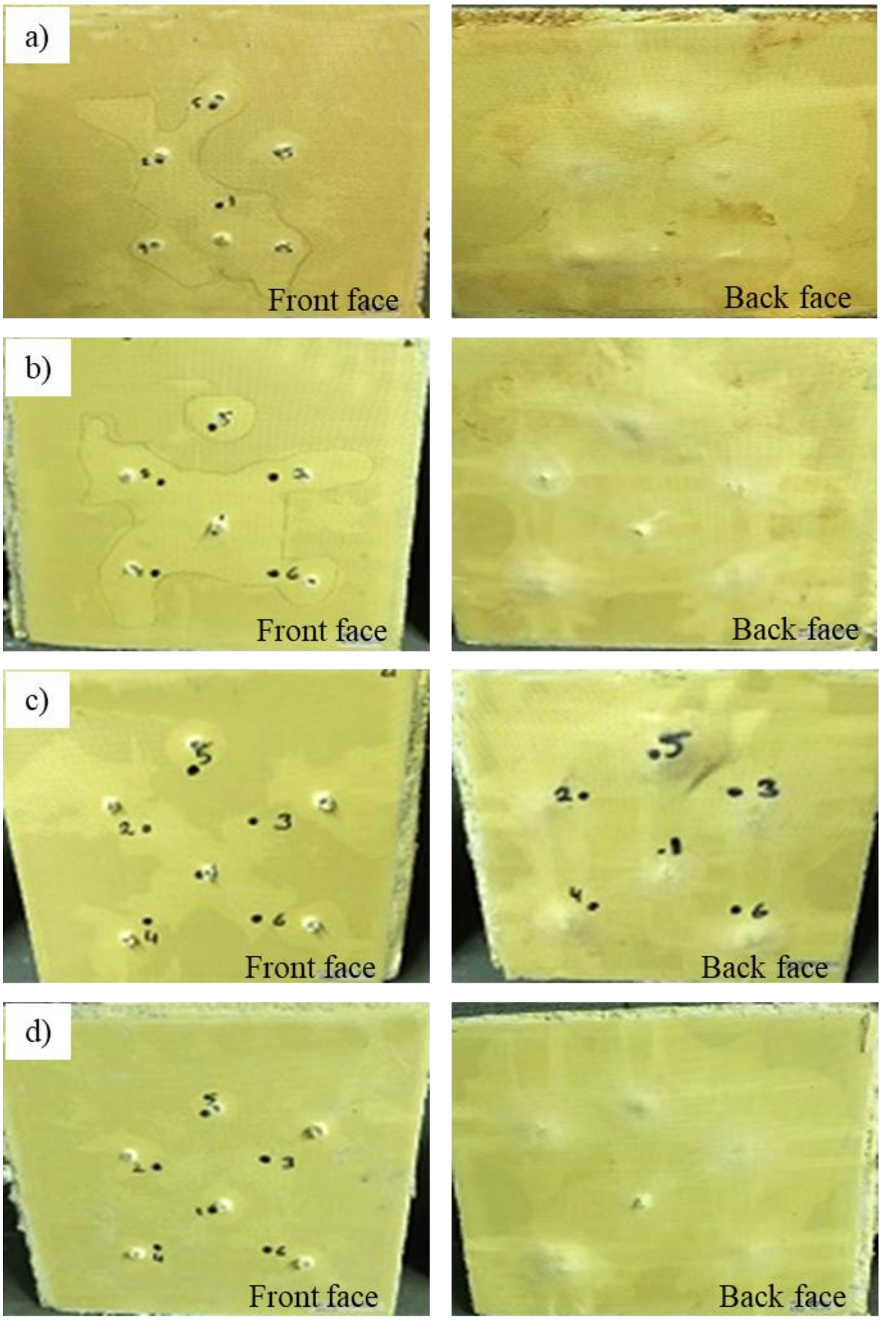

Figure 5. Pictures of the front and back face of the damaged hybrid PMCs, a) C, b) H1, c) H2, d) H3.

Figure 6 show the damage as a result of the ballistic test conducted on 0.5 wt.%, 1 wt.%, and 2 wt.% nano-carbon reinforced H10, H11, and H12 samples. When nano-particles such as nano-carbon are added to the matrix in high rates, strong Van der Wall's bonds show a tendency to aggregation in the epoxy. While the distribution under low rates is accomplished easily, as the rate increases they create barriers that limit the stress waves occur in this area by adhering to each other [26]. This creates an inconsistency for the material, lowering its resistance [27]. As the adherence between these low-resistance points and matrix-fiber decreases in the ballistic tests, damage areas became larger and delamination increased with the increasing nano-carbon rate.

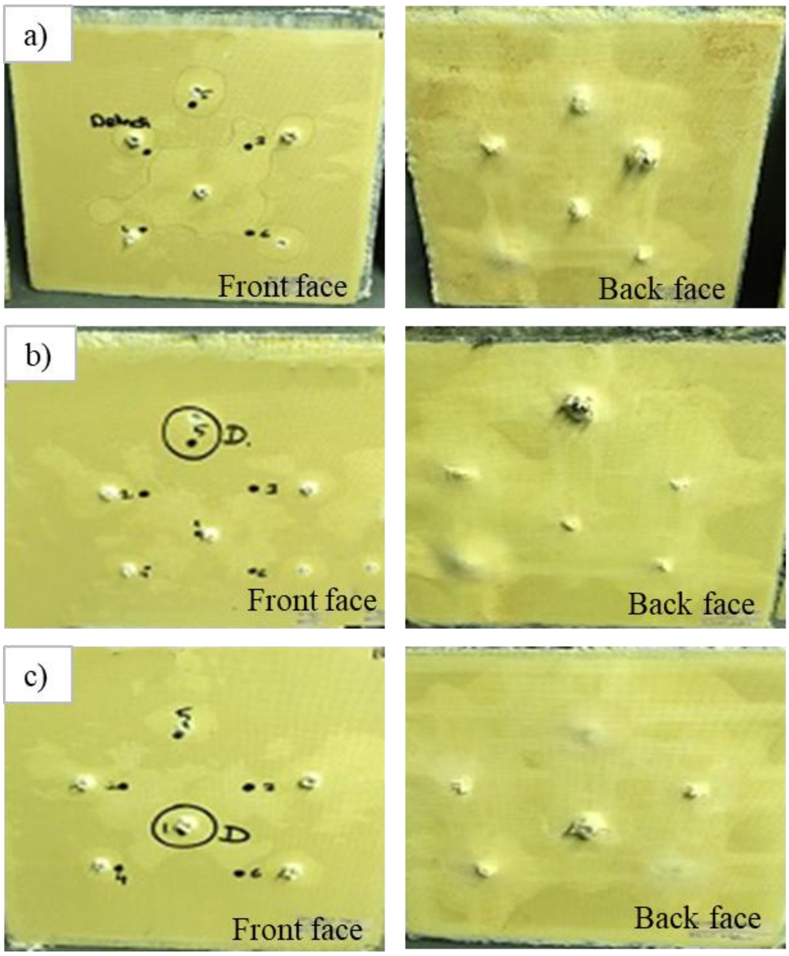

Figure 6. Post damage area of hybrid PMCs a) H10, b) H11, c) H12.

4. Conclusions

This article presents the results of a study of ballistic impact resistance of PMCs where nano-clay, nano-calcite and nano-carbon had been incorporated in the epoxy matrix. Deflection values occurred on the back surface of the material as a result of the tests was measured and the material was examined for the existence of perforations. Damage modes of the material after the tests and deformation areas formed on the material after each impact were calculated. Produced hybrid material combinations and stacking sequences of layers, which provided the maximum ballistic resistance, were assessed.

- In the hybrid PMCs, it was observed that the ballistic strength increased due to stacking sequences of layers.
- Although the weight of hybrid PMCs produced with the addition of S-glass decreased by 20%, ballistic resistance significantly decreased as well.
- In hybrid PMCs with all three nano-particle reinforcements, along with increasing nano-particle rates and lower adherence between the layers and increasing brittleness of the material, ballistic resistance decreased.

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