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Effect of Shape Memory Alloy Wires on High Velocity Impact Response of Basalt Fiber Metal Laminates

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Abstract
Fiber metal laminates (FMLs) are commonly used materials in industrial applications due to low density and excellent mechanical properties such as impact resistance. In this study, the effect of shape memory alloy wires on the impact properties of FMLs is evaluated and discussed. The volume fraction of wires and the pre-strain of wires were selected as the variables of the experiments. The samples were fabricated using hand lay-up method and their behavior was evaluated under high velocity impact test. Based on the results, a significant change in the amount of absorbed energy was obtained using embedded wires. However, with increasing the volume fraction of wires, the absorbed energy decreases due to the discontinuity in mechanical properties of the specimens. On the other hand, applying pre-strain leads to residual stresses in samples. The observed residual stress in specimens with 4 embedded wires and 2% pre-strain level shows the most absorbed energy.

Keywords: Fiber Metal Laminates, Shape Memory Alloys, High Velocity Impact.

1- Introduction

In the past three decades, researches on lightweight materials have shown that it can replace traditional aluminum alloys in aerospace industry. As an optimal structural design, a new material is needed with the ability to combine high strength with low density, high elasticity modulus, adequate hardness, toughness, corrosion resistance and good fatigue properties. Composite materials can meet these requirements, except the fracture toughness; in order to achieve good toughness properties in structures and improve the properties, researchers introduced fiber metal laminates (FML) [1].

Along with the progress in construction of the new composites, the reputation of Shape Memory Alloys (SMAs) was wrapped among engineering designers. Materials with unique properties and supreme ability to recover strain and generating stress. According to this information, composite designing engineers decided to apply the properties of SMAs to composite structures and new kinds of materials called smart hybrid composites and have entered into the engineering competition [2].

Smart Structures are structures which have the ability to adapt with different loading conditions and variable environments. The examples are piezoelectric, shape memory materials, magnetostrictives, etc [3]. Compressive stress which is caused by the shape memory material is very useful in improving impact resistance performance. In this method, pre-strained wires are embedded in composite laminated layers, when the wires' temperature increases, they enter the austenite phase, a recovery tensile stress will be generated and impact resistance of the structure increases significantly [4]. The actual design for enhancing the mechanical properties of the SMA composite is schematically depicted in Figure 1. TiNi fibers are heat-treated to shape-memorize their initial length at higher temperatures (>A_f). Then,

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they are quenched to room temperature (to almost martensite start temperature ¼ M_s).Tensile pre-strain is placed on them. Finally, they are embedded in the matrix material to form a composite [5].

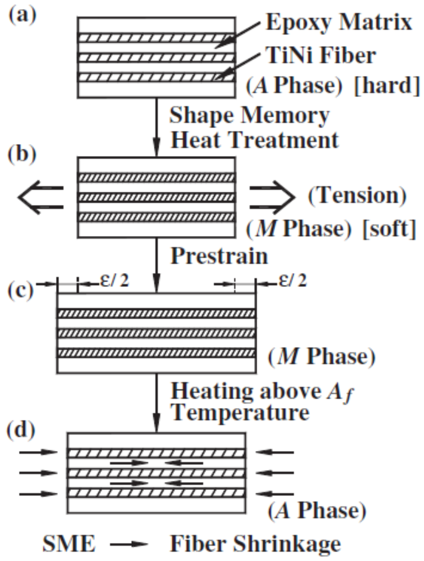

Figure 1. Concept of designing shape memory composites [5].

Researches on designing the shape memory hybrid composites show the effects of volume fraction, surface treatment [6], pre-strain [7] and matrix curing process [8] as parameters which should be evaluated. Recent studies do not consider all of these parameters simultaneously. For example, high pre-strain level is applicable for cases which require a high ability to close cracks. Therefore, studies show that high pre-strain does not enhance thermo-mechanical behavior of composites and that it reduces the quality of the surface [9].

Crawley [10] studied the smart materials in which a sensor and an actuator were used. The results showed that shape memory alloys have better properties than other smart materials. Khalili et al [4] studied the effect of some important parameters in low velocity impact of thin-walled hybrid composite plates with embedded shape memory alloy wires. Results indicated that such physical parameters as volume percentage of SMA wires, orientation of fibers in composites, mass and velocity of the projectile and the length to thickness ratio of plates are the most important factors for structural design.

Schrooten et al [7] showed that the recovery stress in hybrid structures that are embedded with SMA wires, has a direct relationship with temperature but it is inversely related to pre-strain. The rate of the stress is reduced with increasing the strain. In wires with a high pre-strain level (4-6 %), recovery stress starts to rise right after heating, even under A_s, while composites with a lower pre-strain level in their wires start to contract after passing A_s temperature. In this case, the stress rate decreases with increasing pre-strain level.

Vokoun et al [8] during the research on SMA wires, transmitted them to the variable levels of strain at variable temperatures to reach to the information about the optimization of treatment behavior of the shape memory composites. Wires showed a little recovery strain after unloading. Reversible strain was decreased with increasing the temperature but increased with increasing the strain's level.

Taheri-Behrooz et al [11] studied the effect of stacking sequence on the impact behavior of fiber metal laminates (FMLs) under low velocity impact. The form of damage progression in the second layer of aluminum of specimens was completely dependent on the stacking sequence of composite layers.

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Some other researchers studied low velocity impact response of FMLs under different conditions such as temperature [12], impactor size [13], repeated impacts [14] and different fillers [15].

Eslami Farsani et al [16] studied Charpy impact response of basalt fiber metal laminate composites. Gou-Cai Yu et al [17] studied the low velocity impact behavior of the carbon fiber aluminum laminates (CARALL). The purpose of the research was to study the applicability of carbon fiber in FMLs and the effect of the properties of aluminum alloy on the low velocity impact response of CARALL. Ahmadi et al [18] studied the resistance of glass-reinforced laminates with different thickness ratios (ratio of the thickness of glass/epoxy plies to aluminum sheets) subjected to high-velocity impact.

According to the literature, it can be seen that simultaneous study on FMLs with SMA wires under high velocity impact is a subject that has not been looked into yet. In this study, SMA's properties are applied to enhance absorbed energy and impact resistance of FMLs.

2- Materials and experiment procedure

For manufacturing the FML's composite part, Basalt woven fibers and epoxy resin EPON 828 with 10% hardener were used. For the metal part, aluminum sheets of 6061-T6 with 0.5 mm width were used. The SMA wires were Nickel-Titanium with 0.4 mm diameter that were made by Highland Metals Inc. The martensite and austenite transformation temperatures of these wires are shown in table 1.

Table 1. Transformation temperature for NiTi wires [19]

Austenite start (A_s)	Austenite finish (A_f)	Martensite start (M_s)	Martensite finish (M_f)
5.35 °C	19.71 °C	-42.61 °C	-65 °C

In this study, the number of SMA wires and pre-strain of the wires were chosen as the parameters. For determining the effect of embedding SMA wires in the specimens, three different numbers of wires (2, 4 and 8 wires) were predicted. Embedding a wire in the middle of specimens could deflect the projectile. To avoid projectile's deflection, SMA wires were embedded around the middle line of the specimens with 1 cm distance. According to the literature, low pre-strain levels have more positive effect in mechanical properties, therefore, 0, 2 and 4 percent of pre-strain was predicted to be applied to the SMA wires. An FML specimen without SMA wires was also fabricated as a reference. For each specification, 3 specimens were fabricated to ensure reliable results.

In the composite part, 4 layers of Basalt fibers-epoxy were fabricated with the hand lay-up method. Basalt fibers were manufactured by Basaltex Company. Some of the given properties of Basalt fibers are listed in table 2. The SMA wires were placed 1 cm apart, between the third and the fourth layers of the composite. Figure 2 shows the fixture which was used to produce the specimens and the mechanism of applying pre-strain. Figure 3 shows a view of the construction process and figure 4 shows a schematic view of a constructed specimen.

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Table 2. Properties of Basalt fiber

Property	Value
Density (Kg/dm^3)	2.67
Specific surface weight (g/m^2)	350
Thickness (mm)	0.19

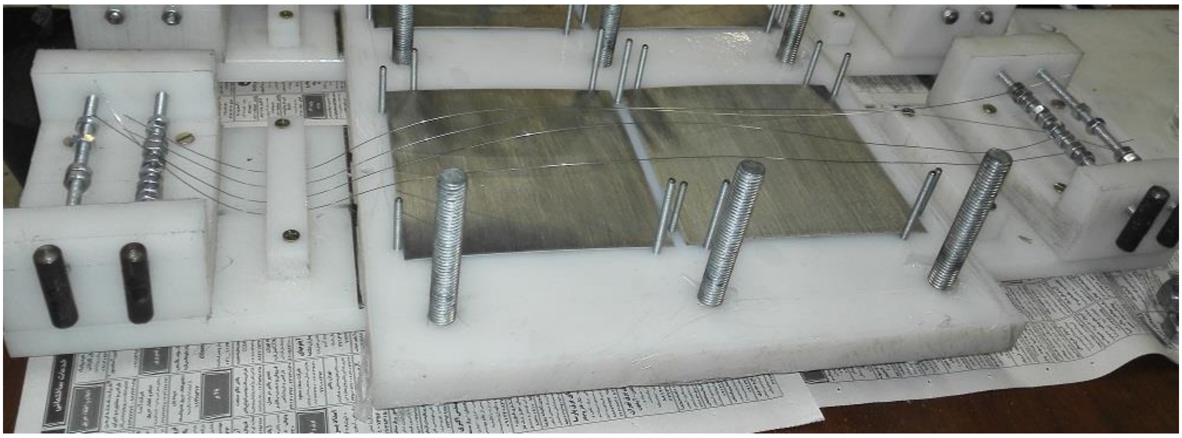

Figure 2. Fixture used for producing specimens and mechanism of applying pre-strain.

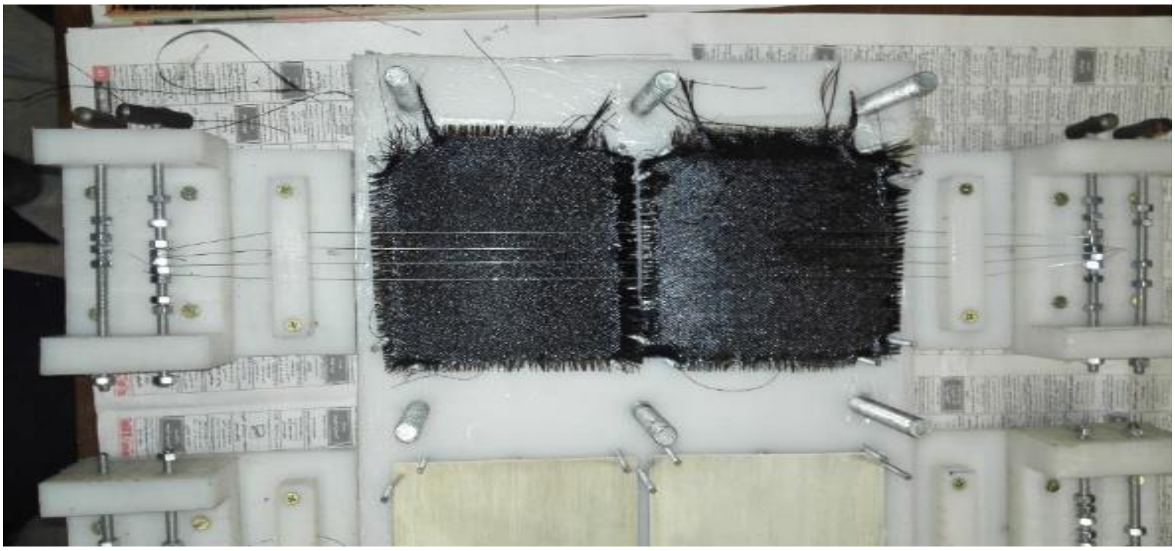

Figure 3. View of the construction process.

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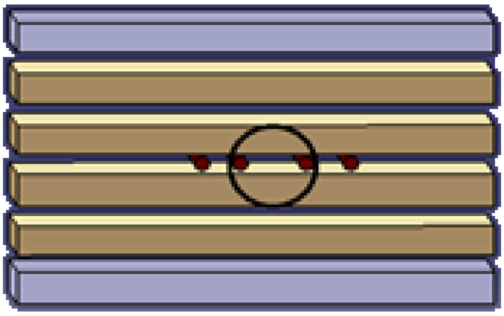

Figure 4. Schematic view of constructed specimen.

The gas gun high velocity impact tester was used for testing the specimens (figure 5). The projectile had a diameter of 21.5 mm and weighed 27 g. The initial velocity was 122 m/s. For simplification, the specimens were named as shown in table 3.

Figure 5. Gas gun high velocity impact tester.

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Table 3. Codes for Specimens

Number	Specimens code	Number of wires	Wires pre-strain (%)
1	BFML0W	**0**	**0**
2	BFML2W0%	**2**	**0**
3	BFML2W2%	**2**	**2**
4	BFML2W4%	**2**	**4**
5	BFML4W0%	**4**	**0**
6	BFML4W2%	**4**	**2**
7	BFML4W4%	**4**	**4**
8	BFML8W0%	**8**	**0**
9	BFML8W2%	**8**	**2**
10	BFML8W4%	**8**	**4**

* The numbers before W refer to amount of wires and the numbers after W refer to wire's pre-strain.
* BFML = Basalt Fiber Metal Laminates

3- Results and discussions

3-1- Results for FML specimens without wire

In the first step, the reference specimen was tested, the purpose was to compare the normal FML and the smart FML. The initial pressure for shooting the projectile was 6.5 bar. In this test, the output of the system was the residual velocity of the projectile. For BFML0W, residual velocity was obtained 88 m/s. In this step, limit velocity and absorbed energy should be calculated. Limit velocity is the least velocity for fully perforating the specimen. Equations 1 and 2 were used to calculate the limit velocity (V_b) and the absorbed energy (E_{abs}) [20]:

$$V_b = \sqrt{V_i^2 - V_r^2} \qquad \text{m/s} \tag{1}$$

$$E_{abs} = \frac{1}{2} m_p V_b^2 \qquad \text{J} \tag{2}$$

In equation 1, V_b, V_i and V_r refers to the limit velocity, initial velocity and residual velocity, respectively. In equation 2, E_{abs} and m_p refers to the absorbed energy and the mass of projectile. With respect to the equations 1 and 2, the amounts that were derived for BFML0W are shown in table 4.

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Table 4. Limit velocity and energy absorbed for BFML0W

Specimen	V_b (m/s)	E_{abs} (J)
BFML0W	84.49	96.37

3-2- Results for FML specimens with 2 embedded wire

Figure 6 shows the backward view of the specimens with 2 SMA wires, BFML2W0%, BFML2W2% and BFML2W4%. Damaged area shows that the absorbed energy was distributed in whole area of the sheet. As it shown in BFML2W0%, damaged area is larger than two others and damage's propagation is in 2 direction. In BFML2W4, damaged area shows that the absorbed energy wasn't distributed in whole area of the sheet and just the middle part was damaged.

(a) **(b)** **(c)**

Figure 6. a) Backward view of the BFML2W0% after impact, b) Backward view of the BFML2W2% after impact and c) Backward view of the BFML2W4% after impact.

In the table 5, residual velocity for these three specimens are shown. Table 6 shows the limit velocity and energy absorption that are derived from equations 1 and 2 and also it shows percentage of the increased energy compared to BFML0W.

Table 5. Residual velocity for FML specimens with 2 SMA wires

Specimen	BFML2W0%	BFML2W2%	BFML2W4%
Residual Velocity (m/s)	69	73	75

Table 6. Limit velocity and Energy absorbed for FML specimens with 2 SMA wires

Specimen	BFML2W0%	BFML2W2%	BFML2W4%
Limit Velocity (m/s)	100.61	97.74	96.22
Energy Absorbed (J)	136.65	128.96	124.98
Increased Energy (%)	41	33	30

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As it is shown in table 6, after embedding the wires, the residual velocity of the BFML2W0% was reduced from 88 m/s to 69 m/s because of the more energy absorption in the specimen. Embedding wires increases the Young modulus of specimens which leads to increase the internal stress. After applying pre-strain to the embedded wires, the residual velocity was increased, 73 m/s for 2% pre-strain and 75 m/s for 4% pre-strain and subsequently limit velocity and absorbed energy had a decreasing trend.

Increasing the pre-strain level in specimens with 2 embedded wires does not help to increase the limit velocity and absorbed energy. Accordingly, in the 2 wires condition, negative effect of applying pre-strain, which is creating interface damage, defeats the positive effect. Figures 7 and 8 show the limit velocity and absorbed energy in 2-wires specimens, respectively. The maximum error between the specimens which were tested for each condition was 4%.

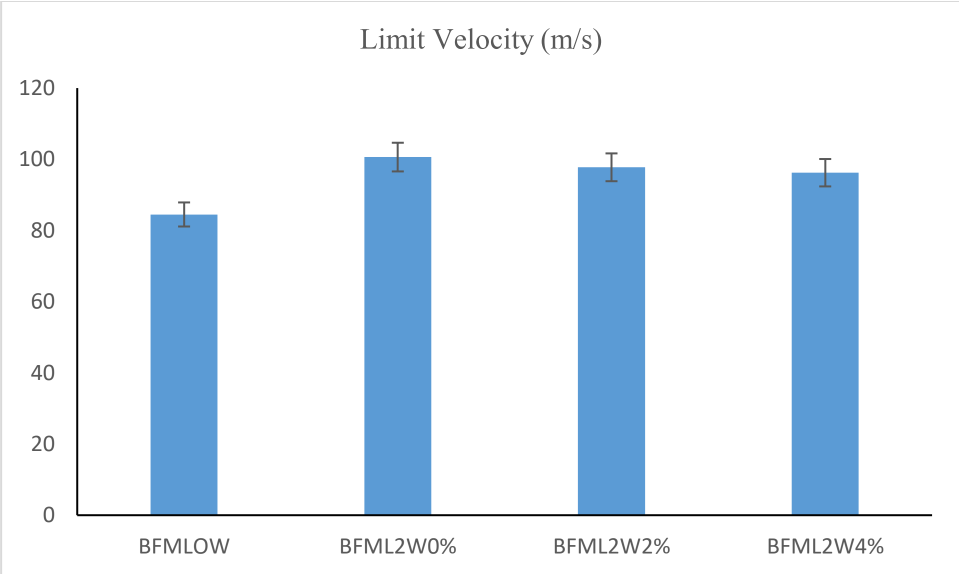

Figure 7. Changing procedure of limit velocity in FML specimens with 2 SMA wires.

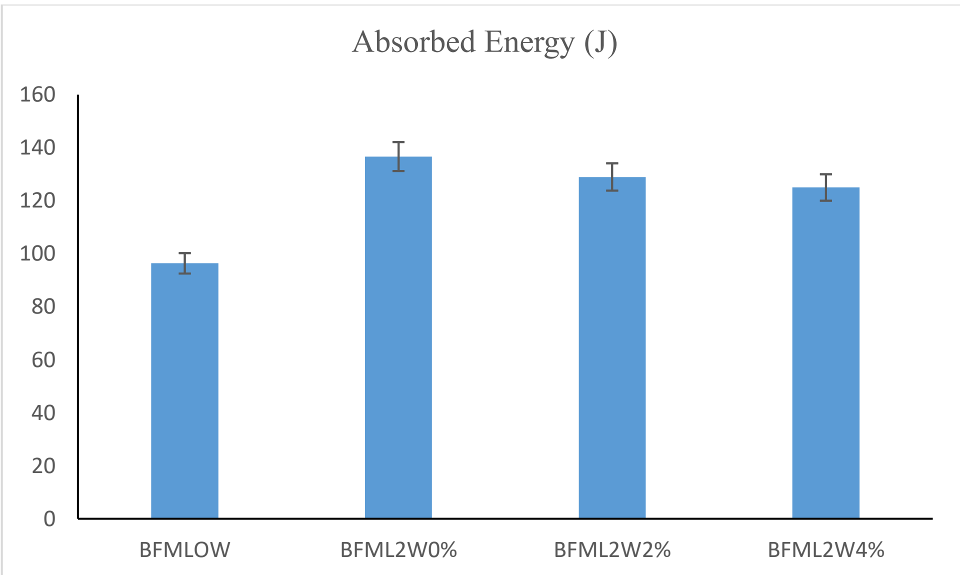

Figure 8. Changing procedure absorbed energy in FML specimens with 2 SMA wires.

As it is shown in the figures 7 and 8, absorbed energy was increased significantly with embedding wires. Applying pre-strain causes the wires to pull-out from epoxy matrix, thus, absorbed energy was decreased after applying pre-strain. In figures 6-a, 6-b and 6-c, the larger damaged area shows this fact that specimens absorbed more energy after hitting of the projectile and more area of the specimens was damaged.

3-3- Results for FML specimens with 4 embedded SMA wire

Figure 9 shows the backward view of the specimens with 4 SMA wires, BFML4W0%, BFML4W2% and BFML4W4%. In figures 9-a and 9-c, damaged area shows that impact energy of the projectile wasn't distributed in the whole area of the sheet and just the middle part was damaged, but in figure 9-b, damaged area shows that absorbed energy was distributed in whole area of the sheet.

(a) **(b)** **(c)**

Figure 9. a) Backward view of BFML4W0% after impact, b) Backward view of BFML4W2% after impact and c) Backward view of BFML4W4% after impact.

Table 7 shows the residual velocities for these three specimens. Table 8 shows the limit velocity and the absorbed energy for 4-wire specimens that is derived from equations 1 and 2 and also it shows the percentage of increased energy compared to BFML0W.

Table 7. Residual velocities for FML specimens with 4 SMA wires

Specimens	BFML4W0%	BFML4W2%	BFML4W4%
Residual Velocity (m/s)	73	66	72

Table 8. Limit velocity and energy absorbed for FML specimens with 4 SMA wires

Specimens	BFML4W0%	BFML4W2%	BFML4W4%
Limit Velocity (m/s)	97.74	102.6	98.48
Energy Absorbed (J)	128.96	142.11	130.92
Increase Energy (%)	33	47	35

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As it is shown in table 8, absorbed energy was increased after embedding the SMA wires up to 33%, similar to the 2-wire specimens, but unlike 2-wire specimens, which was decreased after applying pre-strain. In this case, limit velocity and absorbed energy was increased after applying 2% pre-strain up to 47%, but it was decreased after applying 4% pre-strain (35%) and the amounts for BFML4W4% were almost equal to BFML4W0%. This can be observed by comparing the damaged area between three specimens (figure 9). The more damaged area the more energy absorption and impact resistance.

Figures 10 and 11 show the limit velocity and absorbed energy in 4-wire specimens, respectively. Applying 2% of the pre-strain increased the absorbed energy. It means that in this specimen (BFML4W2%), the positive effect of SMA's volume fraction and pre-strain level, overcome its negative effect but in BFML4W4%, absorbed energy was decreased. High levels of the pre-strain lead to the inter-laminar damages and weaken the bond strength between the wires and the polymer matrix, which is resulted to decrease in the absorbed energy. In BFML4W4%, absorbed energy is less than BFML4W2%, because of the rupture occurred in the specimen after applying high level of the pre-strain.

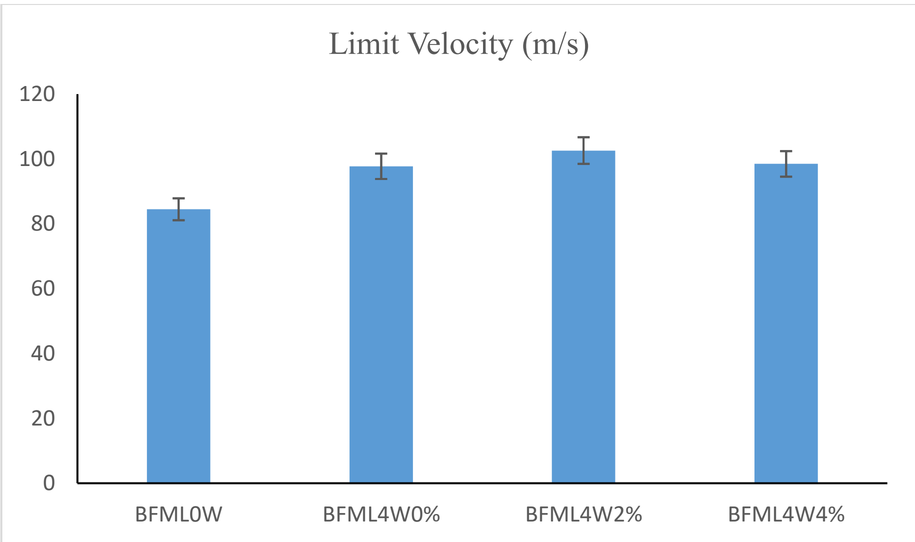

Figure 10. Limit velocity in FML specimens with 4 SMA wires.

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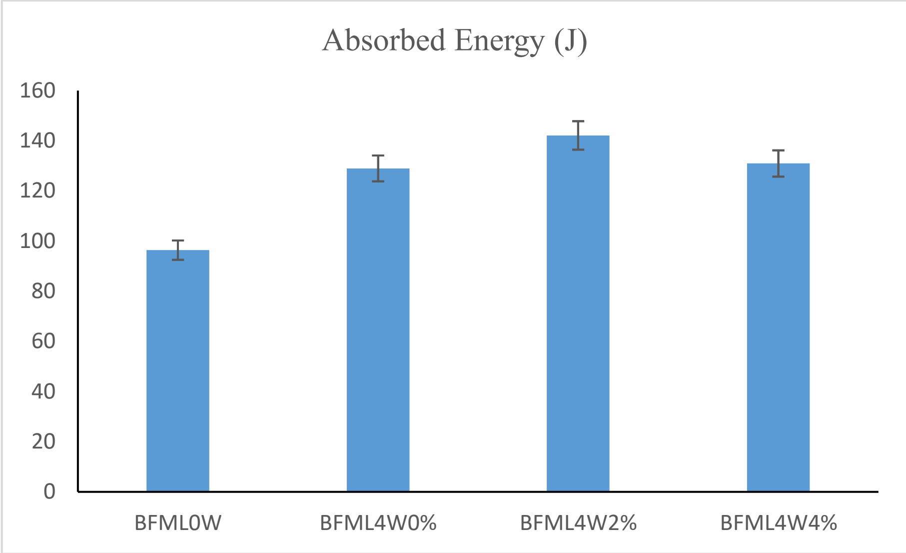
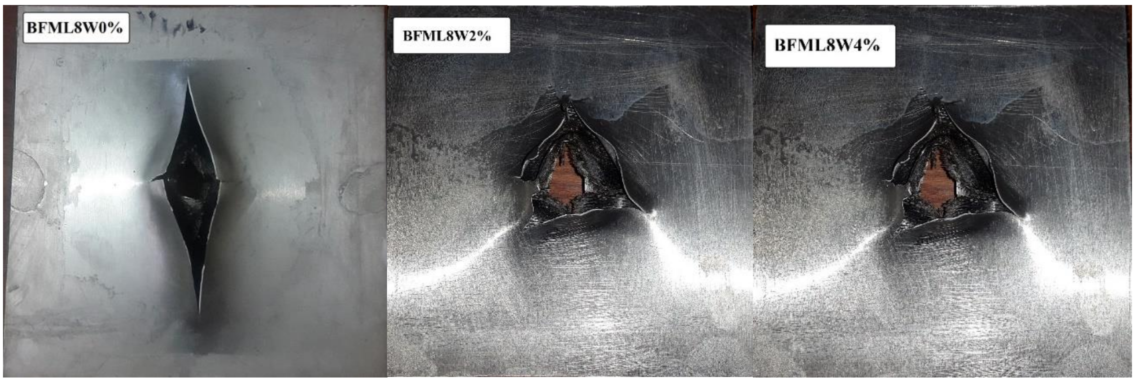


Figure 11. Absorbed energy in FML specimens with 4 SMA wires.

3-4- Results for FML specimens with 8 embedded wire

Figure 12 shows the backward view of the BFML8W0%, BFML8W2% and BFML8W4%. As it shown, damaged area in BFML8W0% is larger than two others. This is due to the more energy absorption. More delamination in a specimen shows that the specimen absorbed more energy after hitting the projectile.



(a) **(b)** **(c)**

Figure 12. a) Backward view of BFML8W0% after impact, b) Backward view of BFML8W2% after impact and c) Backward view of BFML8W2% after impact.

Table 9 shows the residual velocities for FML specimens with 8 embedded wires. Table 10 shows the limit velocity and the absorbed energy for 8-wire specimens that are derived from equations 1 and 2 and also it shows the percentage of the increased energy compared to BFML0W.

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Table 9. Residual velocities for FML specimens with 8 SMA wires

Specimens	BFML8W0%	BFML8W2%	BFML8W4%
Residual Velocity (m/s)	70	72	73

Table 10. Limit velocity and energy absorbed for FML specimens with 8 SMA wires

Specimens	BFML8W0%	BFML8W2%	BFML8W4%
Limit Velocity (m/s)	99.91	98.48	97.74
Energy Absorbed (J)	134.75	130.92	128.96
Increase Energy (%)	39	35	33

As it shown in table 10, like 2-wire specimens, absorbed energy and limit velocity were decreased after applying the pre-strain (39, 35 and 33%), despite the 4-wire specimens. Embedding wires in a specimen may causes the rupture and discontinuity in the mechanical properties, this could be neglected by applying the pre-strain in 4-wire specimens, but in 8-wire specimens, the number of the SMA wires leads to the rupture in the specimens and absorbed energy will not be increased. Figures 13 and 14 show the comparison between limit velocity and absorbed energy respectively.

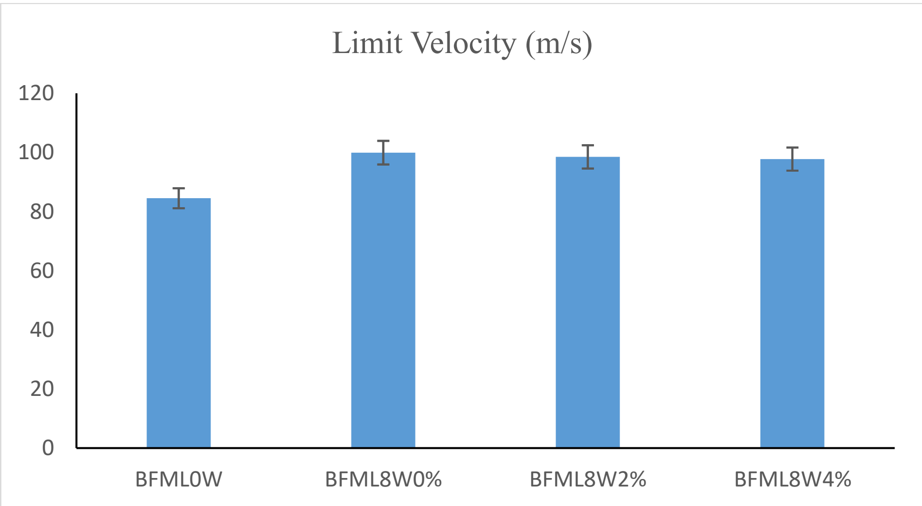

Figure 13. Changing procedure of limit velocity in FML specimens with 8 SMA wires.

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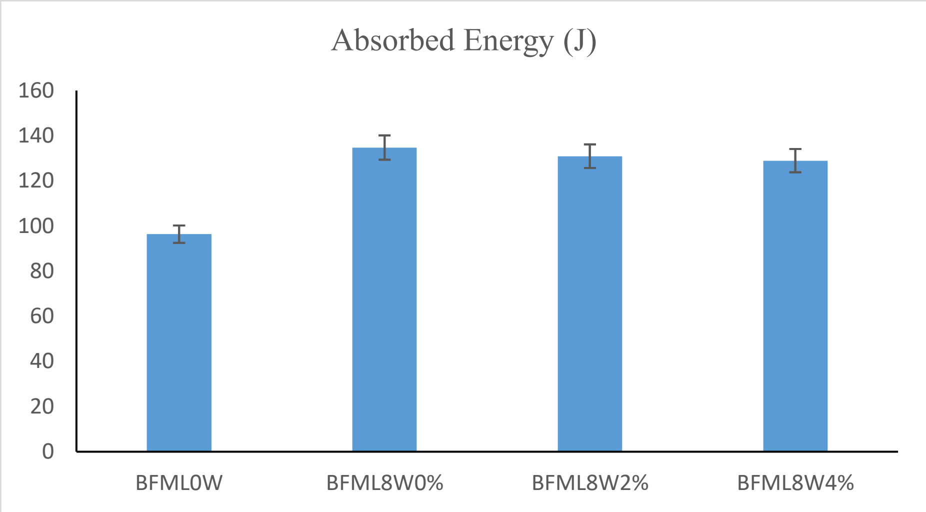

Figure 14. Changing procedure of absorbed energy in FML specimens with 8 SMA wires.

3-5- Comparison between FML specimens with SMA wires and without pre-strain

In this section, absorbed energy for specimens without pre-strain level is compared to obtain the effect of this parameter (volume fraction of the SMA wires). Values of the absorbed energy are 136.65, 128.96, 134.75 for BFML2W0%, BFML4W0% and BFML8w0%, respectively. It shows that just embedding the more wires couldn't help to increase the impact resistance. This is because of the rupture and discontinuity occurred in the mechanical properties of the specimen. Rupture leads to the difference between mechanical properties from point to point.

4- Conclusions

In this study, promotion of high velocity impact response of basalt fiber metal laminates with embedded shape memory alloy wires was discussed. Volume fraction and the pre-strain level of the wires were considered as variables. Amounts of pre-strain levels were 0%, 2% and 4% and the numbers of wires were 2, 4 and 8 SMA wires. Each of these variables have advantages and disadvantages. The results are as follows:

- When a shape memory alloy wire is placed in the composite, it results to the increasing in the elasticity modulus and releases a compressive stress which tends to promote the mechanical properties. In this study, after embedding 2, 4 and 8 shape memory alloy wires in the FML specimens, the absorbed energy was increased to 41, 33 and 40%, respectively, compared with simple FML (without SMA wire). The energy absorption was not increased after embedding the more wires because of the rupture in the interface layers.

- In the case of 2 and 8 shape memory alloy wires was used, increasing the pre-strain leads to decrease in energy absorption. Therefore, according to the results, increase the pre-strain in 2-wire and 8-wire specimen don't help to the improvement of the impact resistance.

- In the case of 4 shape memory alloy wires was used, the specimen with 2% of pre-strain showed 47% increase in the absorbed energy, compared to the simple FML. This condition is the optimized condition of this research.

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• Applying 4% of the pre-strain couldn't help to increase in the absorbed energy, this is due to the interface damages and pulling out of wires from matrix that was happened after applying the pre-strain. The residual stress caused by the shape memory effect couldn't overcome this interface damage and impact energy was decreased.

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