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Evaluation of Repeated High Velocity Impact on Polymer-Based Composites Reinforced with Basalt and Kevlar Fibers

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Abstract

In the present study, the influence of laminate thickness on the resistance to repeated high velocity impacts of basalt, Kevlar, and basalt-Kevlar fibers hybrid reinforced epoxy composites was evaluated. The composites were fabricated with three different numbers of layers and then subjected to the repeated high velocity impact test with three levels of impact energy. The speed of the projectile was chosen in the high velocity criteria which were 40, 50 and 60 m/s. Impact test repeated for each sample until fully perforating and the numbers of impacts up to perforation were measured and compared with others. The Taguchi design of experiment (DOE) method was applied to predict the results and also to determine the effect of each parameter in the resistance to the repeated high velocity impact. According to the results that, basalt fibers reinforced composites showed higher resistance to damage in the repeated impact, in comparison with Kevlar and fibers hybrid reinforced composites. The effect of important parameters, including the number of the layers, the thickness of each layer and the impact velocity was also investigated on the results.

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Keywords: Repeated high velocity impact, Taguchi method, Hybrid composite, Basalt fibers, Kevlar fibers.

1. Introduction

In past decades, composite materials have been used as an alternative choice for conventional structural materials like metals and light metallic alloys in some applications such as parts of the vehicular body and aerodynamic structures. Composite materials in these applications are subjected to different loading conditions during their in-service applications including static and dynamic loadings. One of the most important properties of the composite structures is that they are more sensitive to impact damage than similar metallic structures. In this regards, several types of research have been carried out to evaluate the impact resistance of the different composite materials by subjecting the composite sample to the high velocity impact. The impact damage resistance of different materials can be compared using this testing method. During high velocity impact, polymer matrix composites slow down the projectile by absorbing its kinetic energy due to shear deformation between layers of the composite and delamination [1].

Many studies have been carried out on the behavior of composite materials under impact loading and various impact parameters have been investigated on the results. Eslami and Khazaie studied the high velocity impact response of basalt fiber metal laminates [2]. Nasirzadeh and Sabet studied this loading on sandwich panels [3]. Higuchi et al studied the progressive failure under high velocity impact on composite laminates [4]. Pasquali and Gaudenzi studied the high velocity impact resistance of thin woven fabric composite targets [5]. Khalili and Saeedi studied the dynamic response of laminated composite beam reinforced with shape memory alloy wires subjected to low velocity impact of multiple masses [6]. Yarmohammad et al studied low and high velocity impact response of a composite sample [7]. Hazard et al studied the effect of fiber orientation on the low velocity impact response of thin Dyneema® composite laminates [8]. Khalili et al studied the effect of thermal cycling on hardness and impact properties of polymer composites reinforced by basalt and carbon fibers [9]. Furthermore, the effect of thermal cycling on hardness and impact properties of polymer composites reinforced by basalt and carbon fibers is studied by this group [10]. Hybridization effect of basalt and carbon fibers on impact and flexural properties of phenolic composites was studied by Najafi et al [11].

In order to obtain the impact damage tolerance, a new technique is applied, which is based on repeated impacts at the same level of impact energy [12]. In this method, the composite sample will be subjected to the repeated low velocity impact until full perforation. The number of impacts to perforation and the damage criteria after each impact will be evaluated. Fiber and matrix breakage, delamination, and interface rupture are internal defects that can occur under repeated low energy impacts [13].

Several studies have been done on the repeated impact of composite materials. Jang et al. [13] studied the effect of repeated low velocity impact on the performance of carbon epoxy composites with three different stacking sequences. They developed an elastic energy approach to predict the threshold incident energy for samples. In a research by Moriniere et al. [14] the effect of thickness of the laminates on the resistance to repeated low energy impacts of different fibers epoxy composites was evaluated. The glass fibers epoxy composite exhibited the most enhancement in the impact tolerance with increasing laminate thickness.

De Morais et al. [15] carried out an experimental investigation on the repeated impact response of woven E-glass/epoxy composites with different thicknesses and presented a phenomenological equation for characterizing the macroscopic damage in the sample. Boukhili et al. [16] studied the damage propagation during the repeated impacts. They categorized the damage of samples with three stages corresponding to matrix cracking, rapid delamination, and slow delamination. Schrauwen and Peijs [17] studied the results of drop weight impact tests on glass fiber reinforced laminates. They concluded that damage evolution in repeated impact is significantly affected by both matrix and reinforcement mechanical properties. Arikan and Sayman [18] fabricated E-glass fiber reinforced composites and subjected them to the low velocity single and repeated impacts. The effect of epoxy resin's type on the impact tolerance of composites was investigated.

Atas and Dogan [19] studied the effect of thermal aging on the low velocity impact response of E-glass/epoxy composites. Yarmohammdad et al. [7] investigated the repeated low velocity impact on fiber metal laminates. The influence of impact's distance on plate response, damage parameters, and absorbed energy was also considered. The effect of laminate thickness on the repeated impact response of the composites was experimentally investigated by Atas et al. [12]. Rajkumar et al. [20] also studied the effect of the repeated low-velocity impacts on tensile strength of fiber metal laminates using a drop weight impact tester.

The literature survey shows that many researchers focused on the impact tolerance of composite materials by subjecting the sample to the repeated low velocity impact test. In this study, the other kind of repeated impact is being introduced which is repeated high velocity impact. Three types of laminates including Kevlar fibers, basalt fibers, and basalt-Kevlar fibers hybrid with epoxy matrix were investigated. Fabricated samples with 3 various thicknesses subjected to the repeated impacts with 3 different impact energies. The number of impacts to failure (NIF) is

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obtained for each sample and also an equation is introduced for the relationship between the NIF and influenced parameters.

2. Materials, methods and sample's preparation

2.1. Experimental

The epoxy matrix and hardener used in this study were EPON 828 (shell, Inc.). The epoxy has a 9:1 resin to hardener mixing ratio according to the manufacturer. Samples were fabricated with hand layup method with 4, 6 and 8 layers of basalt, Kevlar, and hybrid of basalt and Kevlar fibers and epoxy resin. The volume fraction of fabrics was 48% for all tested samples. Basalt and Kevlar 29 woven fibers were supplied by Basaltex company and PMP company, respectively. The physical and mechanical properties of basalt and Kevlar fibers are introduced in Table 1. The respective thicknesses for each fabricated sample with the different number of layers are tabulated in table 2. For simplification, samples were named as shown in Table 3. Dimensions of each sample were chosen as 13 cm×13 cm. Stacking sequences for hybrid samples were B/K/K/B, B/K/B/B/K/B and B/K/K/B/B/K/K/B (B: basalt, K: Kevlar).

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Table 1. Mechanical and physical properties of the basalt and Kevlar fibers.

Fiber	Surface density (g/m^2)	Thickness (mm)	Tensile strength (MPa)	Tensile modulus (GPa)	Weave type
Basalt	350	0.4	3000	89	Twill
Kevlar	220	0.3	3600	70.5	Plain weave

Table 2. The thickness of fabricated samples with a different number of layers and fibers.

Fiber	Number of layers	Thickness (mm)
Basalt	4	1.6
Basalt	6	2.4
Basalt	8	3.2
Kevlar	4	1.2
Kevlar	6	1.8
Kevlar	8	2.4
Basalt-Kevlar	4	1.4
Basalt-Kevlar	6	2.1
Basalt-Kevlar	8	2.8

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Table 3. Codes for samples.

Number	Sample ID	Fibers	Number of layers	Velocity of the projectile (m/s)
1	B4-40	Basalt	4	40
2	B4-50	Basalt	4	50
3	B4-60	Basalt	4	60
4	B6-40	Basalt	6	40
5	B6-50	Basalt	6	50
6	B6-60	Basalt	6	60
7	B8-40	Basalt	8	40
8	B8-50	Basalt	8	50
9	B8-60	Basalt	8	60
10	K4-40	Kevlar	4	40
11	K4-50	Kevlar	4	50
12	K4-60	Kevlar	4	60
13	K6-40	Kevlar	6	40
14	K6-50	Kevlar	6	50
15	K6-60	Kevlar	6	60
16	K8-40	Kevlar	8	40
17	K8-50	Kevlar	8	50
18	K8-60	Kevlar	8	60
19	H4-40	Hybrid	4	40
20	H4-50	Hybrid	4	50
21	H4-60	Hybrid	4	60
22	H6-40	Hybrid	6	40
23	H6-50	Hybrid	6	50
24	H6-60	Hybrid	6	60
25	H8-40	Hybrid	8	40
26	H8-50	Hybrid	8	50
27	H8-60	Hybrid	8	60

2.2. Tests

The gas gun high velocity impact tester was used to test the samples. The projectile had a diameter of 21.5 mm and weight of 27 g and had no plastic deformation after hitting the sample. Three different impact velocities in the high velocity criteria [21, 22] were chosen as the initial velocities of the projectile which were 40, 50 and 60 m/s. The projectile was thrown toward each

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sample with the mentioned speeds, repeatedly. Fig. 1 shows the schematic view of the dimensions of the sample and placement in the fixture.

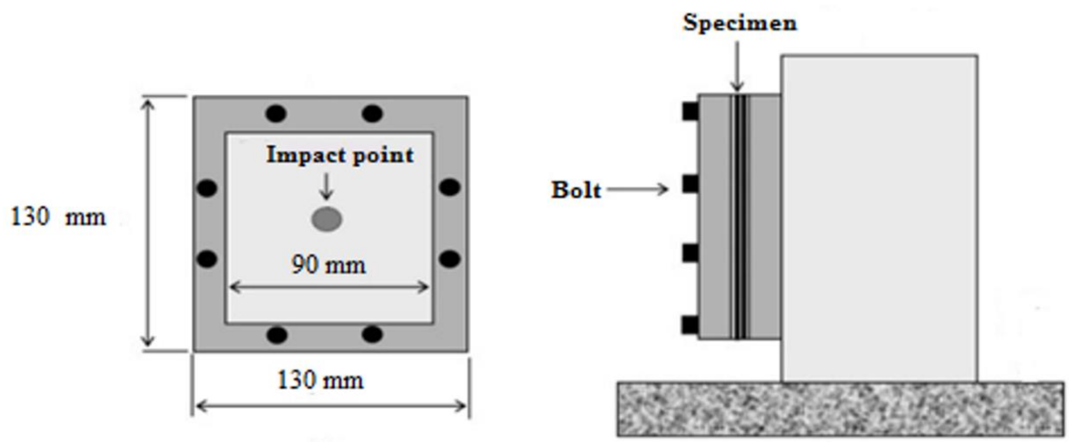

Figure 1. Dimensions of the sample and placement in the fixture.

2.3. Taguchi design of experiments method

Taguchi design of experiments (DOE) method is used to reach the minimum number of samples for tests and to predict the other values and also to determine the effect of each parameter in the NIF. In this regards, the L9 array was applied and 9 conditions introduced. Table 4 shows the factors and levels and table 5 shows the Taguchi DOE matrix designed by MINITAB 18 software. Tabulated samples should be fabricated and tested. After fabricating and testing, Taguchi could predict the values for 18 untested samples.

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Table 4. Factors and levels for Taguchi DOE method.

Levels	Fibers	Number of layers	Projectile's velocity (m/s)
1	Basalt	4	40
2	Kevlar	6	50
3	Hybrid	8	60

Table 5. Taguchi DOE matrix.

Number	Fibers	Number of layers	Velocity
1	Basalt	4	40
2	Basalt	6	50
3	Basalt	8	60
4	Kevlar	4	50
5	Kevlar	6	60
6	Kevlar	8	40
7	Hybrid	4	60
8	Hybrid	6	40
9	Hybrid	8	50

3. Results and discussions

3.1. Experimental results

High velocity impact was applied to Taguchi recommended samples. The impacts were repeated until fully perforation occurred and the number of impacts to the failure of samples are reported in Table 6. Fig. 2 shows a forward view of samples after the final impact.

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Table 6. NIF for the Taguchi recommended samples.

Sample	B4	B6	B8	K4	K6	K8	H4	H6	H8
Impact velocity (m/s)	40	50	60	50	60	40	60	40	50
NIF	4	7	3	1	1	7	1	5	5

Figure 2. Damaged samples after impact tests.

The obtained amounts for NIF of Taguchi predicted samples in table 6 exported to the software and it predicted amounts for un-tested samples which are shown in the next section.

3.2. Taguchi predictions

Fig. 3 shows the effect of the number of layers and velocity of the projectile on impact tolerance of the basalt fibers reinforced epoxy samples subjected to the repeated high velocity impact.

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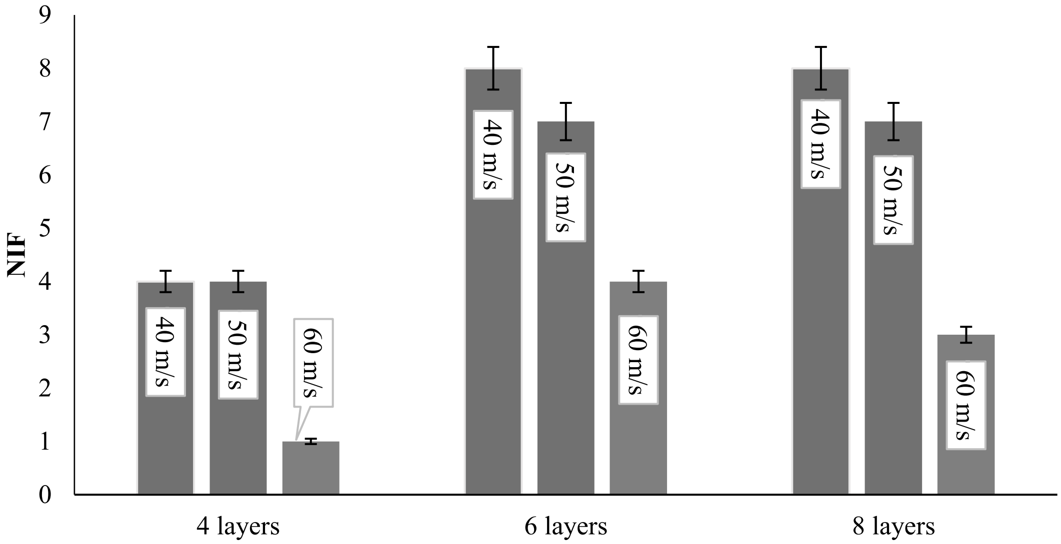

Figure 3. NIF for basalt fibers epoxy composites.

As it is shown in Fig. 3, in different layers, amounts of NIF in velocities of 40 and 50 m/s are approximately equal together (4 for 4-layer samples, 8 and 7 for 6-layer and 8-layer samples). When the velocity of projectile increases, the NIF decreases dramatically. It is obvious that increasing the projectile's velocity may lead to the less impact tolerance. For basalt fibers, it is shown that the decrease of NIF occurs in the 60 m/s.

Fig. 4 shows the effect of number of layers and velocity of the projectile on the impact tolerance of the Kevlar fibers reinforced epoxy subjected to the repeated high velocity impact. Despite basalt fibers, the decrease of NIF after increasing the projectile's velocity happened in the velocity of 50 m/s. It shows the less impact tolerance of Kevlar fibers in comparison with basalt fibers. The NIF results for the basalt-Kevlar fibers hybrid laminates are also presented in Fig. 5. Comparing Figs. 4 and 5 demonstrate the effect of hybridizing of the Kevlar and basalt fibers on

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NIF. According to the results, basalt fibers reinforced epoxy laminates showed the highest resistance to the repeated impact damage in all velocities.

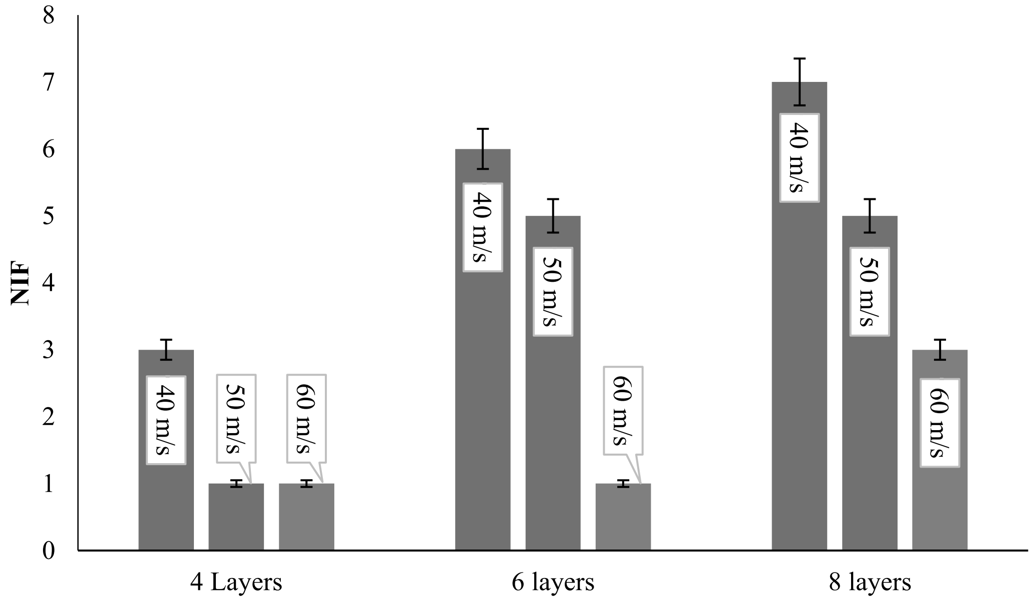

Figure 4. NIF for Kevlar fibers-epoxy composites.

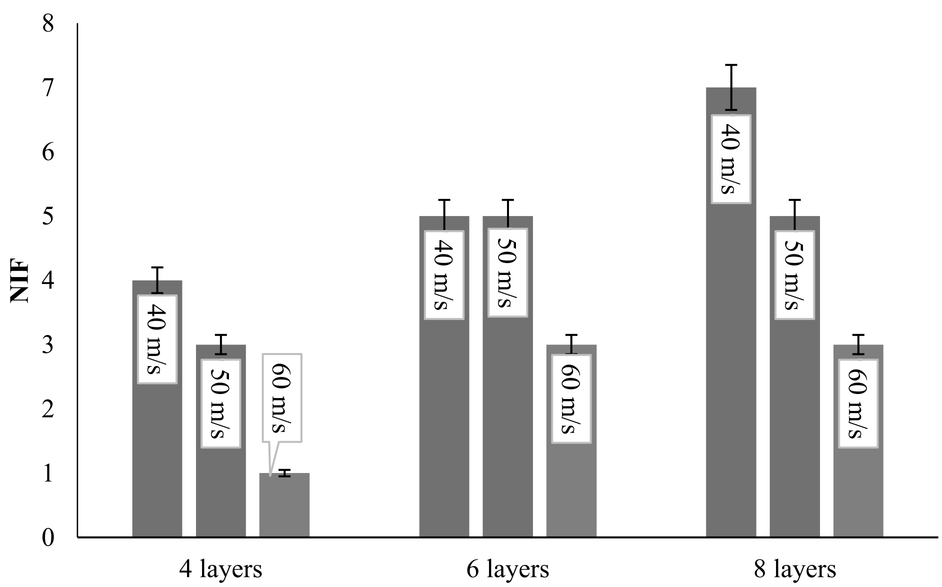

Figure 5. NIF for basalt-Kevlar fibers hybrid-epoxy composites.

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The NIF parameter for each laminate is a function of the impact velocity and thickness of each laminate. Using the obtained experimental and predicted results, a characteristic equation for the NIF parameter can be obtained by the surface fitting method. A second order equation for both thickness and velocity variables can be utilized as equation 1.

$$NIF = P_{00} + P_{10}t + P_{10}v + P_{20}t^2 + P_{11}tv + P_{02}v^2 \quad (1)$$

Where t and v are the laminate thickness and impact velocity, respectively. The unknown constants, P_{00}, P_{10}, P_{10}, P_{20}, P_{11}, P_{02} are calculated by the least square method for each laminate and are presented in Table 7. Fig. 6 demonstrates the surface fitting method for different types of laminates.

Table 7. Calculated constants for different types of laminates.

Laminate	P_{00}	P_{10}	P_{10}	P_{20}	P_{11}	P_{02}
Basalt	4.667	1.01	-1.299	-0.375	-0.1875	-0.375
Kevlar	4.111	1.443	-1.588	-0.5	-0.375	-0.125
Hybrid	5.00	0.9669	-1.4	-0.6627	-0.118	-0.344

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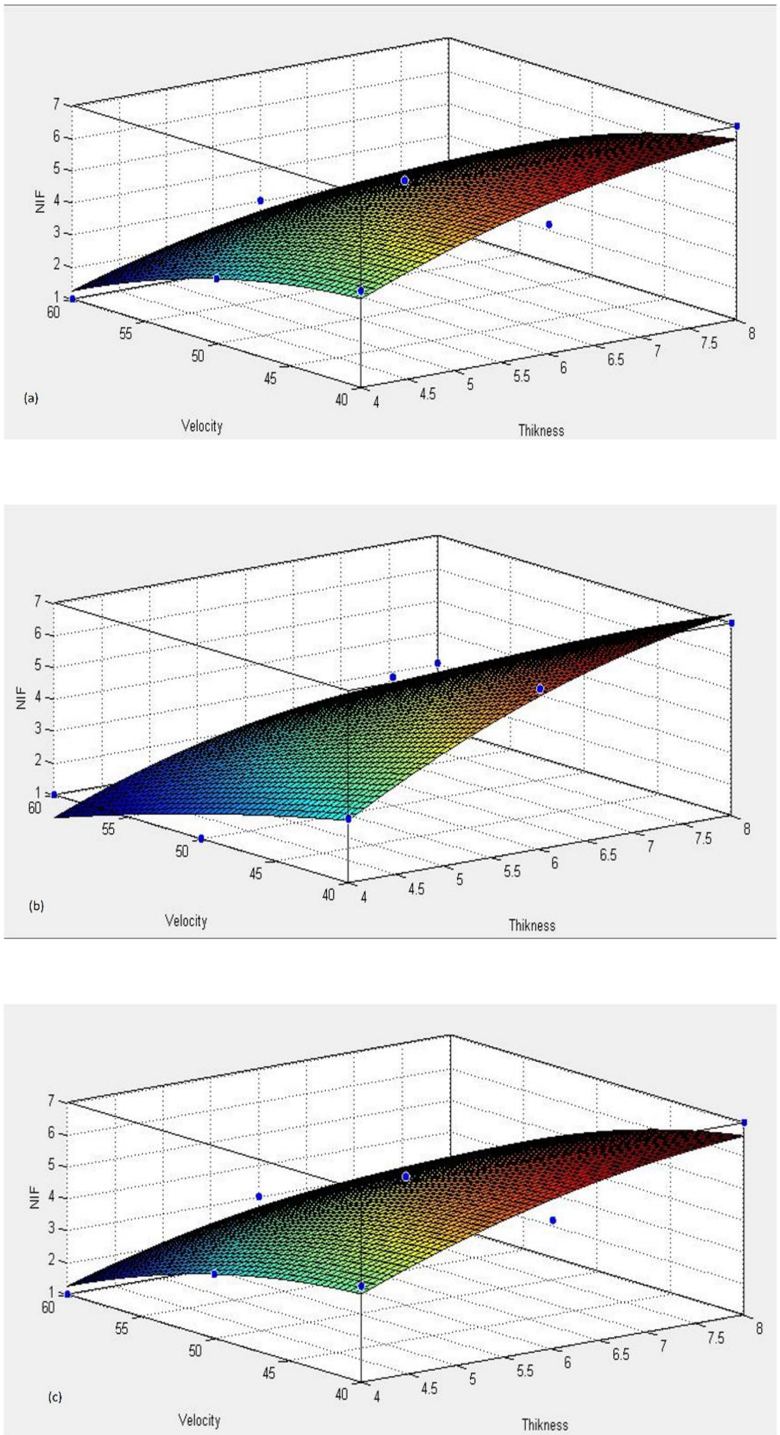

Figure 6. Surface fitting for a) basalt, b) Kevlar and c) hybrid samples.

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In order to investigate the effect of each parameter, the mean of means diagram can be utilized. Fig. 7 shows analysis of Taguchi design imported from software.

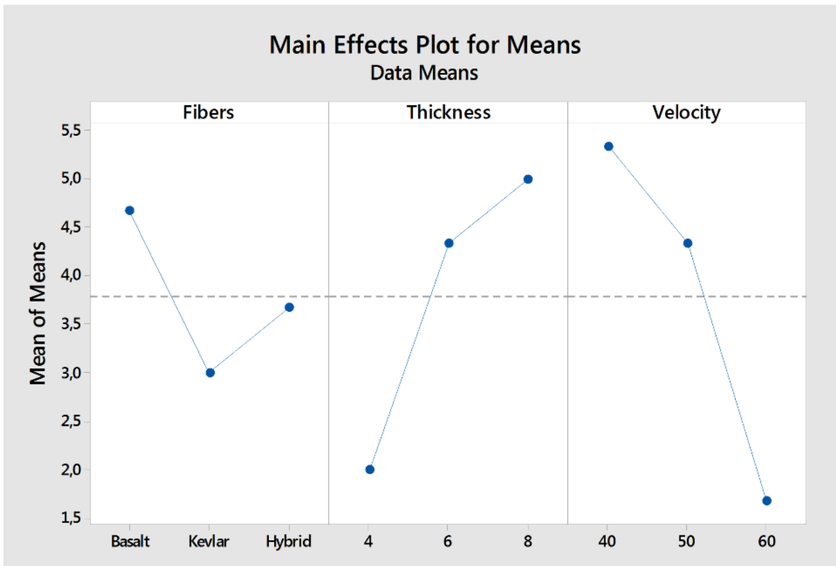

Figure 7. Graphs for effect of each factor supplied by Minitab 18.

Fig. 7 reveals the effect of each parameter on NIF. It can be seen that basalt fibers have more impact tolerance than Kevlar and fibers hybrid. Researches from other researchers also show the better impact resistance of basalt fibers compared to the other fibers such as carbon and glass [10,11]. In this case, the basalt fibers epoxy composites also show better properties than Kevlar and basalt-Kevlar fibers hybrid.

About the effect of thickness, it is obvious that more thickness leads to more impact tolerance and Fig. 7 also shows this phenomenon and so as for projectile's velocity, which less velocity leads to more NIF. Table 8 shows the mechanism of crack propagation in different types of tested composites.

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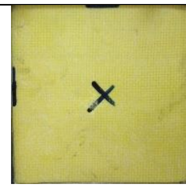
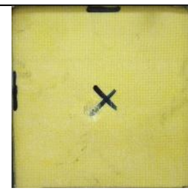
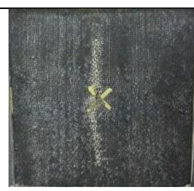
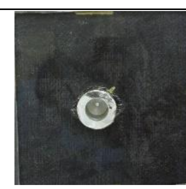
Table 8. Damage evolution of samples after each impact.

Impacts	Basalt epoxy	Kevlar epoxy	Basalt-Kevlar epoxy
Impact #1			
Impact #2			
Impact #3			
Impact #4			
Impact #5			
Impact #6			

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Impact #7		

As it is demonstrated in Table 8, for basalt epoxy samples, the failure of the sample occurred along a vertical line, due to the type of woven fabrics. After each impact, the failure line became longer, up to the failure of the sample. However, figures for Kevlar epoxy show the different mechanism. The crack propagates around the impact region and the failed area is up to the projectile's cross-section area. In Kevlar epoxy, the impact energy distributed in a less area than basalt epoxy. Accordingly, basalt epoxy demonstrated better behavior to the repeated high velocity impacts. Therefore, it can be concluded that besides the effect of fabric materials, the type of weaving also has an influence on the results by changing the failure mechanism.

3.3. Effect of thickness of each layer

As it is mentioned in Table 1, the layer thickness for basalt and Kevlar fibers were 0.4 mm and 0.3 mm, respectively. It reveals that polymer composites reinforced with basalt and Kevlar fibers with same layers have different thicknesses. In this part, samples with the same thickness are compared to each other to obtain the effect of different fiber's type.

B6 and K8 have the same thickness which is 2.4 mm. Fig. 8 shows the NIF for basalt samples with 6 layers and Kevlar samples with 8 layers. As it is shown in Fig. 8, basalt fibers epoxy composites have more NIF than Kevlar fibers epoxy composites in all three different samples. It means that basalt fibers due to the better impact tolerance have more NIF than Kevlar fibers.

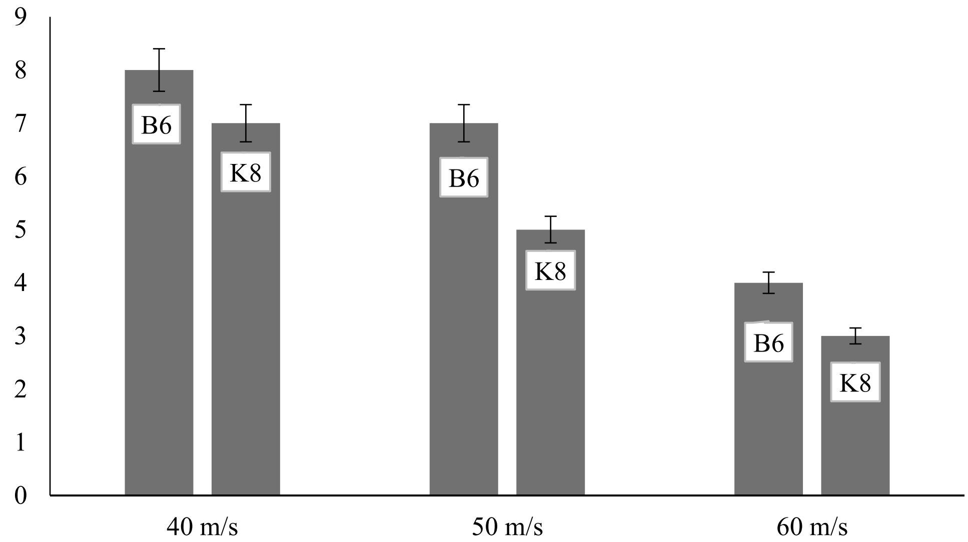

Figure 8. NIF for B6 and K8.

4. Conclusion

In this study, the response of basalt and Kevlar fibers epoxy composites to the repeated high velocity impact is evaluated. Samples with basalt and Kevlar and basalt/Kevlar fibers hybrid with different thicknesses were subjected to the high velocity impact with various energy levels repeatedly. This shows the impact tolerance of the samples. The results showed that the basalt fibers reinforced epoxy had the highest damage tolerance in comparison with Kevlar and hybrid samples with different impact velocities and laminate thicknesses. However, in the highest impact velocity (60 m/s) the numbers of impacts were close together for 3 different types of the laminates. Moreover, having used the surface fitting method, characteristic equations for calculating the number of impacts to failure for different types of laminates were obtained.

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