

Compression after high-velocity impact behavior of pseudo-elastic shape memory alloy embedded glass/epoxy composite laminates

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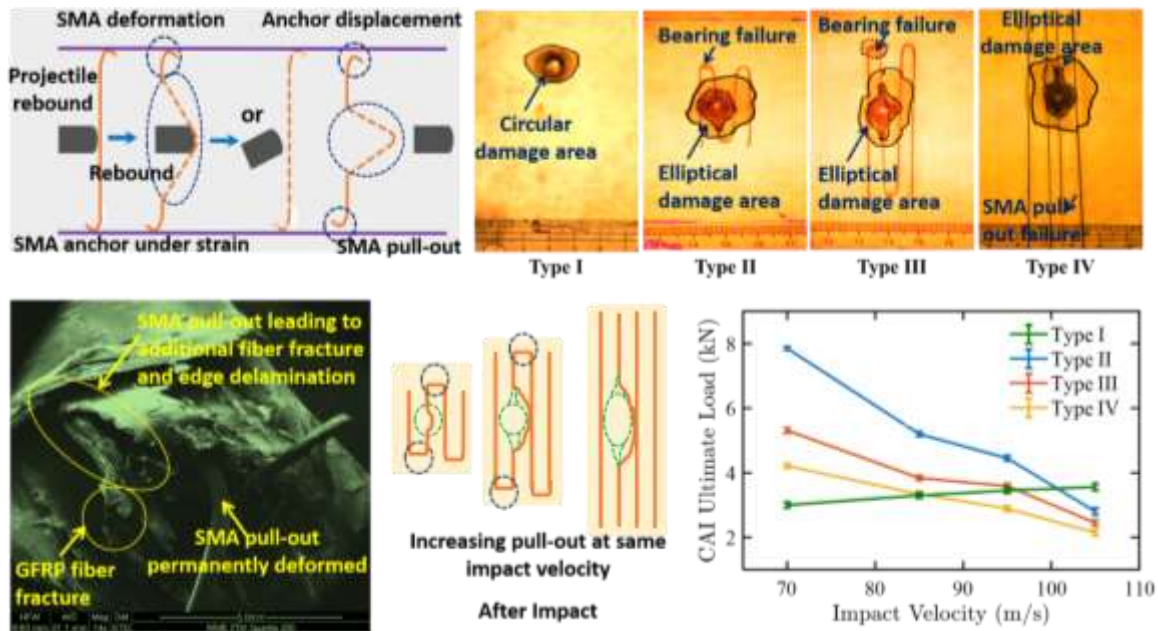
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Graphical Abstract



Highlights

1. Novel configuration of PE-SMA embedded GFRP composite laminates are fabricated.
2. Compression after high-velocity impact (CAI) behavior is determined.
3. The ballistic limit of PE-SMA GFRPs is (maximum 72.72 %) higher than that of the homogeneous ones.
4. Real-time damage progression of different composite laminates is monitored and discussed.

Abstract

The compression after high-velocity impact (CAI) behavior of pseudo-elastic shape memory alloy (PE-SMA) embedded glass/epoxy composite laminates manufactured via vacuum-assisted resin infusion (VARI) technique was investigated experimentally. High-velocity impact tests were performed on the glass/epoxy composites using an in-house build gas-gun set-up at four different velocities (70, 85, 95, and 105 m/s). To elucidate, the series of damage events undergone on the composites under the high-velocity impact, a high-speed camera was used. Quasi-static compression-after-impact (CAI) tests were performed to evaluate the damage tolerance of different composites subjected to high-velocity impact. Real-time damage progression during the CAI as well as the extent of damage was characterized by using a 2D Digital Image Correlation (DIC) technique. Three different types of embedment configurations of PE-SMA wire, namely, with length variation (35, 70, and 150 mm) and also with and without anchors, were used. The impact test results show that the ballistic limit of anchored PE-SMA composites with an embedment length of 35 mm is 72.72 % higher than that of the homogeneous glass/epoxy composites. CAI results indicate that the PE-SMA based composites have better damage tolerance with respect to the homogeneous ones at 70 m/s. In contrast, at higher velocities, the delamination area decreases in the homogenous glass/epoxy composites due to more localized damage and present a higher compressive strength.

Keywords: Pseudo-elastic shape memory alloys (PE-SMA), high-velocity impact, digital image correlation (DIC), compression after impact (CAI), glass/epoxy, composite laminates, GFRP.

1. Introduction

In the past few decades, research has established the prowess of composite laminates over the traditional metals due to their high stiffness and strength to weight ratios, improved fatigue endurance, corrosion resistance and design flexibility. They have outmatched metals when it comes to applications where stress dominates in the direction of the primary fibers in the structural element. These composites that render the above advantages should also be equally resistant to impact conditions that occur in the lifetime of their usage (for example, bird strikes, tool drop, collisions with floating debris, docks, and particle impact on propeller blades and wind turbine blades) [1-3]. Assessment of the performance of the composites during the impact events and quantification of energy dissipation

vis-a-vis metals will help in designing better composites. Unlike metals that exhibit good isotropy, complexities in the assessment occur because of the numerous failure modes possible in a composite material. Early studies on the impact behavior of the composites point to their low energy absorption capabilities [1-2].

In composite laminates; under the impact loading, energy absorption occurs through numerous failure modes such as matrix cracking, debonding, fiber pull-out, penetration, and fiber fracture [4-7]. In the past, researchers have investigated the effect of employing different kinds of fiber systems such as aramid, carbon, and glass fibers with different lay-ups for composite manufacturing. They have evaluated the energy absorption capabilities by embedding different materials in composites [8-12]. Though optimal fiber geometry and fiber material properties may improve the energy absorption capabilities to a certain extent, it still suffers from less energy absorption since fibers fail at relatively low strain levels [13]. To solve the need for higher energy absorption under the impact, materials with good ductility has to be embedded. One such material that has a high failure strain and self-centering properties is pseudoelastic shape memory alloy (PE-SMA) [14-16]. PE-SMAs are highly ductile alloys with high endurance in the plastic deformation regime. This behavior of PE-SMA has attributed to the phase transformation mechanisms that occur internally under thermomechanical loading [17-19]. Thus, PE-SMA embedded composite has expected to serve well in such applications compared to conventional composite structures where resistance to penetration and damage during ballistic impact critically affects the design [20-24].

Earlier studies on hybrid SMA-graphite composite laminates reveal an increase in the absorbed energy and peak impact force with a reduction in impact damage under low-velocity impacts [25-27]. At high-velocities, composite samples embedded with SMA show promise in terms of perforation toughness [28]. In its wire form, if laid bi-directionally, SMA composites show a negative effect leading to an increase in damage area when compared to unidirectional SMA during impact tests [29]. With the increase in energy absorption, many researchers have tried to reduce the damage in the samples using the embedment of SMA. Researchers have stitched SMA into the composites to reduce the risk of delamination [26]. Different surface treatment techniques, such as chemical oxidizing and wetting of the SMA surface, have been employed to increase bonding with matrix [20, 30-32]. Though

these methods improve surface properties to a certain extent, their effectiveness reduces, once debonding between the SMA and composite initiates at the impact point.

After impacting composites with SMA embedded as secondary reinforcements, failure in compression is an important phenomenon to be looked at carefully. Residual strength determination is a critical parameter after performing an impact as it gives an idea about how much weakness has induced due to impact load [33]. Many researchers have investigated the compressive strength of the composites after impact (CAI). Physical attributes such as impact location, area, and aspect ratio of damage due to impact load have shown to affect the residual compressive strength of composites [34]. Regarding the failure modes, damage appears to be initiated by the interlaminar failure in the impacted region. This damage extends in the form of local buckling and delamination in the sample [35]. Crack growth occurs from the impact damage zone [36-37]. The increase in the delamination area reduces buckling stresses and residual compressive strength, leading to failure [38-39]. The investigation of SMA embedded GFRP under compression after impact is still in the nascent stage.

Though work has performed under low-velocity impact regime, there is scant information available in the literature on composites under the high-velocity impact. At high velocities, impact perforation becomes localized. Due to this, the failure modes also change. SMA embedment introduces additional SMA failure modes at high-velocity impact. The effect on the conventional failure modes due to SMA embedment has not been widely studied. Limited literature is available on the prediction of residual properties such as compression after impact (CAI) at high velocities. Moreover, there are very few reported work available for SMA hybrid composites at high-velocity impact and how embedment affects the ultimate compressive failure strength of the composite.

Thus, in this work, the energy absorption characteristics and residual compressive properties of PE-SMA embedded glass/epoxy composite laminates have been investigated under high-velocity impact loadings. Bi-directional woven GFRP has been used as a parent material to embed PE-SMA [40]. Three different types of embedment configurations of PE-SMA wire, with length variation and also with and without anchors, have been employed. To elucidate, the series of damage events undergone on the composites, a high-speed camera was used. After impact, compression tests have been carried out to find out the residual failure strength and how compression

failure modes vary spatially. To better understand, the effect of length variation and anchors on energy absorption, a digital image correlation (DIC) study has conducted in quasi-static conditions.

2. Experimental procedure

2.1 Material and fabrication

Woven roving mat (WRM) glass fiber of areal density 360 g/m^2 was used as primary reinforcement and pseudoelastic shape memory alloy (PE-SMA), which is a NiTi alloy (i.e. 50 % of NiTi) of diameter 0.5 mm, was used as secondary reinforcement. Epoxy resin (LY556) and hardener (HY951) were used as matrix material in the weight ratio of 10:1. *Table 1*, *Table 2*, and *Table 3* summarize the properties of PE-SMA, glass fiber, and epoxy, respectively. Sample configurations are represented in *Figure 1*. PE-SMA was embedded in three different configurations in the composite laminates. The laminates were prepared using six layers of glass fibers and PE-SMA was embedded at the mid-plane of the laminate. The stacking sequence of the fiber mat and PE-SMA is shown in *Figure 1*. The distance between PE-SMA wires were kept approximately 4 mm such that a projectile can hit the wire in the primary impact region. Samples were prepared by the vacuum assisted resin infusion process. The laminates were allowed to cure for 24 hours under the vacuum pressure of 30 mm Hg. The samples of dimension 150 x150 mm were cut out using abrasive water-jet cutting. The weight percentage of PE-SMA was considered to be a maximum of 1% of the fiber weight.

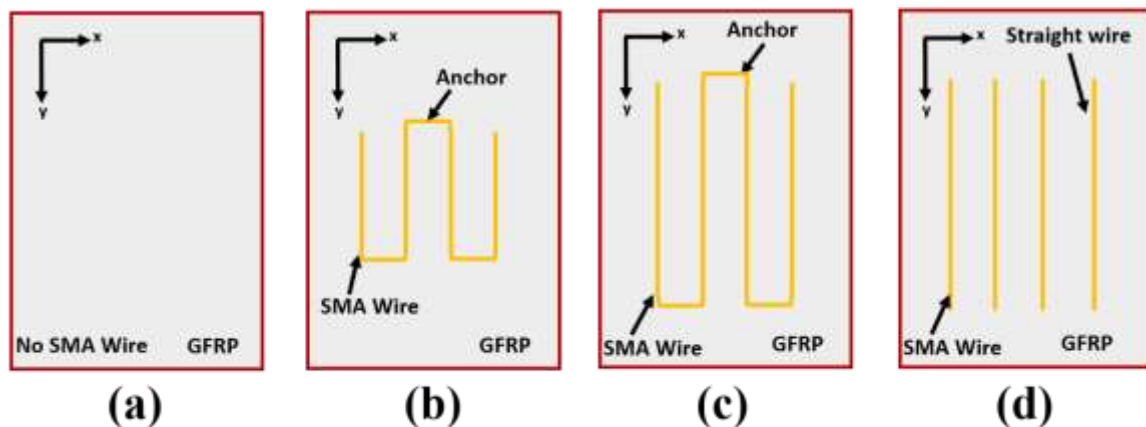


Figure 1: Schematics of different composite samples considered in this study (a) Type-I (b) Type-II (c) Type-III and (d) Type-V

Table 1: Material properties of PE-SMA

S.No.	Properties	Values (PE-SMA)	Units
1	E_{aus}	80	GPa
2	E_{mar}	40	GPa
3	Poisson's ratio	0.3	
4	Density	6800	Kg-m ³
5	Yield stress	800	MPa

Table 2: Material properties of glass fibers

S.No.	Properties	Values (PE-SMA)	Units
1	Young's modulus	76.6	GPa
2	Specific modulus	0.0340	GPa-m ³ /Kg
3	Specific strength	0.6200	MPa-m ³ /Kg
4	Poisson's ratio	0.25	

Table 3: Material properties of epoxy

S.No	Properties	Values	Units
1	Specific gravity	1.28	
2	Young's modulus	3.792	GPa
3	Poisson's ratio	0.30	

Table 4 summarizes the nomenclature of different samples considered in this study. In Type II, III, and IV samples, the PE-SMA wires were laid in between the GFRP layers as shown in *Figure 1S*. Type II and III samples were anchored, which means the PE-SMA wires were continuous and turned into U-shape at the ends so that they act as restrainers. The embedded PE-SMA length in Type II and Type III samples were 35 and 70 mm, respectively. In Type IV, four straight wires were laid without any connections between them. These changes in the configurations were done to find out the effect of anchored and unanchored configurations on energy absorption and failure modes of the GFRP composite laminates. The thickness of the samples was around (3.15±0.2 mm).

Table 4: Configuration details of different samples

S. No.	Configuration	Embedded PE-SMA length	Anchor types	Nomenclature
1.	Glass/epoxy (GFRP)	No SMA	Homogeneous	Type I
2.	35 mm SMA embedded GFRP	35 mm	Anchored	Type II
3.	70 mm SMA embedded GFRP	70 mm	Anchored	Type III
4.	150 mm SMA embedded GFRP	150 mm	Unanchored	Type IV

2.2 High-velocity impact tests

High-velocity impact tests were conducted on the GFRP samples using a gas-gun, as shown in *Figure 2*, at four different velocities (70, 85, 95, and 105 m/s). For each testing condition, four samples were tested. The target laminates were clamped from all four sides. A projectile of dia. 7 mm and mass 9 g was used to impact the clamped samples. The impact events were captured using two high-speed cameras of Phantom V611 at 50,000 fps. One of the cameras was used to measure the velocity of the projectile. The other camera was employed to capture the progression of damage in the GFRP samples. To calculate the delamination damage area of different samples Image J software was used.

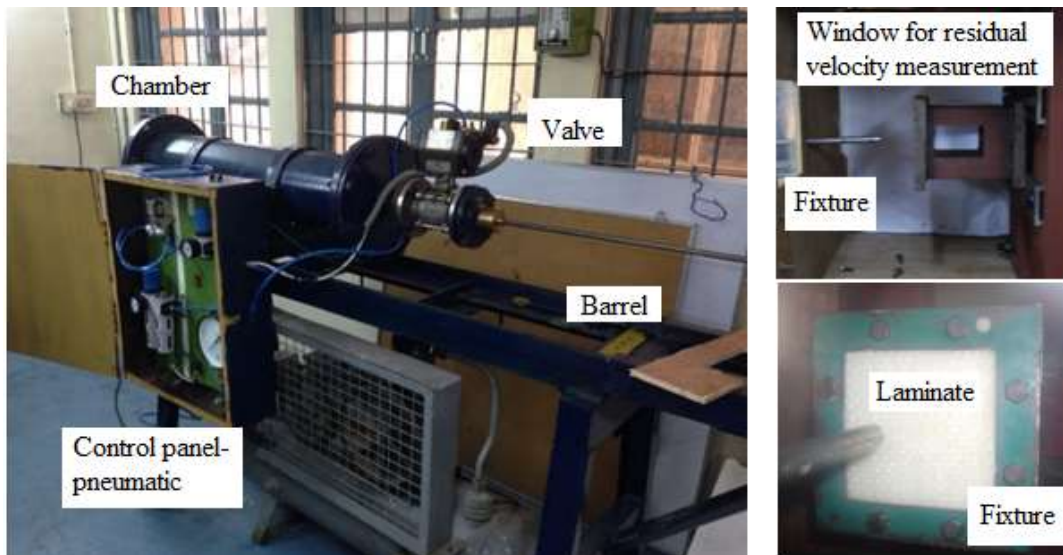


Figure 2: Gas gun experimental set-up used for impact testing on the composite laminates

2.3 Compression after impact test with digital image correlation (DIC)

INSTRON 8801 universal testing machine (UTM) of capacity 100 kN was used to perform quasi-static compression tests. Cross-head speed was maintained at 1 mm/min. *Figure 3(a)* shows the ASTM D7137M-12 CAI test fixture. To find out how damage profile varies in different GFRP configurations, the compression tests have been conducted along with digital image correlation (DIC). While performing the compression tests, images were acquired using image acquisition software Vic-Snap 2010 with a charge-coupled device (CCD) camera, as shown in *Figure 3(b)*, having a resolution of 1920x1080 pixels (Prosilica GX1910). The images were captured at a rate of 25 fps.

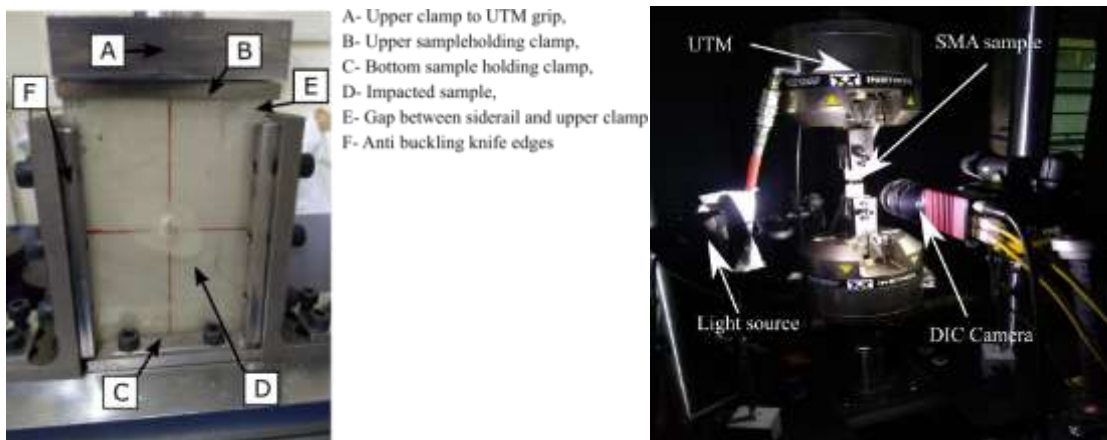


Figure 3: (a) Compression after impact (CAI) test set-up (b) Digital image correlation (DIC) test method

3. Results and Discussions

3.1. Damage progression in PE-SMA embedded GFRP composites

The schematics of different SMA failure modes are shown in *Figure 4*. When PE-SMA wire is embedded inside GFRP, energy absorption takes place predominantly due to SMA associated failure modes in addition to the conventional failure modes (matrix cracking, fiber/matrix debonding, fiber breakage, etc.). The SMA associated failure modes include SMA deformation, SMA anchor displacement, and SMA pull-out. In the presence of PE-SMA as a secondary reinforcement, these SMA failure modes get activated in a sequence. *Figure 5* shows the sequence of failure modes in a PE-SMA embedded GFRP under high-velocity impact load.

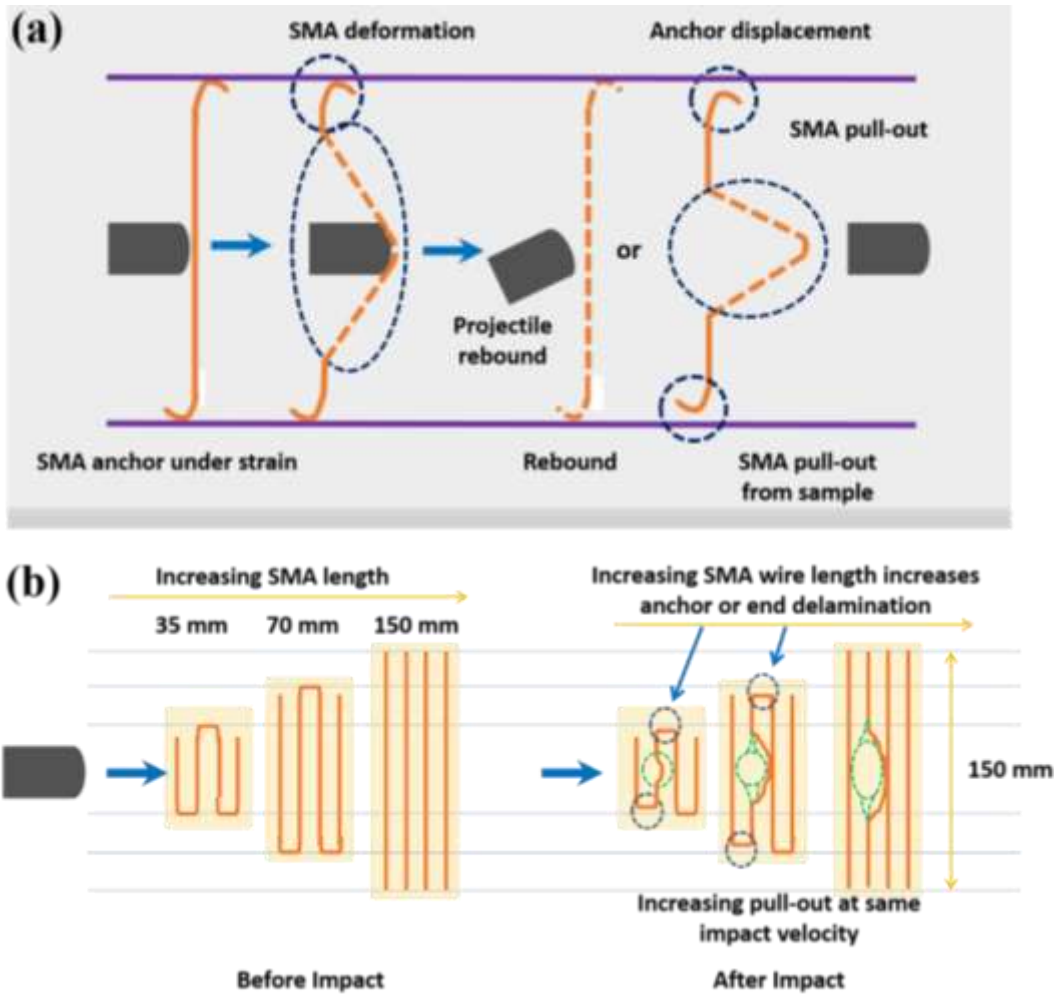


Figure 4: Schematics showing (a) different SMA associated failure modes under high-velocity impact load (failure modes include SMA deformation, SMA anchor displacement, and SMA pull-out) and (b) change in failure profile with SMA configuration.

Damage progression on the back face is shown using a high-speed camera, with *Figure 5 (a)*, is the first image, which captures the frame when the projectile is about to hit the sample. As shown in *Figure 5* and *Figure 6*, due to PE-SMA embedment, delamination progresses predominantly along with the SMA wire, which is generally not the case for homogeneous GFRP [41]. When a projectile impacts the composite and comes in contact with PE-SMA wire, it starts undergoing deformation, and the region away from the primary impact region encounters strain due to this deformation. The limiting strain value at which the PE-SMA wire displaces is lesser than that of the plastic strain and depend on the embedded SMA configuration. This factor leads to changes in the delamination area depending upon impact velocity and pull-out extent.

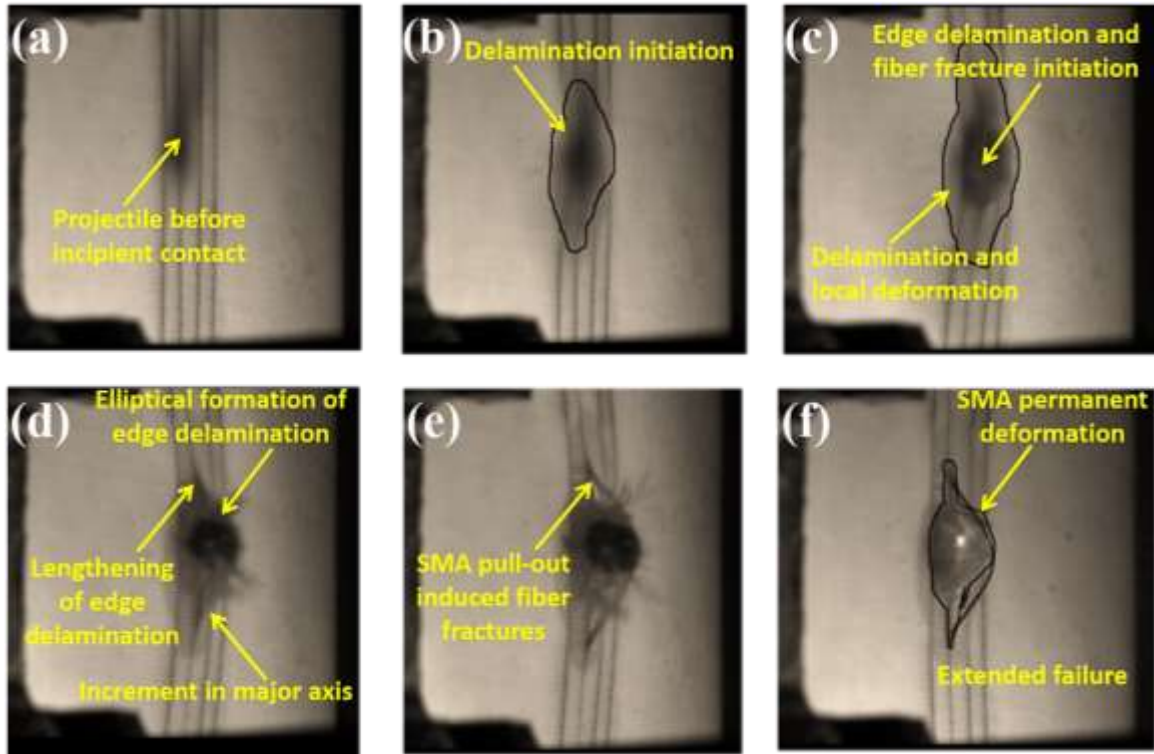


Figure 5: (a-f) Sequence of images showing typical damage progression in a SMA embedded composite under high-velocity impact.

In Type II and III samples, due to the presence of anchors, SMA pull-out is highly restricted or constrained (*Figure 6(a)*). SMA deformation in and around the primary impact region undergoes a higher amount of strain because of anchors, as bonding between GFRP and PE-SMA wire is strong in the anchored area, as shown in *Figure 4*. As the strain increases further in the wire, it reaches a limiting value beyond which anchors displace, indicating a bearing failure. The moment when anchor displacement failure mode takes place, SMA pull-out failure mode happens in the impact region. If SMA pull-out occurs, it will lead to a large amount of energy absorption. The reason is that pull-out is preceded by the SMA deformation and the anchor displacement.

As projectile penetrates further (*Figure 5 (c-f)*), due to the SMA pull-out, extended fiber fracture and edge delamination (*Figure 2S*) take place in the primary impact zone and along the PE-SMA wire. This event leads to a change in the damage profile (aspect ratio) of the SMA embedded samples in comparison to that of the homogeneous GFRP ones. In the homogeneous GFRPs, the extend of edge delamination and fiber fracture depends on the projectile diameter and happens around the region fractured by the projectile. Edge delamination in Type I

configuration is circular, as shown in *Figure 6*. In contrast, in SMA embedded GFRPs, there is a shape change of edge delamination failure mode from circular to elliptical even before the pull-out. This shape change is due to an increase in edge delamination failure mode along the embedded SMA, termed as a major axis, as shown in *Figure 5* and *Figure 6*.

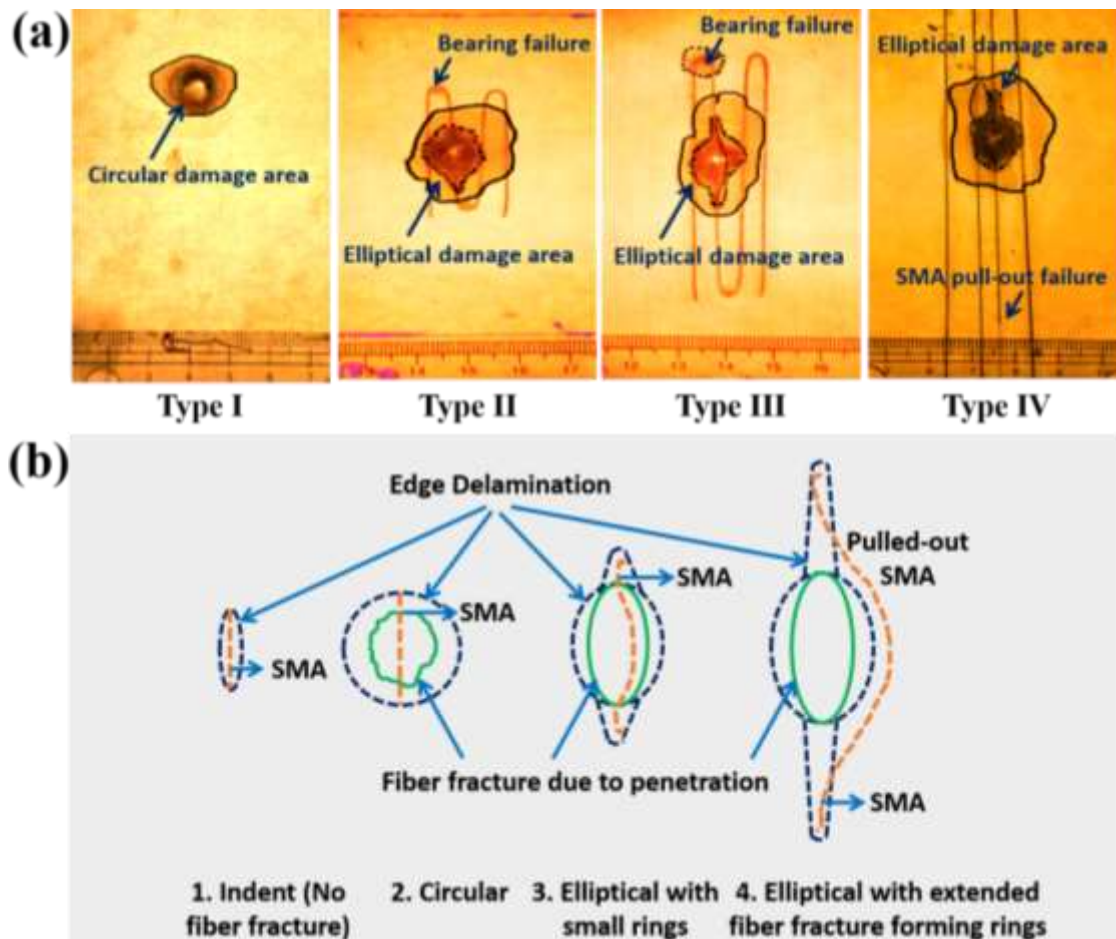


Figure 6: (a) Post-impact photographic images showing typical damage profiles in different GFRP samples and (b) schematic of change in fiber fracture and edge delamination due to change in SMA pull-out. Either increase in velocity or SMA length changes extend of edge delamination and fiber fracture failure mode.

The damage growth in the minor axis is very less in comparison to that in the major axis. Thus, leading to the formation of an elliptically shaped edge delamination. This delamination growth in the major axis is due to the contact of the projectile with SMA and its effort to pull-out the SMA. As the projectile leaves the sample, there is an SMA pull-out failure mode, which is visible as in *Figure 5 (f)*, due to permanent damage encountered by SMA in the primary impact region. At the impact point, PE-SMA wire undergoes the maximum strain value leading to

their permanent deformation or damage. This permanent deformation of the PE-SMA wire can be verified from the SEM image shown in Figure 7.

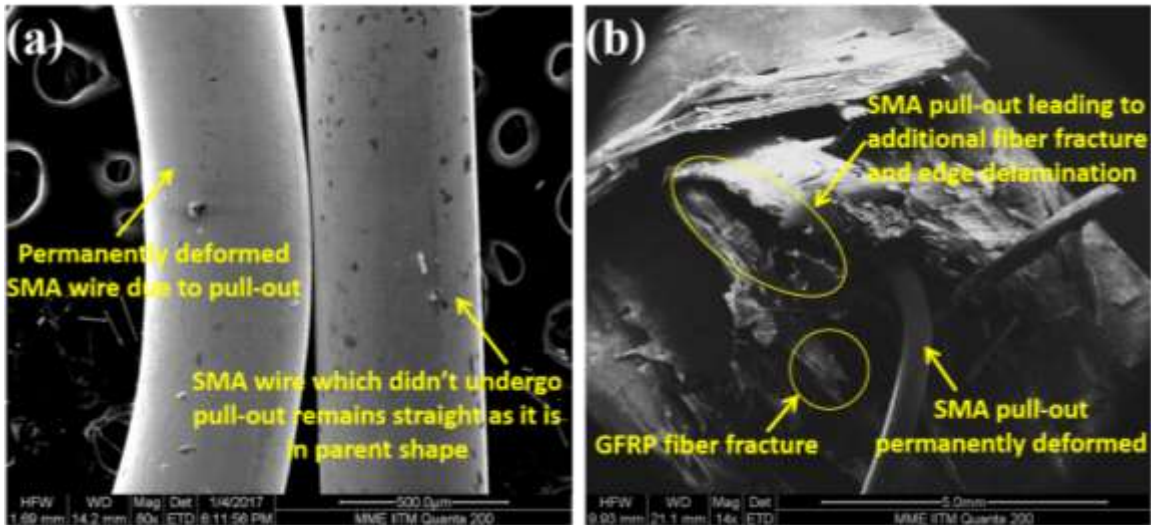


Figure 7: SEM micrographs showing (a) typical SMA pull-out, and (b) different damage modes.

3.2. Effect of employing anchors in embedded SMA on the overall delamination area

Figure 8 depicts the post-impact photographic images of different GFRP samples impacted at velocities 70, 85, 95, and 105 m/s. These figures clearly show the effect of impact velocity and SMA configuration on the SMA pull-out and other major failure modes. The overall delamination area is affected when PE-SMA is embedded in GFRP, in comparison to the homogeneous GFRPs. In the Type I samples, the overall delamination area decreases with increasing impact velocity (Figure 9), as it is maximum at 70 m/s and a minimum at 105 m/s. On the other hand, for the PE-SMA based samples, the overall delamination area increases with an increase in velocity. At higher impact velocities, SMA leads to an increase in damage due to the delamination induced by the pull-out. Moreover, PE-SMA configuration embedded in a GFRP plays an important role in the overall pull-out length. Table 5 summarizes the average SMA pull-out length of different impacted GFRP samples calculated via the digital image processing technique. Among the PE-SMA based samples, the Type II samples show the least delamination area. This can be attributed to the small embedded PE-SMA length and placement of anchors near the primary impact region (so the pull-out length is less in Type II). As shown in Figure 9 and Table 5, increasing embedment length across Type II to IV lead to an increase in pull-out. Thus, when strain increases, in Type III configuration, the

anchor displaces much earlier than in Type II configuration, leading to an increase in pull-out length at the same velocity.

At 70 m/s, though projectile rebounded for Type II and III configurations, there is a permanent dent that is visible on PE-SMA wire (*Figure 8*). Thus without getting pulled-out, the projectile permanently deformed the length of wire equal to the projectile diameter. The same is true for Type II at 85 m/s. Once, anchor displacement happens in any configuration, a further increase in velocity leads to a rise in the pull-out. For Type II configuration, impact velocities 70 m/s and 85 m/s are below the ballistic limit. At these velocities, much anchor displacements are not observed. But for Type III, the projectile penetrated at 85 m/s, and anchor displacement is observed. Thus, at the same velocity, anchor displacements change with SMA configuration. Also, at higher impact velocities, the anchor displacement due to pull-out is less for Type II. Due to this, the delamination area is smaller in Type II.

It has been observed that deformation in the PE-SMA wire is higher in the anchored configurations (Type II, III) in comparison to the unanchored ones (Type IV). The deformation in anchored configurations continues in the wire until it reaches a strain where the anchor cannot hold anymore inside the GFRP. For Type IV, as anchors are not there (embedded wire is straight and not connected) and the PE-SMA length is also higher, the wire displaces at a load value much less than that at which displacement of the anchored configuration can take place. This will lead to an increase in the pull-out length (easy to displace the wire from the GFRP) and perhaps decreases the energy absorption. With more pull-out length, damage in the sample due to interlaminar separation (delamination) of the layers increases (*Figure 8*).

Thus, it can be said that, at higher velocities, in all the SMA based configurations the delamination area increases, while in Type I samples it decreases. The overall delamination area will decrease with a decrease in embedded SMA length at the same velocity. Among the PE-SMA embedded configuration, Type II is the most effective as the delamination area remains the minimum at all velocities.

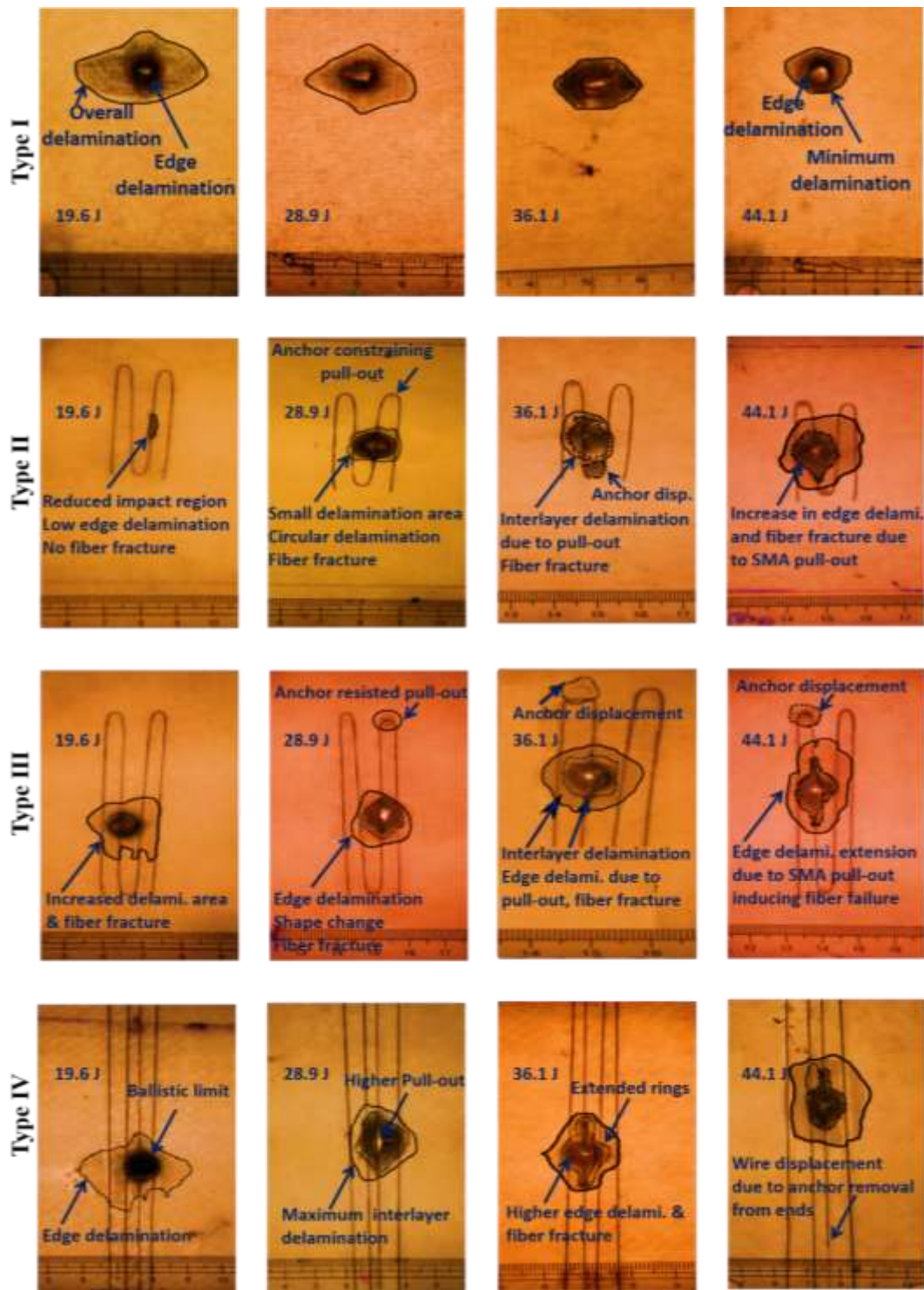


Figure 8: Damage due to various failure modes in Type I, Type II, III and IV configurations at respective energy levels of velocity 70 m/s, 85 m/s, 95 m/s and 105 m/s. (Energy levels 19.6, 28.9, 36.1 and 44.1 J corresponds to impact velocities 70, 85, 95 and 105 m/s, respectively).

Table 5: Pull-out length in different SMA embedded configurations at different velocities.

S. No.	Velocity (m/s)	Pull out length (mm)		
		Type-II	Type-III	Type-IV
1	70	8	8	11
2	85	8	12	14
3	95	12	15	20
4	105	15	18	24

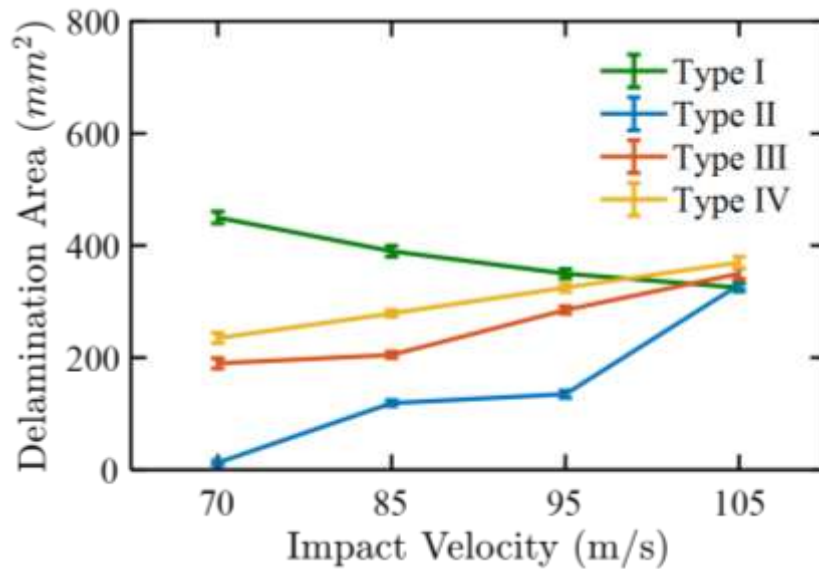


Figure 9: Overall delamination area versus impact velocity plot for different GFRP samples impacted at velocities 70, 85, 95, and 105 m/s.

3.3. Ballistic limit (penetration velocities)

Table 6 summarizes the residual velocity for different types of GFRP samples at various impact velocities 70, 85, 95, and 105 m/s. For the Type I sample, all the four impact velocities are above the ballistic limit. On the other hand, when PE-SMA wire is embedded, the ballistic limit increases. Besides, varying the embedment configuration, such as SMA length and presence of anchors, changed the ballistic limit. For Type II, Type III and

Type IV samples, the ballistic limit is 95, 85, and 70 m/s, respectively, as the projectile rebounded (Figure 8). These limits are significantly higher than that of Type I, where projectile penetration occurred at 55 m/s.

Table 6: Rebound and residual velocities after high-velocity impact for different configurations

Initial velocity (m/s)	Energy (J)	Sample No.	Residual velocity (m/s)			
			Type I	Type II	Type III	Type IV
70	19.6	1	27.56	26.25 (Rebound)	20.00 (Rebound)	0 (Ballistic limit)
		2	28.58	25.94 (Rebound)	22.20 (Rebound)	0 (Ballistic limit)
		3	28.89	25.25 (Rebound)	21.10 (Rebound)	0 (Ballistic limit)
		4	28.12	24.54 (Rebound)	21.20 (Rebound)	0.16 (Rebound)
85	28.9	1	57.56	31.90 (Rebound)	23.89	54.60
		2	57.20	32.50 (Rebound)	24.13	55.00
		3	58.84	33.68 (Rebound)	24.6	53.10
		4	57.90	32.39 (Rebound)	25.372	55.50
95	36.1	1	72.97	40.25	34.2	58.25
		2	73.3	43.75	37	57.67
		3	73.6	43.92	35.41	56.92
		4	72.02	42.95	36.2	60.00
105	44.1	1	87.54	52.00	51.90	67.42
		2	86.07	54.40	52.49	69.02
		3	86.92	52.60	50.70	65.17

3.4. Total energy absorption

Figure 10 shows the plot of absorbed energy versus velocity for different GFRP samples. The absorbed energy has been calculated by finding out the projectile velocity before and after the impact using a high-speed camera (the difference between the initial and residual kinetic energies) [42]. The ballistic limit for GFRP is estimated to be 55 m/s. At higher velocities, the amount of absorbed energy decreases. The reason behind this can be attributed to the decrease in the conventional failure modes such as delamination (i.e. more localized damage), as shown in Figure 8. Embedding PE-SMA wire within GFRP leads to a relatively higher absorbed energy. At 70 m/s, the Type IV sample absorbs the maximum impact energy as it is the ballistic limit for the same. As impact velocity increased, the absorbed energy of the Type IV sample decreases (similar to Type I).

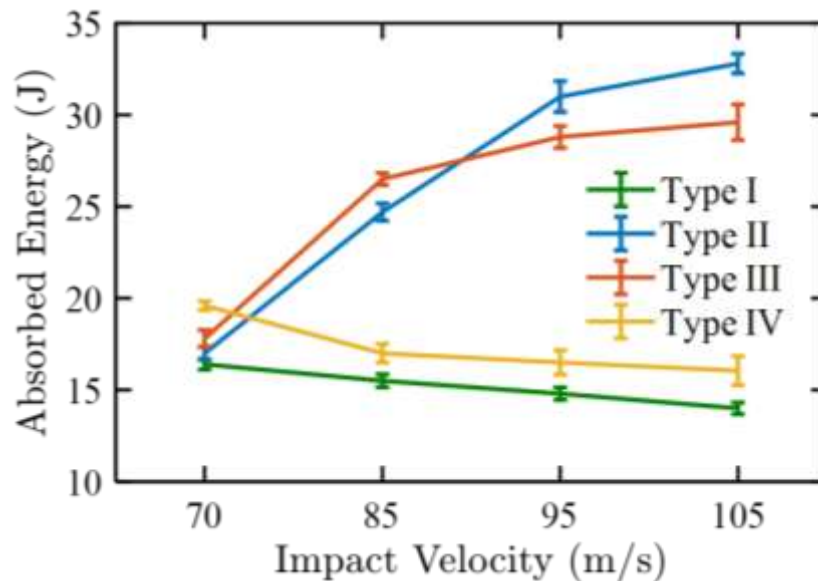


Figure 10: Absorbed energy versus impact velocity plot for different GFRP samples impacted at velocities 70, 85, 95, and 105 m/s.

Unlike the Type IV sample, the absorbed energy increases from 70 to 105 m/s in Type II and Type III samples. The impact velocity 70 m/s is below the ballistic limit for both the configurations. At 85 m/s and above, the absorbed energy increases further because of the SMA pull-out (Figure 8), in which anchors have to displace

unlike Type IV. At 95 m/s and above, the absorbed energy of Type III was lower than that of Type II due to higher impact damage in the sample (*Figure 8*). As anchors are not present in Type IV samples, SMA pull-out failure mode happens easier in comparison to other PE-SMA wire embedded configurations. Hence, energy absorption in Type IV configuration is minimum among all the SMA based samples. With the help of these investigations, it can be concluded that the smaller the anchored embedment length, the higher will be the ballistic limit.

3.5. Compression after impact (CAI) test

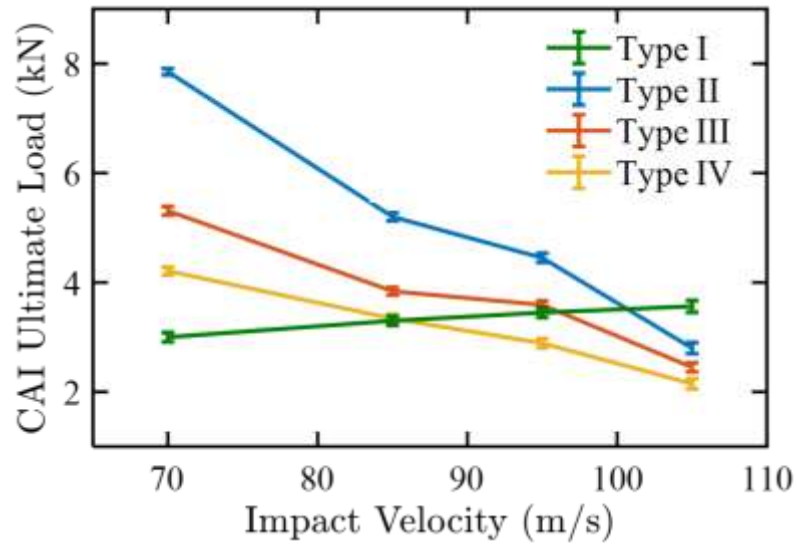


Figure 11: Ultimate compression load versus impact velocity plot for different GFRP samples impacted at velocities 70, 85, 95, and 105 m/s.

During impact, when the PE-SMA wire is pulled out, failure modes such as fiber fracture and interlaminar separation near the region in which pull-out has taken place increases, as evident in *Figure 8*. With an increase in these failure modes in and around the primary impact region, residual strength decreases. The role of different PE-SMA embedment on the residual strength of the impacted samples is evaluated via compression after impact (CAI) tests. The ultimate compression load of different samples at various impact velocities are shown in *Figure 11*. *Figure 12* shows the post-impact compressive damage profile of different samples at various impact velocities.

For an impact velocity of 70 m/s, the projectile rebounds for Type II and III configurations (*Figure 8*). Since the damage was smaller for Type II, the compressive strength is expected to be higher, as seen in *Figure 11*.

For the Type IV sample, the compressive strength is the lowest in comparison to the other two SMA based configurations. The reason is the maximum damage due to impact occurs in Type IV samples compared to Type II and Type III ones at the same impact velocity. With a further increase in the impact velocity, the compressive strength decreases for all three SMA configurations. This response is because of an increase in the number of operative failure modes, as explained earlier in Sections 3.1 and 3.2. The main factor determining the compressive strength is the intensity of failure modes in and around the primary impact region. For PE-SMA embedded samples, the SMA pull-out becomes a major factor in determining the compressive strength as it induces and exacerbates the failure modes such as interlaminar separation, fiber fracture, and edge delamination. Thus, the higher the pull-out length, the greater will be the interlayer separation (*Figure 12*). Due to this interlayer separation, initiation of local buckling takes place from the primary impact region during compression (in all the impacted samples). On the other hand, for the Type I sample, the delamination area decreases at higher velocities, as shown in *Figure 8*, leading to an increase in the compressive strength.

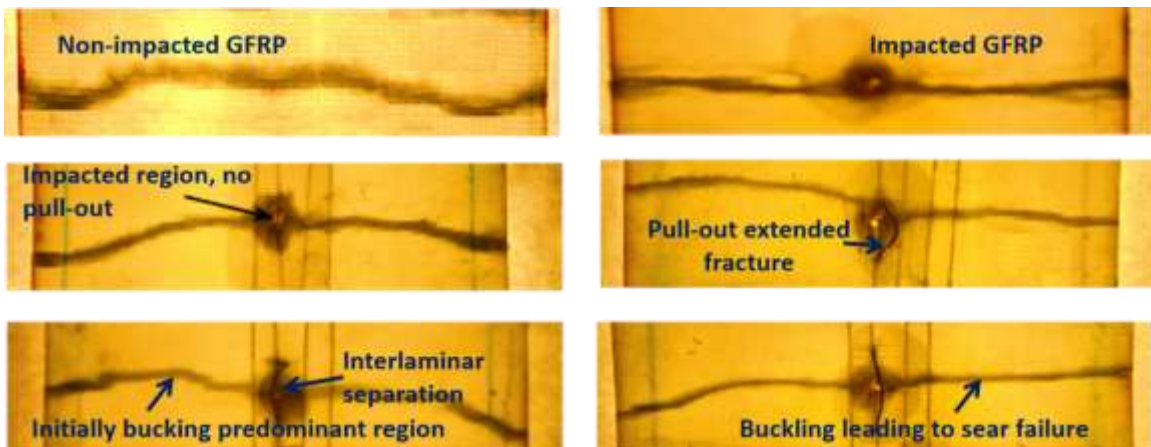


Figure 12: Photographic images showing typical damage modes in different GFRP samples subjected to CAI test.

4. Conclusions

In this paper, the compression after high-velocity impact (CAI) behavior of pseudo-elastic shape memory alloy (PE-SMA) embedded glass/epoxy composite laminates manufactured via vacuum-assisted resin infusion (VARI) technique was studied experimentally. High-velocity impact tests were performed on the glass/epoxy composites at four different velocities (70, 85, 95, and 105 m/s). Three different types of embedment configurations

of PE-SMA wire, namely, with length variation (35, 70, and 150 mm) and also with and without anchors, were used. This study presents the following important conclusions:

1. Embedding PE-SMA wire in GFRPs increases the ballistic limit. Besides, varying the embedment configuration, such as SMA length and presence of anchors, changed the ballistic limit. For Type II, Type III and Type IV samples, the ballistic limit is 95, 85, and 70 m/s, respectively. These limits are significantly higher than that of Type I, where projectile penetration occurred at 55 m/s.
2. At higher velocities, in all the SMA based configurations, the delamination area increases, while in the Type I samples, it decreases. At higher impact velocities, SMA leads to an increase in damage due to the delamination induced by the pull-out, while Type I samples show more localized damage.
3. An increase in the embedment length across Type II to IV leads to a raise increase in the overall delamination area at the same velocity. Among the PE-SMA embedded configuration, Type II is the most effective as the delamination area remains the minimum at all the impact velocities.
4. In Type II and III samples, due to the presence of anchors, SMA pull-out is highly restricted or constrained. SMA deformation in and around the primary impact region undergoes a higher amount of strain because of anchors, as bonding between GFRP and PE-SMA wire is strong in the anchored area.
5. For Type IV, as anchors are not there (embedded wire is straight and not connected) and the PE-SMA length is also higher, the wire displaces at a load value much less than that at which displacement of the anchored configuration can take place. This feature led to an increase in the pull-out length (easy to displace the wire from the GFRP), and thus decreases the energy absorption.
6. CAI results indicate that the PE-SMA based composites have better damage tolerance with respect to the homogeneous ones at 70 m/s. In contrast, at higher velocities, the delamination area decreases in the homogenous glass/epoxy composites due to more localized damage and present a higher compressive strength.

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