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Mechanical response of Shape Memory Alloys based hybrid composite subjected to low velocity impacts

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Abstract

One of the most common problems with composite materials is their low resistance to impacts with foreign objects because of their tendency to dissipate impact energy through internal delamination, weakening a large area of the structure. One of the possible solutions to increase impact resistance is to use of shape memory alloy wires in order to exploit their unique superelastc behaviour and the hysteresis that characterises their stress-strain curves. In this work, composite laminates where hybridised by embedding a network of SMA within the laminate structure and subjected to low velocity impact in order to analyse their response in comparison with a traditional composite. Ultrasonic C-Scan analysis was undertaken on the samples after the impact, in order to estimate the extension of the internal delamination. Results show that the SMA wires embedded in the laminate are able to absorb a large amount of energy, reducing the extension of the internal delamination.

1. Introduction

In recent years, laminated composites have replaced traditional structural materials for many structural applications, especially in the field of aircraft engineering, because of their high mechanical properties and very low weight. However, because of their weak resistance to through-the-thickness impact loading, these materials are susceptible to delamination damages under impact loads that can compromise the integrity of the entire structure.

Unlike metals, in which a surface dent will only increase strain hardening locally, for composite materials even at the barely visible level, impact damages are associated with the separation of interior plies, and therefore they must be avoided.

Over the past years, a considerable amount of research has been devoted to evaluate an effective solution to this problem, in order to improve impact resistance of composite structures. According to these researches, this can be achieved following two different approaches, depending on the kind of intervention on the composite structure. A first approach is to modify one of the components of the material in order to increase its specific properties, reducing its weaknesses, thus improving the compatibility between the different phases that form the composite material. Strengthen mechanisms such as matrix toughening [1], interface toughening [2] and fibres surface modification [3] belong to this category as they operate increasing the properties of the existing phases within the material structure. On the other hand, a different approach consists of "hybridise" the composite by adding additional components within its structure that can improve impact resistance without affecting the other (desirable and needed) mechanical properties. There are many different component that can be included within the laminate such as hollow fibres [4], single and multi-walled carbon nanotubes [5, 6], graphene nanolayers [7] and through-the-thickness reinforcement [8]. Among those, a very important category is represented by fibre-metal laminates (FMLs) which are hybrid systems based on thin metallic layers bonded together by several intermediate fibre/epoxy layers [9]. Because of the advantages generated by their hybrid nature, these materials have attracted the interests of a large number of researchers, leading to several commercially available products especially aimed towards aerospace applications such as: Glass Reinforced Aluminium Laminates (GLARE) [10, 11], Aramid Reinforced Aluminium Laminates (ARALL) [12, 13] and Carbon Reinforced Aluminium Laminates (CARALL) [14].

Another possible solution is to hybridise the composite by embedding shape memory alloy (SMA) wires because of their superelastic behaviour. Indeed, the particular properties of SMA rise from the transition from austenite to martensite which is activated when the material is subjected to a load. The phase transformation generates a plateau region in the stress-strain curve, resulting in an hysteretic behaviour of the material. This unique property makes SMA able to absorb more energy during an impact event and can increase the damage impact resistance of a composite part when they are embedded within its structure. The aim of this work is to investigate the mechanical behaviour of SMAs based hybrid composite panels, by analysing their response to low velocity impacts (LVI). The peak force, displacement and energy absorption have been evaluated for hybrid panels subjected to impact with different energy levels and compared with a traditional laminate. The results obtained from the impact tests have been interpreted with the correspondent internal delamination extents gathered using an ultrasonic scanning technique in order to understand the differences in the energy dissipation mechanisms between the hybrid and the traditional laminates.

2. SMA-Composites

The idea of using SMA as reinforcement for composite panels was first proposed by Rogers in 1988 [15]. A comprehensive review of the state of the art of SMA hybridised composites for the purpose of damage suppression has been undertaken by Angioni et al [16]. Paine and Rogers [17] investigated experimentally the possibility to exploit the superelasticity of SMA for improving the impact resistance of composite parts subjected LVI. Impact tests with 18 and 23 J were conducted on samples manufactured with a cross-ply layup of graphite/bismaleide hybridised with Nickel Titanium (NiTi) wires in the lower 0º/90º interface. Their results showed that the presence of the SMA within the composite structure prevented the samples to be completely perforated and reduced the internal delamination area in comparison with a traditional graphite laminate. Moreover they determined that the peak impact forces of the hybrid samples were much higher than the ones recorded for the un-reinforced material. The study conducted by Birman et al. [18] investigates the design optimisation of hybrid cross-ply composite laminates, concluding that the embodiment of SMA fibres enhances impact resistance and that a further improvement can be given optimising their distribution throughout the structure. Khalili et al. [19] developed a complete model for studying the effect of an impact on a smart hybrid composite with or without prestrain in the SMA wires. Results have demonstrated that the hybrid composite damps more uniformly and rapidly than the unreinforced sample for thin laminates, while no positive effect was seen for thick laminates. Moreover, they observed that the volume of SMA wires within the composite plays a key role as it can affect maximum contact force, maximum contact force time and contact time during an impact event. The study conducted by Tsoi et al. [20] analysed the effect of several aspect that need to be taken in account when looking at the impact damage behaviour of hybrid composites, such as prestrain rate, SMA positioning and density. They find out that increasing the prestrain of the SMA wires, the internal delamination area decreases; moreover, in order to improve the resistance to damages caused by fibres breakage it is preferred to embed the SMA wires in the lower half of the sample.

2.1 *Superelasticity*

A superelastic shape memory alloy is characterised by the property of being completely deformable at room temperature and to return to its original shape when the load is removed [21]. This unique capability allows this kind of materials to absorb and dissipate energy more than any other metallic wire, and it is activated by the thermoelastic phase transition between two different crystalline structures: austenite (A) and martensite (M). This mechanism is defined as *diffusionless* as it does not involve any chemical modification of the material but only a rearrangement of the crystalline structure at the lower energy configuration for a given temperature. In normal conditions, an SMA starts to change its structure in martensite when it is cooled down below a temperature Ms so that when a temperature Mf is reached the material is in its fully martensitic phase. On the contrary, the reverse crystalline modification (from M to A) is activated when the material is heated up above a certain temperature As and ends when a temperature Af is reached. However, when the material in its austenitic form is subjected to a load, it is possible to activate the formation of martensite even above the Mf, generating the so called Stress-Induced Martensite (SIM) which is able to withstand higher macroscopic deformations due to its crystalline structure. The effect of this phase transition can be observed on a stress-strain curve as a plateau region, in which the material increases its strain at a constant stress level. Above a certain temperature (Mf) SIM cannot be generated as the energy required for its formation is higher than that needed to move internal dislocations.

When a load is applied to an alloy which is at T>Af, the SIM transformation occurs and the material is able to withstand higher strain deformations. When the load is removed, since the martensite is not stable at this temperature, the reverse transformation (from SIM to austenite) is activated and the material recovers its initial shape.

3. Experimental

3.1 *Sample Manufacturing*

Hybrid composite panels were manufactured by Alenia Aeronautica S.p.A. embedding an aramid warp knitted biaxial tape reinforced with SMA wires within a thermoplastic Polyphenylene Sulfide/Carbon fibres (PPS/CF) laminate. The wires were trated in a proprietary manner to improve the adhesion with the fibres. The samples were produced via compression moulding technique. As it is possible to observe from Figure 1, which represents the lay-up schematics for the hybrid composite, the SMA/aramid plies are sandwiched between two extra layers of PPS in order to ensure a good impregnation of the SMA wires with the thermoplastic matrix.

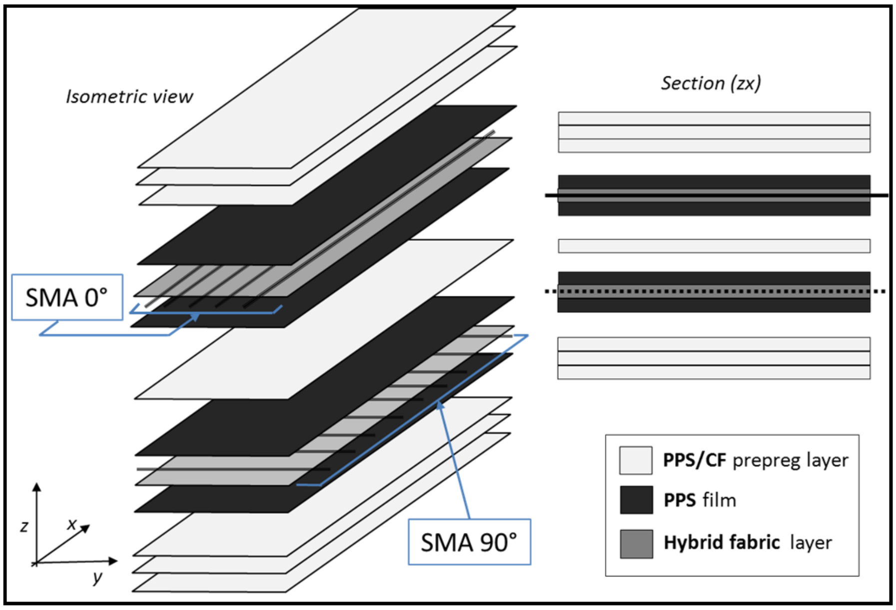


Figure 1 - manufacturing schematic of PPS/CF SMA hybrid composite

In order to analyse the improvement of the impact properties of the SMA based hybrid composite, a traditional PPS/CF laminate has been also manufactured and used as a baseline. After the forming process, composite plates were cut to 100mm squares with a thickness of 2.6mm using a diamond cutter.

3.2 *Experimental Analysis*

Multiple Low velocity impact tests (four for each sample typology) were conducted using a drop tower equipped with an hardened steel head (20mm hemispherical head and force-time history were acquired using a load cell (Kistler). The impactor assembly has a total mass of 12.6 kg and it is lifted using a winch and released via remotely activating a solenoid connected with two quick release pins. The values for impact impact Energy (E_{imp}), height of the falling mass (h_{imp}) and impact velocity (v_0) are summarised in Table 1 together with the specifications for the impactor.

The impact height h_{imp} was calculated from the equation: $E_{imp} = mg\,h_{imp}$, where g is the acceleration due to gravity (~9.8ms^{-2}). Velocity of the impactor (v_0) is independent from the mass and can be calculated from the conservation of energy (neglecting the drag force caused by air resistance), obtaining: $v_0 = \sqrt{2gh_{imp}}$.

E_{imp} *(J)*	h_{imp} *(m)*	v_0 *(m/s)*
20	0.16	1.7
30	0.24	2.1
40	0.32	2.5
Impactor mass (*kg*)	head geometry	head diameter (*mm*)
12.6	hemispherical	20

Table 1 - specification for LVI tests

Samples were clamped on the edges using several miniclamps on a steel frame in order to reduce the chance of movement or vibration of the sample during the impact (see Fig

2a). It is important to underline that the type of clamp used strongly affects the final results, therefore tests obtained using different clamping conditions may be different [22].

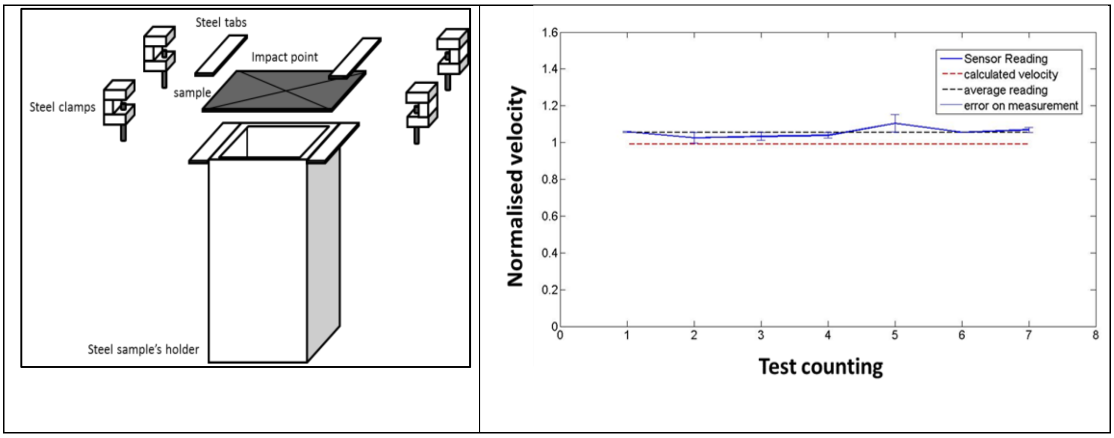


Figure 2 – a) Clamping condition used during impact tests; b) difference beween theorical and measured velocity during the impact tests

The impactor rig has been accurately manufactured in order to reduce as much as possible the drag exerted by the rails. This has been experimentally evaluated for low impact heights with using a uLog USB Light Gate Sensor (see Fig 2b), while when very high energy levels are required (higher heights), the falling mass may come in contact with the rails because of some instabilities, thus affecting the reading and the effect must be taken in account. Because the energies involved in this work are moderately low and the impactor is characterised by a relatively large mass it is possible to assume that the falling mass does not touch directly the rails and the only effect that could affect the velocity is the friction with air.

In order to evaluate acceleration, velocity and displacement history during the impact, a numerical method has been applied. Indeed, the velocity of the impactor v(t) can be obtained by integrating the force history (F_{imp}) following the equation:

$$v(t) = v_0 - \frac{1}{m}\int_{t_0}^{t} F_{imp}\, dt \ .$$

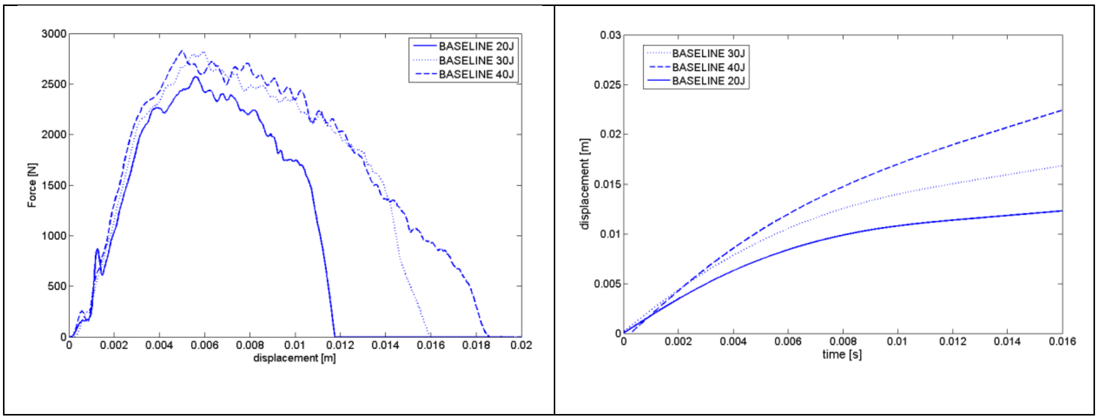
In the same way, the displacement can be calculated by integrating the velocity history. Based on the values of velocity, it is possible to evaluate the energy history transferred from the impactor to the composite sample by solving the equation:

$$KE(t) = \frac{1}{2}mv_0^2 - \frac{1}{2}m(v(t))^2.$$

According to several authors [23-25], ultrasonic technique can be used to evaluate the size of the projected damage area, in order to identify the principal fracture mechanisms that occurs when a composite panel is subjected to a LVI. C-Scan is a non-destructive technique that uses a piezoelectric probe to send ultrasonic waves through a sample and measure the reflected signal obtained when a barrier like a defect or the back of the sample is reached. Analysing the difference between the signal sent and the one collected by the detector it is possible to assess the delamination region within a laminate. In this work, a pulse-echo ultrasonic scanning analysis was carried out by using a probe with a frequency of 5MHz set to scan the entire area of the sample with an increment of 500μm.

4. Results and Discussion

Result obtained from the impact test are shown in Fig 3 and 4, which represents respectively the data collected for the PPS/CF samples and those for the PPS/CF+SMA hybrid composites.



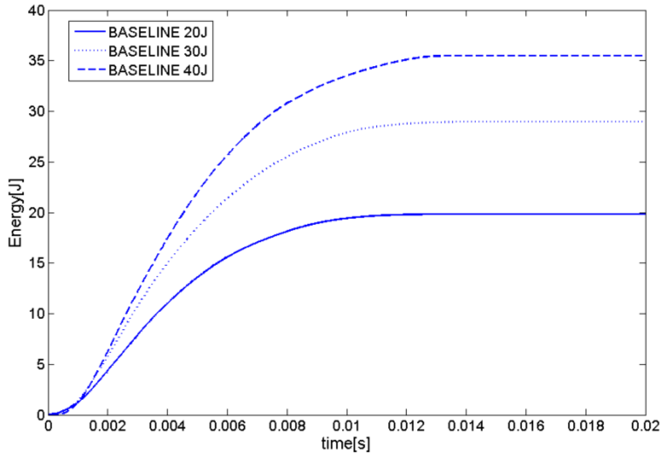
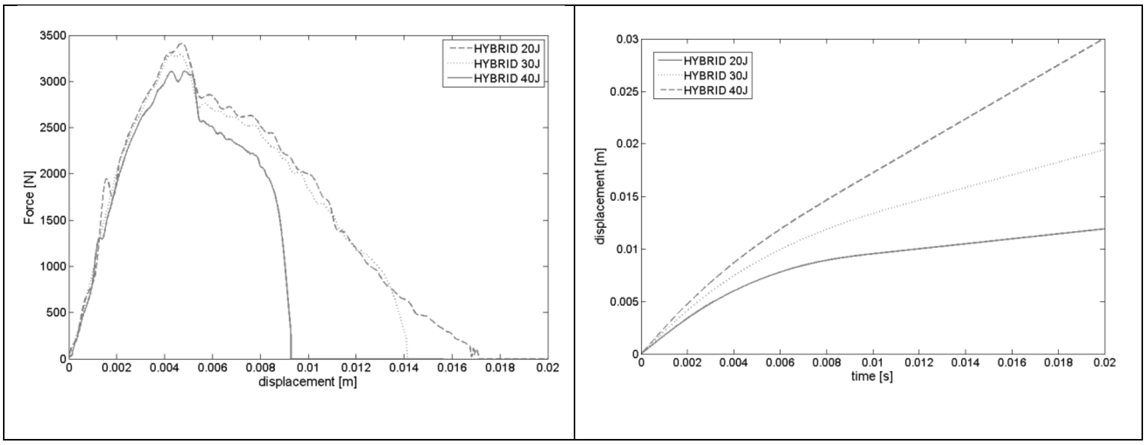


Figure 3 - data results for baseline (PPS/CF) samples: a) force displacement behaviour; b) time displacement; c) Energy absorption history

Fig 3a represents the typical force/displacement curves for impacts on the baseline samples with three different impact energies (20, 30 and 40J). As it is possible to observe from the curves, the force peak reaches higher values when the energy of the impact increases. Indeed, moving from 20J impact to 30J, the maximum force recorded during the impact event shows an increase of ~9%, while for the higher energy impact (40J) there is almost no improvement (~0.7%).



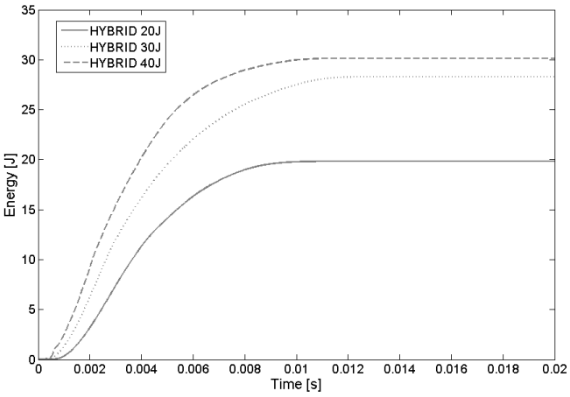
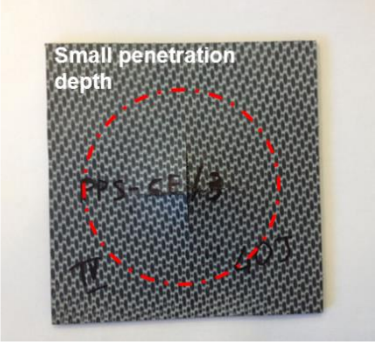
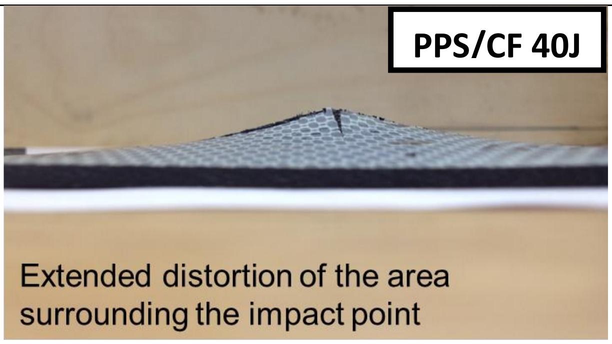


Figure 4 - data results for hybrid (PPS/CF+SMA) samples: a) force displacement behaviour; b) time displacement; c) Energy absorption history

A similar trend can be observed in Fig 4a for the impacts on the hybrid samples, in which it is possible to observe that the maximum force is increased by 6% in the passage between 20 and 30J and by an additional 4% for the 40J impact.

Analysing Fig 3b and 4b, which represent the behaviour of the displacement recorded from the instrumentation during the impact time for both the unreinforced and hybrid composites, it is possible to see that for all the tests the impactor penetrated through the sample thickness without any elastic rebound. The penetration depth however, reaches higher values for higher energy levels as the number of fibres that are actually broken by the impactor head increases taking the more the shape of a ‘volcano’.





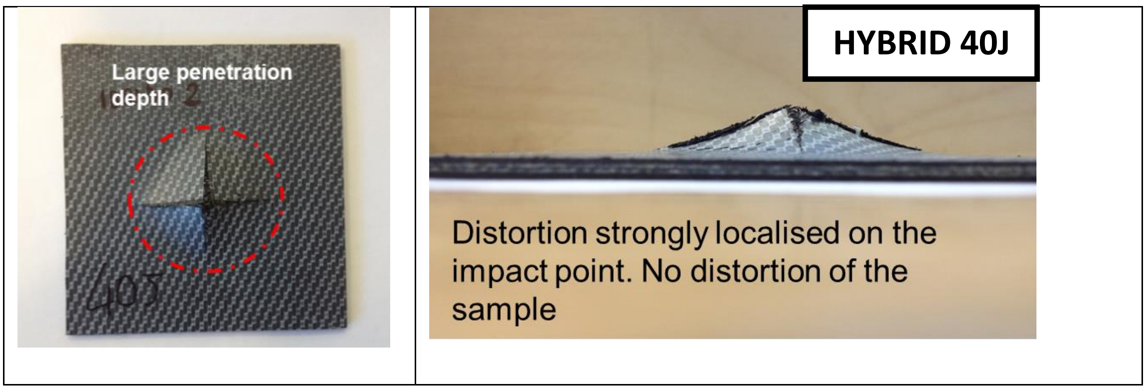
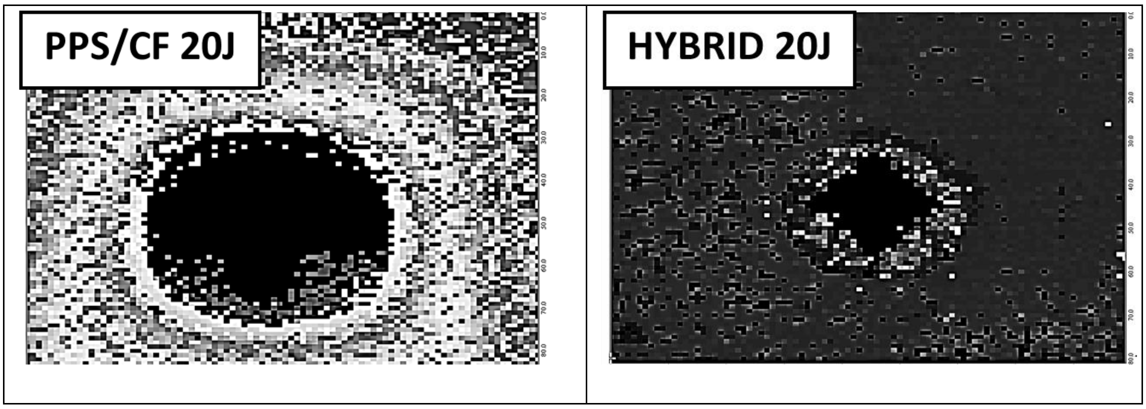


Figure 5 - Visual inspection of impacted samples: a) PPS/CF unreinforced sample; b) PPS/CF+SMA hybrid sample

The behaviour of the kinematic energy transferred from the impactor to the sample is represented in Fig 3c and 4c for both PPS/CF and hybrid samples. As it is possible to observe, increasing the incidental energy, the quantity of energy absorbed during the impact event increases almost linearly for the unreinforced composite going from 44% from 20 to 30J and 25% from 30 to 40J. Hybrid samples present a different behaviour, showing an increase of 43% between 20 and 30J and just a slightly improvement for the 40J impact (~6%).

It is important to underline that all the data recorded during the impacts are taken on singular point on the sample surface, therefore in order to analyse more in depth the behaviour of the hybrid composite, it is necessary to take in account the whole area that surrounds the impact point. Fig 6 represent C-Scan images taken for both PPS/CF unreinforced and SMA hybrid samples after the impact tests and the extension of the internal delamination has been analysed with increasing incidental energy.



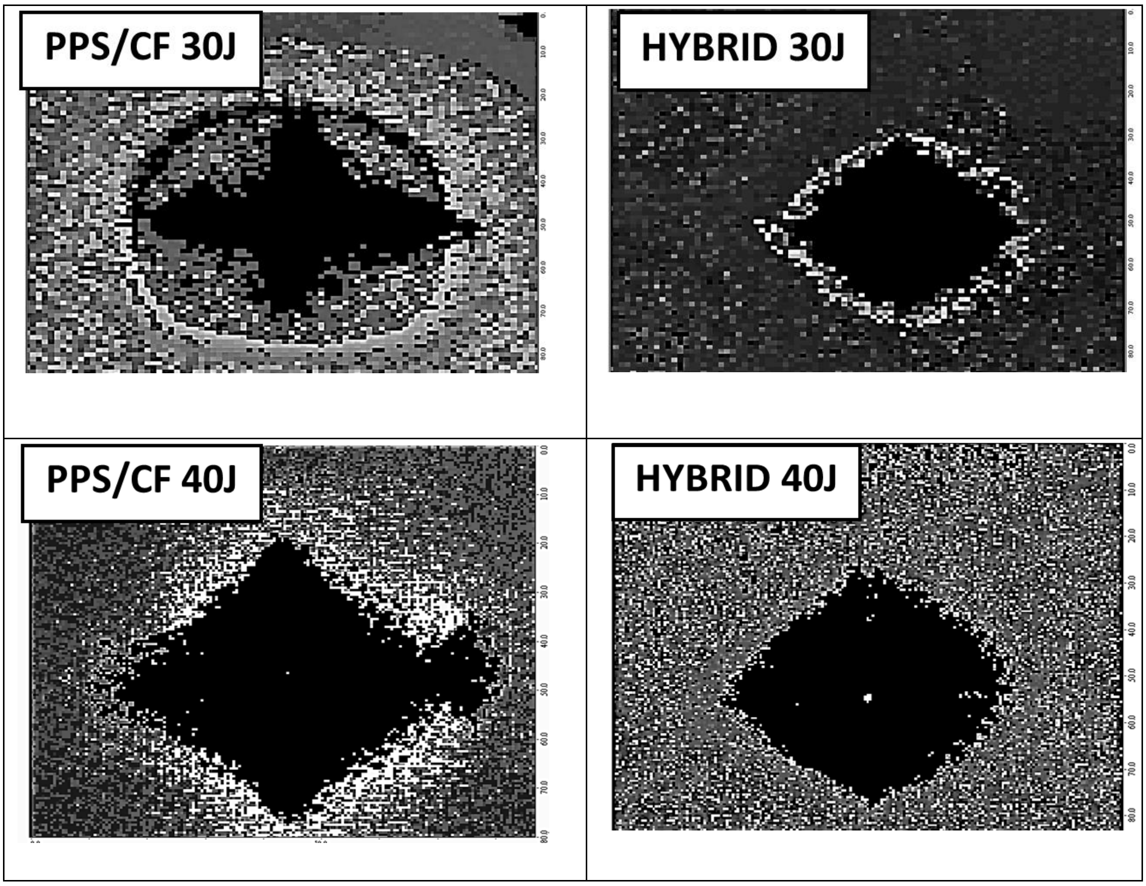


Figure 6 - C-Scan images for hybrid and unreinforced PPS/CF

The comparison between the hybrid composite and the PPS/CF baseline in terms of maximum force, measured displacement, energy absorbed and projected damaged area is shown in Fig 7. As it is possible to see from Fig 7a the values for maximum force are shifted to higher values for the SMA based hybrid composite, showing an increase of ~20% for all the incidental energies. This result suggests that the presence of the SMA within the laminate structure improves the stiffness of the composite resulting in a material which is able to withstand higher-energy impacts.

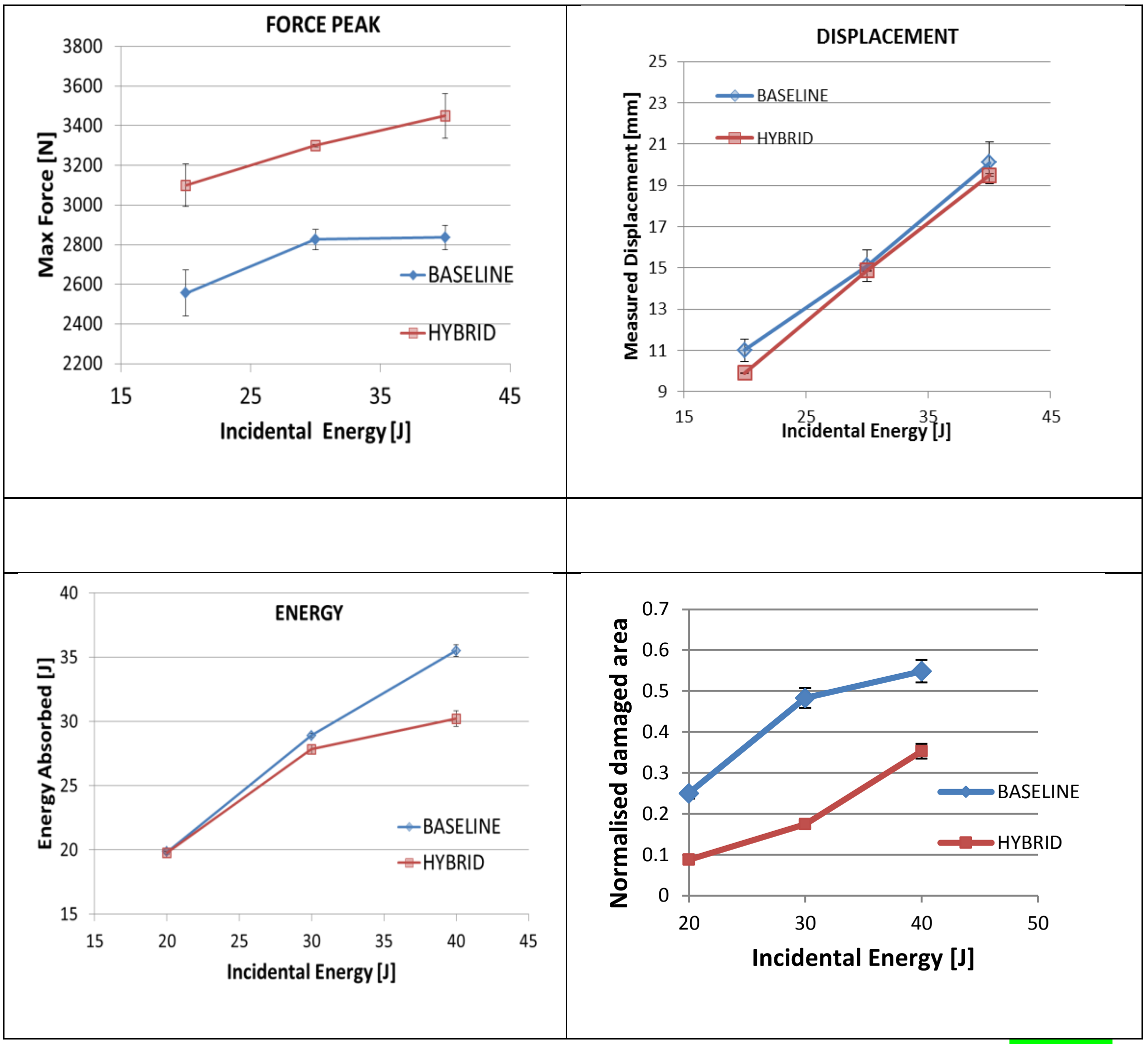


Figure 7 - Comparison between PPS/CF and hybrid composite: a) Maximum Force; b) Measured Displacement; c) Energy Absorption; d) Internal Damage Extension (ratio between the total area and the damaged one)

Another important result is given by the analysis of the measured displacement at different values of incident energy. Indeed, as it is possible to see in Fig 7b, the behaviour of the two materials is quite similar, however at the lower impact energy (20J) the displacement measured for the hybrid samples is slightly lower than the one of PPS/CF composites (-15%). Increasing the incidental energy, this difference tends to decrease to lower results; however as for the 20J and 40J the error bars of the two curves overlap it is not possible to identify a real difference between the two trends. Fig 7c represents the energy absorption values for increasing levels of incidental energy. For the lower impact energy (20J), hybrid composites show a very slightly increase of energy absorption (~0.5%), while for 30J impact this trend is inverted, showing a decrease of (~2%) in the passage between the unreinforced composites to the hybrid ones. This effect is more evident in the data collected for the 40J impacts in which the hybrid composite shows a decrease of the absorbed energy of more than 15%.

When a laminate is subjected to an impact, the energy is transferred and absorbed with a complex mechanism, which comprehends the combination of different sub-mechanisms (fibres breakage, matrix and interphase cracking, structural vibration, material damping, etc.), therefore the values of the absorbed energy have to be analysed in relation with the corresponding delamination areas measured from the C-Scan images. Fig 7d represents the extension of the internal delamination for the samples tested at 20, 30 and 40J. As it is possible to see from the curves and from the ultrasonic images (see Fig 5), the presence of the SMA within the laminate thickness decreases the tendency of the material to dissipate energy through internal delamination, reducing by 7 times the projected damaged area for the lower impact energy (see Figure 6a). This effect tends to decrease when the energy of the impact reaches higher values. However, the hybrid samples still record smaller extent of the internal delamination in comparison with the unreinforced ones (less than 300% for the 30J impacts and less than 50% for the 40J ones). Similar results on PPS/CF hybrid composite have been obtained by Meo et al [26] for the lower velocity impact (between 10 and 24J).

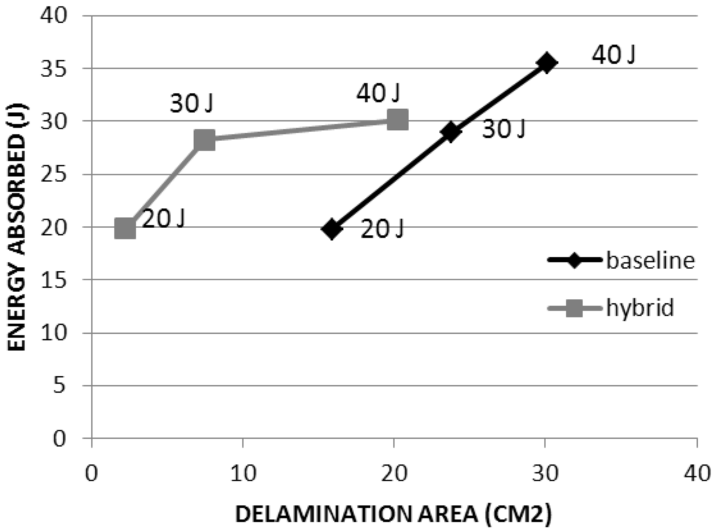


Figure 8 - Relationship between extent of the delamination and energy absorptio for PPS/CF and hybrid composites

Fig 8, clearly summarizes the change in LVI response between traditional PPS/CF composite and hybrid SMA based laminates. Indeed, when subjected to medium velocity impacts (20 and 30J), both the materials absorb the same amount of energy, however, comparing the dimension of the internal delamination, the damaged area for the unreinforced sample is much more extended than the hybrid ones. This indicates that the hybridisation process changes the response to low velocity impacts for the reinforced material changing the energy absorption mechanisms of the structure. The behaviour of the hybrid composites can be explained with the superelastic and hysteretic properties of the SMA wires embedded within the structure, which are able to absorb a large amount of energy during the impact, therefore reducing the amount of energy dissipated through intra-laminar damages formation.

The change in the trend for the energy absorption and the decreasing of the delamination extent difference between the baseline and the hybrid composite with increased incidental energy can be explained with the progressive fracture of the SMA wires within the laminates.

5. Conclusions

This study investigates experimentally the response of PPS/CF composites reinforced with superelastic SMA wires and subjected to low velocity impacts. Impacts at different incident energies (20, 30 and 40J) were carried out and a comparison has been made with a traditional unreinforced composite laminate. Furthermore, the extension of the internal delamination has been evaluated through ultrasonic C-Scan analysis. Results showed that the presence of the SMA wires within the laminate structure increases the stiffness of the composite, shifting the maximum force values to higher levels. Analysing the energy absorption in relationship with the extension of the internal delamination it is possible to observe that for medium incidental energies the amount of energy transferred from the impactor to the samples is almost the same for both unreinforced and hybrid composites. However the hybridisation process changes the energy dissipation mechanism showing a reduction of almost 300% in the extent of the intra-laminar damage for the SMA reinforced samples. This behaviour is less evident when the incidental energy is increased to higher levels because of the progressive failure of the SMA wires. Starting from this last consideration, it is reasonable to hypothesise the presence of a critical energy level for which the delaminated areas will be the same for both traditional and hybrid laminates. As a consequence, this energy threshold could constitute a serious limitation for the use of SMA based laminates in those applications in which high velocity impacts are present.

In conclusion, the results given by this experimental campaign shows that the SMA based hybridisation process is a valid design technique to increase low velocity impact resistance.

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