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Residual Impact Strength of Intra-ply, Inter-ply and Functionally Gradient Basalt/Poly-ester Hybrid Composites Subjected to Charpy Impact

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Abstract

In this paper, the residual impact strength of inter-ply, intra-ply, and functionally gradient composite subjected to Charpy preimpact with various energy levels was experimentally investigated. Basalt and poly-ester fibers along with epoxy resin were used to produce different hybrid composites. The purpose of using this hybrid composite is to simultaneously use the good mechanical properties of basalt fiber and the excellent impact resistance of poly-ester fiber. In all the composite samples, the relative content of basalt fiber to poly-ester fiber was equal to 50 percent. Comparison the results of impact absorption energy in cases without pre-impact and with pre-impact of 1.5 and 3 J cases indicates that in the case of no pre-impact or low-energy pre-impact, the performance of the inter-ply specimen (Interply2) is significantly higher than the FGM specimens, however, by increasing pre-impact energy, the FGM samples have equal or better impact performance than the inter-ply sample. This result is due to the type and extent of damage caused by the pre-impact energy.

Key words: Residual impact strength; Charpy impact; Intra-ply; Inter-ply; FGM

1. Introduction

The development and fabrication of low-cost fiber-reinforced composite is growing recently due to their superior mechanical properties. These composite materials could then replace high-cost and heavy metallic components in various industrial applications without losing appropriate mechanical performance. Some examples of great properties of fiber-reinforced composites are, but not limited to, high strength to weight ratio, good fatigue properties, high durability and excellent dynamic and corrosion properties [1, 2]. Despite these advantages, composite materials are highly susceptible to the impact loads even those with low velocity. However, many of these defects due to the impact are not visible as they would be formed beneath the surfaces. Therefore, the affected composite component might still appear to be undamaged after occurrence of impact load [3–5]. These damages can reduce the mechanical properties of the composites including the impact, tensile, compressive, fatigue and flexural strength, by leading to growth of the defects and causing final fracture [5–7]. Therefore, for an appropriate product design with composites, it is crucial to ensure that the residual strength of a damaged structure or component is within an appropriate range either for service until the damage is detected or for the rest of the service life of that structure.

To find the solution to improve impact properties of fiber-reinforced composites, a good deal of research has been conducted in the literature and the most important proposed methods for this aim are, but not limited to, using toughened matrices, modifying adhesion of reinforcement and matrix, reinforcement of composites through the thickness and using ductile fibers in hybrid composite structures [2, 7-9].

Hybrid composites are a new type of composite materials that enable designers to apply various types of reinforcement in the structure of composites and enhance their flexibility for application in desired conditions by choosing of appropriate materials according to service conditions [2, 7]. Depending on the geometric pattern of fiber arrangements, hybrid composites are classified as inter-ply and intra-ply hybrid composites. In inter-ply hybrid composites, layers of the two (or more) homogeneous reinforcements are stacked layer by layer while in intra-ply hybrid composites, two (or more) constituents of fibers are mixed in the same layer [7, 10]. The impact properties of inter-ply and intra-ply hybrid composites were investigated in detail in various studies in the literature. For example, Pegoretti [10], Zhang [11], Erkliğ [2], Ghasemnejad [12] studied impact and post-impact behavior of inter-ply hybrid composites, experimentally. Furthermore, Tehrani [7], Park and Jang [13], Pegoretti [10], Wang [14], Akhbari [15], ozbek [16], Kaya [17], Rajesh [18] and Zhang [11, 19] investigated impact properties and residual strength of intra-ply hybrid composites.

With combination of intra-ply and inter-ply methods, the third class of hybrid composites called functionally gradient material (FGM) have been proposed. FGMs were first introduced by a group of scientists in Sendai, Japan in 1984 [20]. FGMs are composite materials which are made of two or more constituent phases with properties that vary spatially according to a certain non-uniform distribution of the reinforcement phase. This results in special characteristics such as effective thermal stress relaxation and adhesive properties [21, 22]. Due to the above-mentioned excellent properties of FGMs, their applications in aerospace, nuclear industry, chemical plants and electronics industries are growing, recently. Therefore, novel methodologies and experimental analysis should be be developed to characterize them in more accurate way that would accelerate the product design and structural analysis of the components made with these materials. In this regard, the mechanical behavior of FGM polymer composites which are reinforced with one type of fiber have been studied by several researchers such as Lee [22, 23], Thai [24] and Bafekrpour [25]. However, It is only recently that the concept of FGM has been applied to the field of polymer-reinforced composites with more than one type of fiber (hybrid composites) and therefore, there are few documented researches about FGM hybrid composites. FGM-based hybrid composites have at least two efficient types of reinforcement and the proportion of one reinforcing fiber to another, from the top layer to the bottom layer gradually increases [26, 27]. Among the few published outputs in this concept, Jang and Lee [26, 27] investigated the flexural and instrumented impact properties of a functional gradient of the glass fiber/carbon fiber mixed mat composites.

As mentioned earlier, the behavior of composites under impact loads is an important element in design with composites. Furthermore, due to the lack of sufficient analysis data on FGMs, during component design with FGM composites, a crucial aspect of the problem is to exploit their desirable mechanical properties and enhance their resistance to impact. Therefore, a comprehensive analysis of the problem of impact and damages caused by it on FGM composites are significantly needed. In this study, an attempt was made to compensate the impact property weakness of basalt fiber (as brittle fiber) by combining it with poly-ester (PE) fiber (as ductile fiber) in a FGM, inter-ply and intra-ply hybrid forms. In this process, three kinds of FGMs are fabricated by changing the spatial distribution of the basalt/PE reinforcing fibers. Then, the effect of functionally gradient on Charpy impact properties and residual impact strength are investigated and compared with intra-ply and inter-ply hybrid composites. In addition, the visual inspection and scanning electron microscopy (SEM) was used to determine the extent and type of damage for impacted specimens.

2. Experimental Procedure

2.1. Fibers and matrix materials

In this study, basalt and PE fibers were employed as reinforcing fibers. Basalt fiber was supplied by Hengdian Group Shanghai Russia & Gold Basalt Fiber Co., China. PE fiber was procured from Zhejiang Guxiandao Industrial Fiber Co., China. A thermo-set epoxy resin, supplied by Mokarrar Co. (Iran), was selected as polymer matrix. A ML-506 grade of epoxy resin (density at 25 °C = 1.11 g/cm^3, viscosity at 25 °C = 1450 mPa.s) was mixed with a HA11 hardener at a weight ratio of 90/10. The mechanical properties of the basalt and PE fibers used in this study are presented in Table 1.

Table 1. Properties of the used basalt and PE fibers

Properties	Basalt	PE
Density (*kg/m*^{3})	2700	1120
Tensile modulus (*GPa*)	85	4.05
Tensile strength (*MPa*)	1800	284
Strain at break (%)	2	6.9

2.2. Fabrication of composite laminates and sample configuration

The required reinforcements were prepared with a unidirectional structure and 5 ends/cm counts. Nine different types of reinforcement were produced, including pure basalt, pure PE and seven mixtures of basalt and PE with different volume percentages of basalt fiber. Therefore, the nine samples have 100%, 80%, 75%, 60%, 50%, 40%, 25%, 20%, and 0% basalt, respectively, which could provide us an appropriate spread of volume faction of fibers among the samples in our experimental investigations. In Fig. 1, the composition of each of the reinforcements is shown in more detail. In this figure, reinforcements were coded by using the percentage of the basalt and PE fiber. For example, so-called sample 80B has 80 percent basalt fiber and 20 percent PE fiber.

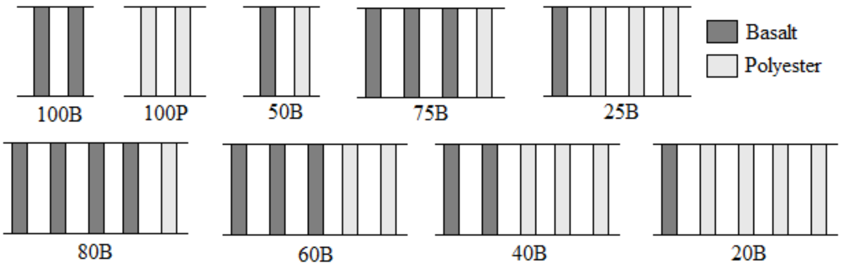

Fig. 1. Schematic view of the reinforcements with different contents of basalt and PE fiber.

The hand lay-up method is used to fabricate all the composite samples. In this study, to investigate the properties of FGM composite and compare them with the properties of inter-ply hybrids and intra-ply hybrid composites, three types of laminates were obtained: (i) inter-ply hybrids (laminates Interply1 and Interply2), (ii) intra-ply hybrids (laminates Intraply) and (iii) FGM hybrid (laminates FGM1, FGM2 and FGM3), as depicted in Fig. 2. In FGM specimens, relative volume fraction of basalt fibers to PE fibers is 100 percent at the top layer and it decreases linearly to zero percent until the bottom layer is reached which is clearly 100 percent PE fiber. In all the hybrid composites, the relative content of basalt fibers to PE fibers is equal to 50 percent. The composites consisted of 12-ply laminates with the cross-ply stacking sequence ($[0, 90]_{3s}$). All the laminates were cured for 3 hours at 40 °C, followed by 1 hour at 80°C under a constant pressure. Then the composites were allowed to slowly cool down to room temperature when they are under pressure. The average thickness, volume fraction of the fibers and the experimental density of the prepared laminates are reported in Table 2.

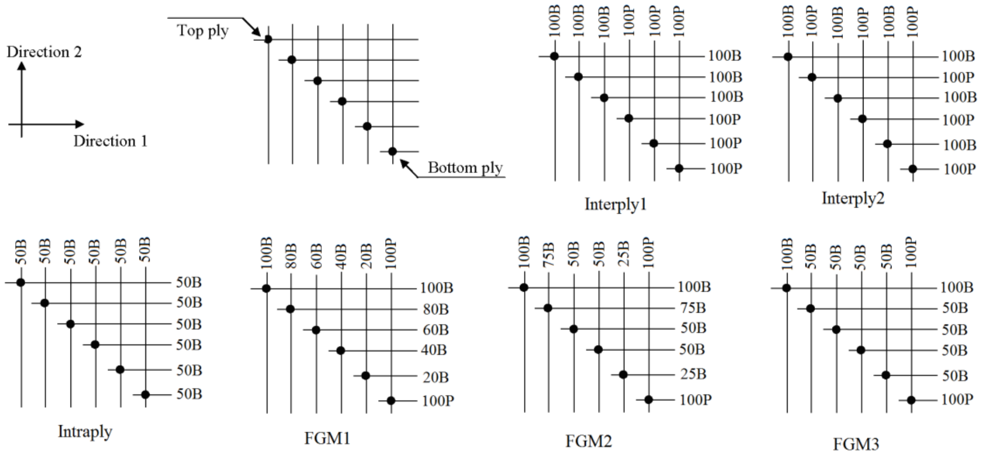

Fig. 2. The layer arrangement of inter-ply, intra-ply and FGM hybrid laminates

Table 2. Thickness, fiber volume fraction and density of the prepared laminates

Laminate code	Thickness (mm)	Volume fraction (%)	Experimental density (kg.m^{-3})

Interply1	3.95	46	1443
Interply2	3.96	46	1447
Intraply	3.96	46	1372
FGM1	3.51	52	1441
FGM2	3.57	51	1433
FGM3	3.79	48	1411

2.3. Charpy impact experiment

Single or multiple Charpy impact tests were performed by a Zwick, D-7900 impact tester with 25 J hammer (Germany). Composite laminates having un-notched and rectangular shapes were prepared according to the prescriptions of the American Society for Testing Material (ASTM) D.256 standard [28] with dimensions of 80 mm×10 mm for impact tests.

The residual impact strength of composite subjected to pre-Charpy impact at various energy levels was measured. For this, two different heights of 4.5 and 9 cm were chosen, corresponding to nominal impact energies of 1.5 and 3 J, respectively. Then, to determine the post-impact properties of specimens, Charpy impact tests were again performed. The maximum height (75 cm equivalent 25 J) was used to determine the impact absorption energy at this step.

Five specimens per each case were tested and the absorbed energy was recorded after the impact. Finally, the impact absorption energy measurements have been divided by the cross-sectional area of the specimens to obtain the normalized measurements for all samples.

2.4. Scanning Electron Microscopy (SEM)

The fracture behavior of the composites was studied using SEM Philips model XL30, Netherlands. Prior to all SEM observations, the specimens were sputtered with gold to prevent charging. The samples were viewed through the surface and cross section area.

3. Results and Discussion

The normalized impact absorption energy for the various composites is summarized in Table 3. It could be observed from the results in Table 3 that the factors that change the impact performance of various composites are differences in hybrid type and stacking sequence of the plies. The results indicate that the inter-ply hybrid composites can achieve better absorption energy compared to the intra-ply and FGM laminates. The results of Table 3 show that the absorbed energy of Interply2 sample is 14 to 30 percent higher than that of Intra-ply and FGM samples. As shown in Fig.2, the full basalt layers are scattered all over the thickness of Interply2 sample. Therefore, the presence of full-basalt layers in the top and bottom sides caused this sample to withstand sudden compressive and tensile stresses and restrict the severity of the impact.

The impact results of the intra-ply and FGM specimens show that the absorption energy of the FGM1 sample is 8 to 20 percent higher than the intra-ply and other FGM samples. This result could be due to the more basalt fibers in the upper layers (compressive side) and less discrepancy of the fiber type between the adjacent layers. In the FGM1 specimen, the discrepancy of the fiber type in the adjacent layers is smaller than the other FGM specimens; therefore, the delamination in this sample is lower than the other FGM samples (see Fig. 3a-c). In FGM3 sample as Interply1 sample, much discrepancy of the fiber type in the adjacent layers has created a large amount of shear force between layers and consequently long splitting between the layers has occurred (see Fig. 3 c and d).

Table 3. Normalized absorbed energy (J/cm^2) obtained from the impact tests

Sample	Pre-impact energy		
	0 J	1.5 J	3J
Interply1	11.64	11.52	5.31
Interply2	16.16	16.03	8.20
Intraply	11.26	8.96	4.67
FGM1	13.96	12.39	7.40
FGM2	12.74	12.60	5.46
FGM3	12.48	9.63	8.57

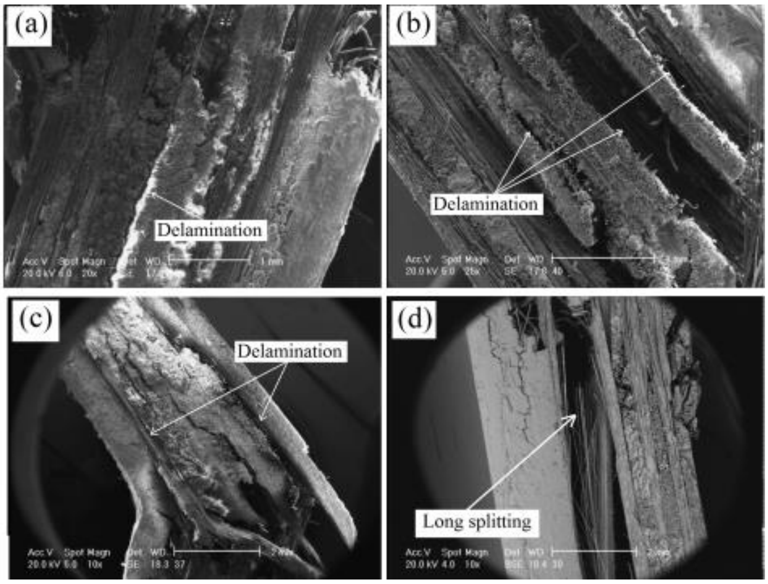

Fig. 3. The fracture surface of the (a) FGM1, (b) FGM2, (c) FGM3 and (d) Interply1 composites.

To investigate the effect of low velocity impact on different samples, these samples were subjected to high energy pendulum impact after 1.5 and 3 joule impact energy, then the residual absorbed energy was calculated based on Eq. 1.

$$\text{Residual impact energy (\%)} = (E_{API} / E_{WPI}) * 100 \qquad (1)$$

where, E_{API} is the impact absorption energy after preliminary impact (J/cm^2) and E_{WPI} is the impact absorption energy without preliminary impact (J/cm^2).

The percent of residual impact absorption energy for the various composites are presented in Fig. 4. The results show that the preliminary impact with an energy of 1.5 joules causes a very small reduction (up to 2%) in the impact strength of the inter-ply and FGM2 specimens. Furthermore, SEM observations of fracture surface, illustrated in Fig. 5, show that after applying impact with an energy of 1.5 joules on the inter-ply and FGM2 samples, very little damage (to the extent of matrix cracking) was caused on the impacted surface. Furthermore, following results in Fig. 4, the absorbed energy reduction in intra-ply, FGM1 and FGM3 specimens was 11 to 23 percent. This could be explained according to SEM observations in Fig. 6, that in these samples, preliminary impact with an energy of 1.5 joules caused the matrix cracking, failure of the basalt fibers and debonding and failure of PE fibers.

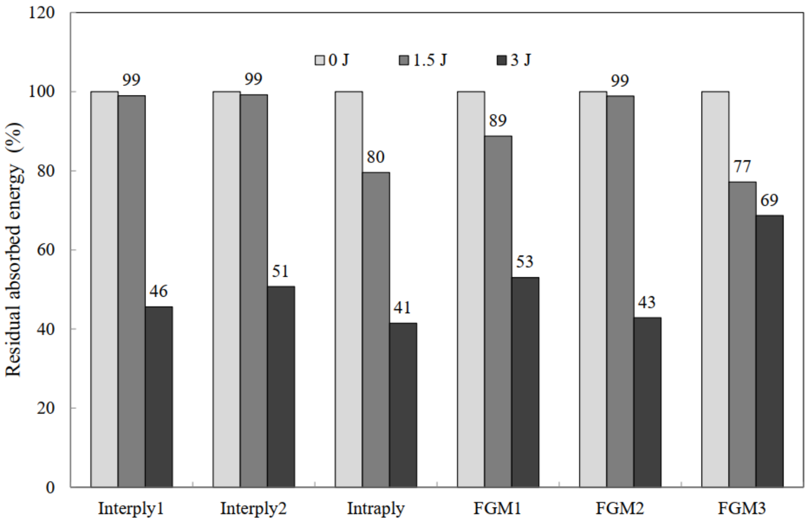

Fig. 4. Residual impact absorption energy of the various composites after preliminary impact

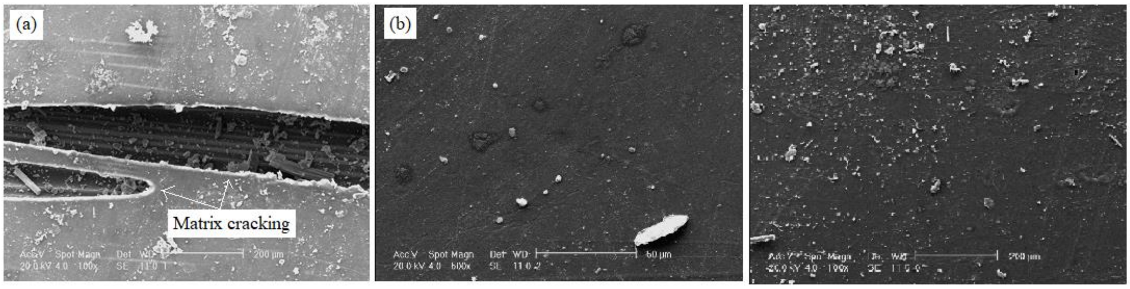

Fig. 5. The fracture surface of the (a) upper surface of Interply1, (b) bottom surface of Interply1 and (c) upper surface of Interply2

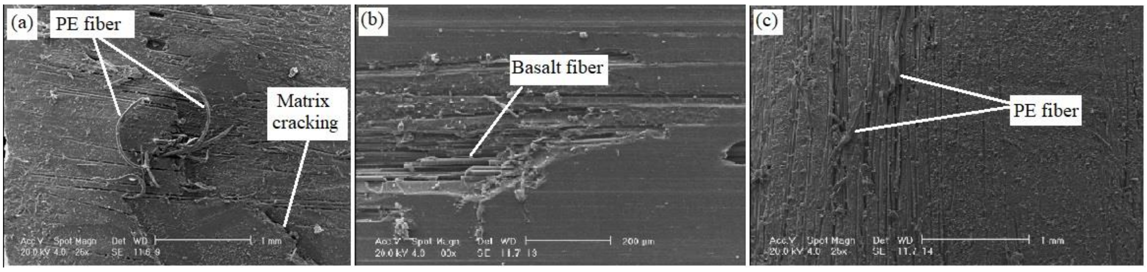

Fig. 6. The fracture surface of the (a) Intraply, (b) upper surface of FGM3 and (c) bottom surface of FGM3 specimens

Moreover, Table 3 provides the normalized impact absorption energy for the various composites after applying preliminary impact with 1.5 joules. The results indicate that in this case, Interply2 and Intraply specimens have the highest and lowest absorbed impact energy, respectively. The absorption energy of the Interply2 sample is 21 to 40 percent higher than the FGM samples. Among FGM samples, samples with a higher percentage of basalt fibers in the upper layers (FGM1 and FGM2 samples) has higher absorbed energy.

It is also observed that the final absorbed energy after applying a 3 Joules pre-impact are completely different with the 1.5 joule pre-impact as well as without a pre-impact cases. The results of Fig. 4 show that pre-impact damage caused by 3 joules of energy causes a very large reduction (31 to 59 percent) in the final absorbed energy of all samples. In this case, the FGM3 sample had the best impact performance. In this sample, the amount of residual absorbed energy was 69 percent. Also, FGM2, Interply1 and Intraply samples had the lowest residual absorbed energy (41 to 46 percent). The decrease in residual absorbed energy in different samples is due to the type and extent of damage caused by the pre-impact of 3 joules. This could be explained by SEM observations that are presented in Fig. 7 and show that on all samples a lot of damages have been created, including matrix fracture, basalt fiber fracture, PE fiber failure, PE fiber debonding and delamination, after applying 3 joules impact energy.

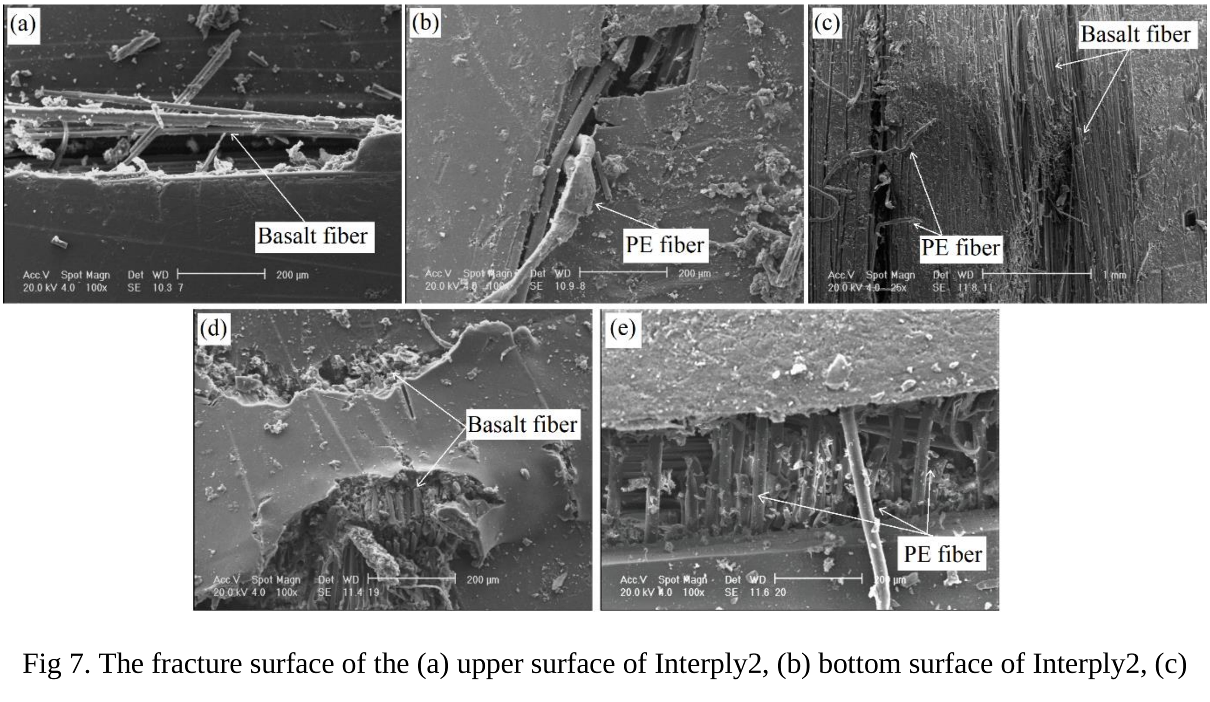

Fig 7. The fracture surface of the (a) upper surface of Interply2, (b) bottom surface of Interply2, (c) Intraply, (d) upper surface of FGM2 and (e) bottom surface of FGM2 specimens

The normalized impact absorption energy for the various composites after applying preliminary impact with 3 joules is summarized in Table 3. The results show that in this case, Interply2, FGM1 and FGM3 specimens have the highest absorbed impact energy and Intraply specimen has the lowest absorbed impact energy. Interply2 and FGM2 specimens have the same absorbed energy. The impact absorption energy of the FGM3 was 45 percent higher than that of the Intraply sample. As can be seen in Fig. 2, the only difference between the structure of FGM3 and Intraply specimens is in the outer layers. In the FGM3 sample, the full-basalt and full-PE layers in the upper and lower sides controlled the compressive and tensile stresses created by the impact, respectively. In the FGM3 sample, the brittle property of full-basalt layer and the ductile property of full-PE layer in the upper and lower sides controlled the compressive and tensile stresses created by the impact, respectively [15, 29].

Comparison the results of impact absorption energy in the case of without pre-impact and with pre-impact of 1.5 and 3 joules indicates that in the case of no pre-impact or low-energy pre-impact (1.5 joules), the performance of the inter-ply specimen (Interply2) is significantly higher than the FGM specimens, but with increasing pre-impact energy (3 joules), the FGM samples have equal or better impact performance than the inter-ply sample (See Table 3). This result is due to the type and extent of damage caused by the pre-impact energy. Fig. 8 shows the extent of damage (delamination) caused by the pre-impact of 1.5 and 3 joules. SEM observations and the results of damaged length show that when the pre-impact energy is low (1.5 joules), the pre-impact damages in inter-ply specimens are of matrix fracture or delamination in a wide extent according to Figs 6 and 8. However, as it is observed in Figs 7 and 8, by increasing pre-impact energy (3 joules), damages are in the form of delamination in a smaller extent, basalt fiber fracture, PE fiber failure and PE fiber debonding. Furthermore, as the pre-impact energy increases, the time required to transfer stress to the fibers and separate the layers is reduced. Fig. 8 also shows that the damaged length (delamination length) in the intra-ply and FGM specimens after pre-impact of 1.5 and 3 joules is less than in the inter-ply specimens. This is due to less discrepancy of the fiber type between layers in intra-ply and FGM specimens.

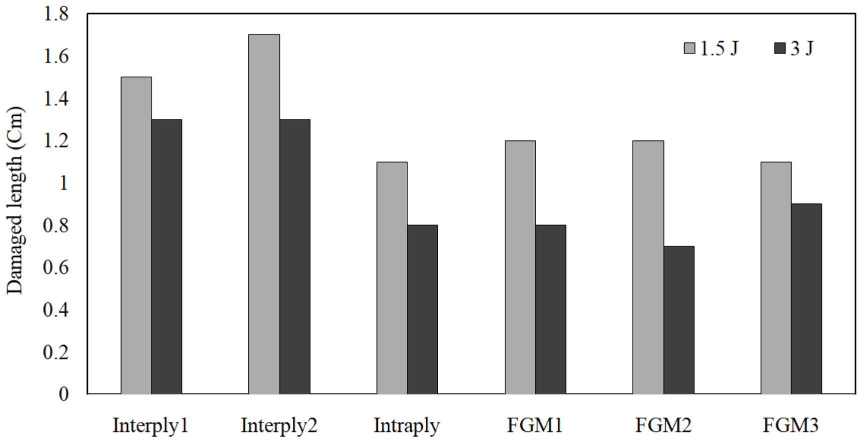

Fig 8. Damaged length of the various composites after pre-impact of 1.5 and 3 joules

Visual inspection of the final impact damaged specimens in the without pre-impact and with pre-impact of 1.5 and 3 joules is presented in Fig. 9. It is revealed in this figure that the damages caused in the pre-impact phase have caused changes in the final fracture mode of the Inter-ply (especially in the Interply1) specimens. From Fig. 9 (a, b and c) it is observed that the fracture mode of the inter-ply specimens in the without pre-impact case is in the form of delamination in a limited length with the failure of the fibers and matrix. However, in the cases with pre-impact of 1.5 or 3 joules, the fracture mode of these samples is in the form of complete separation of layers along the sample length with the other fracture modes. This phenomenon is not seen in other specimens according to Fig. 9 (d, e and f)). Furthermore, from Fig. 8 we could explain that in the pre-impact of 1.5 and 3 joules, the delamination length in inter-ply specimens is higher (approximately 1.5 times) than other samples, therefore, in the final impact phase, the high crack length created in the pre-impact phase in inter-ply specimens caused the rapid expansion of the crack between the layers (delamination Mode II) and complete separation of the layers along the entire length of the sample [30]. It should also be noted that the different types of fibers in the separated layers and the lack of proper connection between these layers has also been very effective in the rapid spread of cracks.

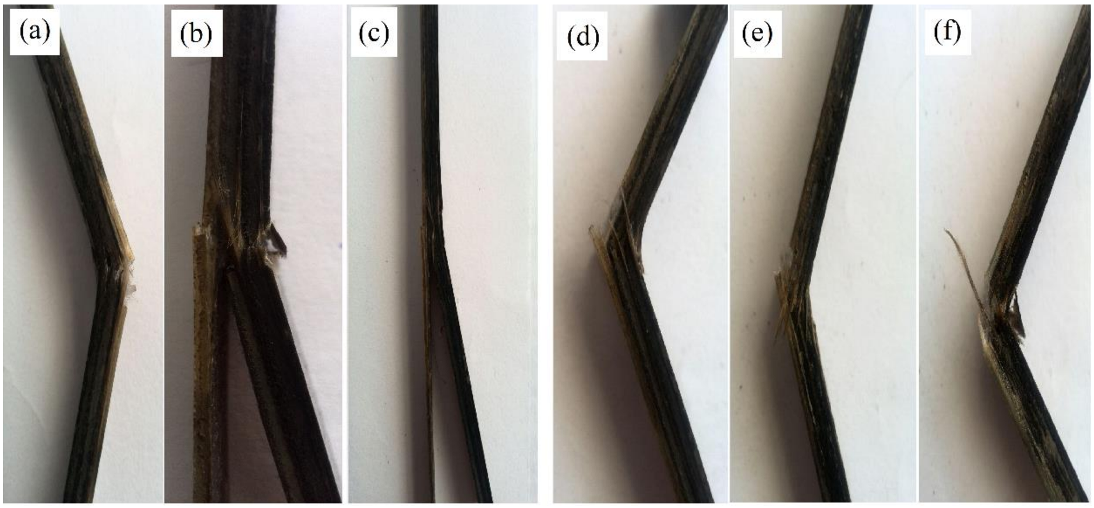

Fig 9. Schematic of damage in (a, b, c) Interply1 and (d, e, f) FGM2 specimens with (b, e) 1.5 J, (c, f) 3 J and (a, d) without pre-impact

4. Conclusions

Three types of basalt-PE/epoxy hybrid composites with similar fiber volume fraction were designed and fabricated, namely inter-ply, intra-ply and functionally gradient material (FGM) hybrid composites. Their Charpy impact properties and residual impact strength of these composites subjected to Charpy pre-impact were investigated. The results indicate that in the case of no pre-impact, the absorbed energy of Interply2 sample is 14 to 30 percent higher than that of Intra-ply and FGM specimens. Furthermore, under above situation, the absorption energy of the FGM1 sample is 8 to 20 percent higher than the intra-ply and other FGM samples. Moreover, in the FGM1 specimen, the discrepancy of the fiber type in the adjacent layers is smaller than the other FGM specimens.

SEM observations show that the stacking sequence of layers with various fiber type and the type of hybrid is very effective on the type and extent of damage caused in the pre-impact stage and ultimately on the residual impact strength. In the case of 1.5 joules pre-impact, absorbed energy reduction in different specimens was 2 to 23 percent. In this case, samples inter-ply and FGM2 had the least reduction in absorbed energy and sample Interply2 had the highest ultimate impact strength. Pre-impact damage caused by 3 joules of energy causes a very large reduction (31 to 59 percent) in the final absorbed energy of all samples. In this case, samples FGM3 had the least reduction in absorbed energy. Also, sample Interply2, FGM1 and FGM3 had the highest ultimate impact strength.

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