EVALUATION OF IMPACT DAMAGE BEHAVIOR OF REPEATEDLY IMPACTED COMPOSITES EMBEDDING STEEL AND SHAPE MEMORY ALLOYS (SMA) WIRES

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ABSTRACT

Reinforced polymer composites with high specific modulus and strength have been used in large-scale structures in fields such as aerospace, marine, automotive and so on. These materials are often characterized by a long time service life, and so they could be subjected to many small and repeated impact loads determining a barely visible initial damage of the material without inducing an evident material cracking.

In this study, the influence of the integration of thin superelastic shape memory alloys (SMA) wires on the life time of repeatedly impacted hybrid composites was studied. SMA represents the most versatile smart material with sensing, controlling and actuating functions. Due to their unique mechanical and thermodynamic properties and thanks to the availability of SMA wires with very small diameters (up to 20-30μm), they are used as smart reinforcements embedded into composite materials, inducing active abilities, tunable properties, self healing properties or damping capacity. Moreover superelastic SMA are used to increase the impact resistance properties of composite materials. In fact superelastic SMA are characterized by a very high strain to failure and a large recoverable elastic strain due to a stress induced martensitic phase transition creating a plateau region in the stress-strain curve. For these reasons superelastic SMA fibers can absorb much more strain energy than other fibers before their failure, partly with a constant stress level.

In particular, the enhancement of damage resistance to low velocity repeated impacts when SMA wires are embedded into thermoset matrix composite laminates was studied. In order to gain a deep insight into the hybridization of glass and carbon fiber reinforced composites with metal wires, preliminary tests were carried out on composite panels embedding steel wires. This experiment can help to highlight the peculiar influence of the martensitic transformation occurring when SMA are used.

1. INTRODUCTION

Composite structures in general have a wide range of damages and defects due either to the manufacturing process either to in service accidental loads. So their impact resistance properties can be weakened during composites lifetime. In applications where the event of an impact needs to be considered, like in the aerospace and transportation industries, it is of fundamental importance to predict the impact behavior and to collect data on impact resistance of candidate materials. In these cases, the composite material must resist, beside to the static and fatigue loads, to random impact loads which can occur during its lifetime. For these reasons there is a need of improving impact resistance behavior of composite structures, without increasing weights or decreasing the other mechanical properties, adopting new techniques and materials, capable to impart innovative and “smart” properties to the composite.
Shape memory alloys (SMA) represent the most versatile way to realize smart materials with sensing, controlling and actuating functions [1-4]. Due to their unique mechanical and thermodynamic properties, and to the possibility to obtain SMA wires with very small diameters (down to 20-30μm) they are used as smart components embedded into the conventional resins or composites to obtain active abilities, tunable properties, self

healing properties and damping capacity. Moreover superelastic SMA can be used to increase the impact resistance properties of composite materials. In fact superelastic SMA are characterized by very high strain to failure and recoverable elastic strain, due to a stress induced martensitic phase transition creating a plateau region in the stress-strain curve. For these reasons superelastic SMA fibers can absorb much more strain energy than other fibers before their failure, partly with a constant stress level.

In this work the integration of thin superelastic SMA wires in fiber reinforced polymer composites, with the aim to increase the impact tolerance, is reported. Other authors investigated the impact behavior of SMA composites, showing that, for low velocity impacts, embedding SMA wires increases the impact properties [5-6]. In this investigation the effect of small diameter (100μm) SMA wires on the impact behavior of repeatedly impacted composites is presented. These results can be exploited for the development of new energy absorbing structures for the aerospace and transportation industries and for the individual protection industry.

Glass and carbon fiber reinforced laminates and hybridized ones were tested with “Charpy method” (ASTM D256). The pendulum hammer was equipped with a piezoelectric sensor in order to obtain the evolution of the force during the impact, and to evaluate the changes in the force-time and force-displacement curves due to the embedding of steel and SMA wires. Samples were subjected to repeated low velocity impacts until fracture occurs. Results of repeated impact loads were reported as peak load as a function of the number of repeated impacts, as in a traditional fatigue plot, thus providing preliminary design rules.

Impact tests were carried out on glass and carbon fiber reinforced composite laminates obtained embedding both steel and SMA superelastic wires in order to distinguish the influence of the martensitic transformation occurring during SMA deformation from the mere introduction of metallic wires into the polymeric matrix.

2. MATERIALS AND METHODS

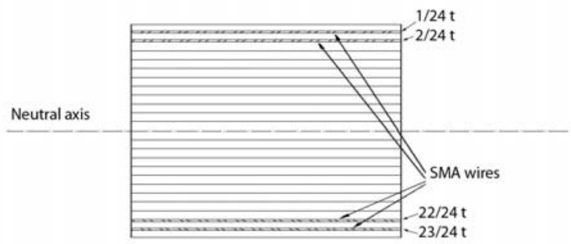
2.1. MATERIALS

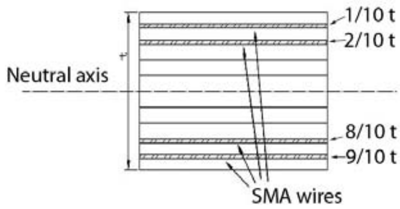
SMA wires made of superelastic 56.00 wt.% Ni balance Ti alloy, straight annealed, and provided by SAES GETTERS were used. The superelastic wires have 100μm diameter, transformation temperature A_f=15°C as measured on finished wires, upper plateau load (at 4% strain)>400Mpa, lower plateau load (at 4% strain)>100Mpa. Steel wires made of AISI 304L alloy of 100μm diameter and characterized by 700Mpa break load and 5% break deformation, provided by COMAR S.r.l., were also embedded in some composite laminates to make the comparison with equivalent SMA composites.

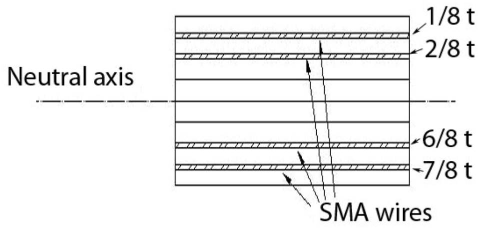
SMA wires were embedded into the composite layers with the aid of special frames designed to equally space the wires (with a distance between the wires equal to 1mm) and to align them in the principal direction of the sample. Four layer of wires were embedded in the composites at different distances from the neutral axis, close to the external surface of the specimen. The volume fraction of the SMA and steel wires embedded into the composites is about 1%. The laminates were fabricated by vacuum assisted resin infusion process, using a vinylester resin provided by Polynt.

Materials and stacking sequences of the composite laminates in which SMA superelastic wires have been embedded are reported in Table1. Table 2 reports their main mechanical properties.

<table>
<tr><th>Laminate code</th><th>Material</th><th>Stacking sequences</th><th>Side views</th></tr>
<tr><td>TS1-glass</td><td>Vinylester resin

Glass fabric EE245 Plain 7/3</td><td>$\left[90^0, W, 0°, W, \left(0°, 90°\right)_5\right]_S$</td><td>
</td></tr>
<tr><td>TS2-glass</td><td>Vinylester resin

Glass fabric EE425 Plain 5.5/6.3</td><td>$[0°,W,90°,W, 0°,90°,0°]_S$</td><td>
</td></tr>
<tr><td>TS3-scarb</td><td>Vinylester resin

Carbon fabric CC420 Twill 2/2</td><td>$[0°,W,90°, W,0°,90°]_S$</td><td>
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<tr><td colspan="4">W indicates the SMA wires.</td></tr>
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Table 1: materials and stacking sequences of the composite laminates in which SMA superelastic wires have been embedded.

Laminate code	**Fiber content** (% by weight)	**Thickness** (mm)	E_1 (Gpa)	E_2 (Gpa)	ε_{1u} (%)	ε_{2u} (%)	σ_{1u} (Mpa)	σ_{1u} (Mpa)
TS1-glass	70	4.5±0.05	15±0.6	15±0.6	3.5±0.3	3.5±0.3	600±18	600±18
TS2-glass	70	3±0.04	16.8±0.5	16.8±0.5	4.2±0.3	4.2±0.3	650±21	650±021
TS3-carb	70	3.2±0.05	32.5±2	32.5±2	2±0.12	2±0.12	530±20	530±20

Table 2: mechanical properties of the composite laminates hybridized with SMA wires.

2.2.EXPERIMENTAL METHODS

From each laminate two types of specimens were obtained for impact characterization: those without any metallic wires and the hybrid ones, embedding SMA wires. Hybrid specimens embedding steel wires were also fabricated from TS2-glass and TS3-carbon laminates in order to study how the changes in impact properties are related to the peculiarity of the martensitic transformation characterized by large elastic deformations.

Impact tests were performed according the Charpy test method (ASTM D256 [9]) by an instrumented impact tester. The pendulum hammer was equipped with an ICP® Dynamic Force Sensor provided by PCB Piezoelectronics, providing the force as a function of the time during the impact test. The maximum energy used to impact the specimens was 25 J: with this energy level the specimens break in a single hit. Samples were hit using different energy levels regulating the pendulum holding and releasing mechanism so to start the swing from a lower height. With these energy levels the specimens can be repeatedly impacted until fracture occurs. Results of repeated impact loads were reported as peak load (F_{max}) as a function of the number of repeated impacts, like in a traditional fatigue plot.

3. APPROACH

A typical damage sequence obtained using repeated Charpy impact tests on composite laminates is reported in Figs 1. Each plot is characterized by different relationship among these quantities:

- F_{max}= maximum in the force-time curve;
- F_i= force at the onset of delamination;
- F_{ult}= breaking load for the composite.

At low impact energies (Figure 1a), although localized matrix cracking is likely to occur in the contact area before the onset of delamination, it is not capable to affect the force vs. time curve, that remains symmetric. When the onset of delamination takes place, an initial drop, as indicated in Figure 1b, is detected and the parameter F_i is determined. At higher impact energies (Figure 1c), this load drop increases as a consequence of ply shear-out. By further increasing the impact energies, shear of plies continues through the thickness resulting in the growth of a truncated pyramid of shear-out material (Figure 1d). Ultimately this pyramid forces the remaining plies to catastrophically fracture as illustrated in Figure 1e.

A schematic representation of the development of damage during the impact fatigue life of a composite laminate with plies oriented in different directions is reported in figure 2 [10]. Changes in F_{max} occurs in three steps: the initial F_{max} decrease is associated to primary cracks formation, then a plateau region, where crack coupling, interfacial debonding and fiber breaking take place, is observed, finally F_{max} sharply decreases due to delamination growth till the sample breaks.

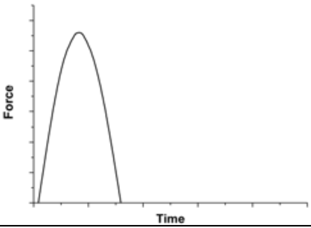
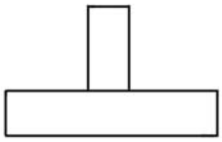
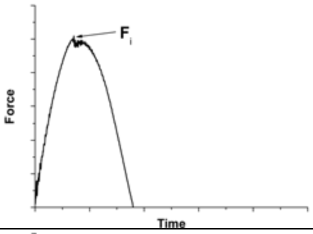
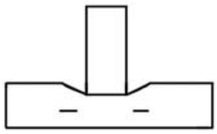
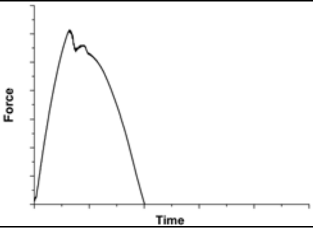
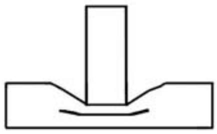
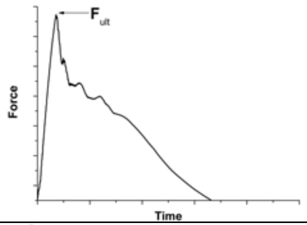
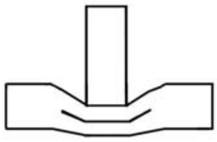
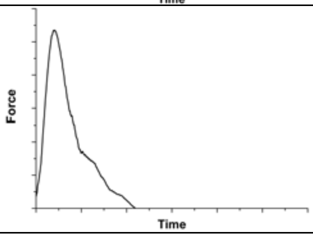
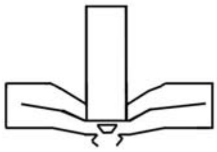
Stage I $F_{max} < F_i$		 **Figure 1a**
Stage II $F_{max} = F_i$		 **Figure 1b**
Stage III $F_{ult} > F_{max} > F_i$		 **Figure 1c**
Stage IV $F_{ult} = F_{max} > F_i$		 **Figure 1d**
Stage V $F_{ult} < F_{max}$		 **Figure 1e**

Figure 1: damage sequence in Charpy laminate specimens under increasing low-velocity impacts.

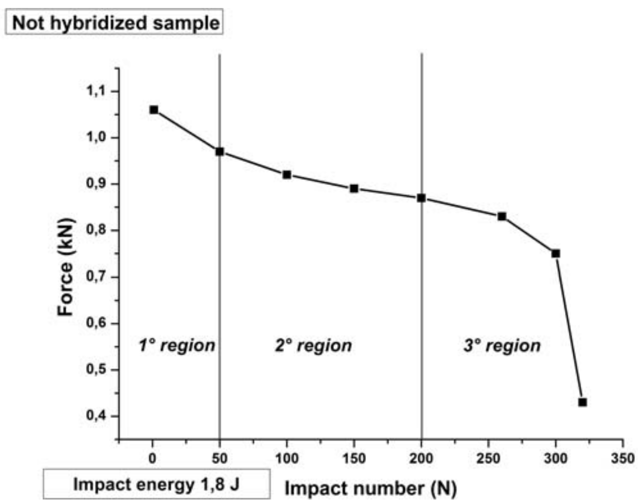


Figure 2: F_{max} Vs N curves during the impact fatigue experiments (adapted from ref [10]).

4. EXPERIMENTAL RESULTS

The force time (F-t) curves obtained using an impact energy between 0.2 and 25 J for TS1-glass laminate are reported in Figure 3. In this experiments a single impact load is applied using impact energy as independent variable. This preliminary characterization is needed either to compare hybrid and neat samples either to set the proper conditions for impact fatigue tests. Impact energies lower than 8.84 J were not high enough to fracture the samples with a single impact, but they are capable to damage the specimen. As shown in this figure, hybridization increases the energy at which the onset of delamination takes place ($F_{max} = F_i$); moreover samples with SMA wires are characterized by a higher F_{max}, while the energy at which the sample breakes ($F_{max} = F_{ult}$) is the same for both type of composites. It appears that hybridization affects the damage initiation but not the ultimate properties of the composite.

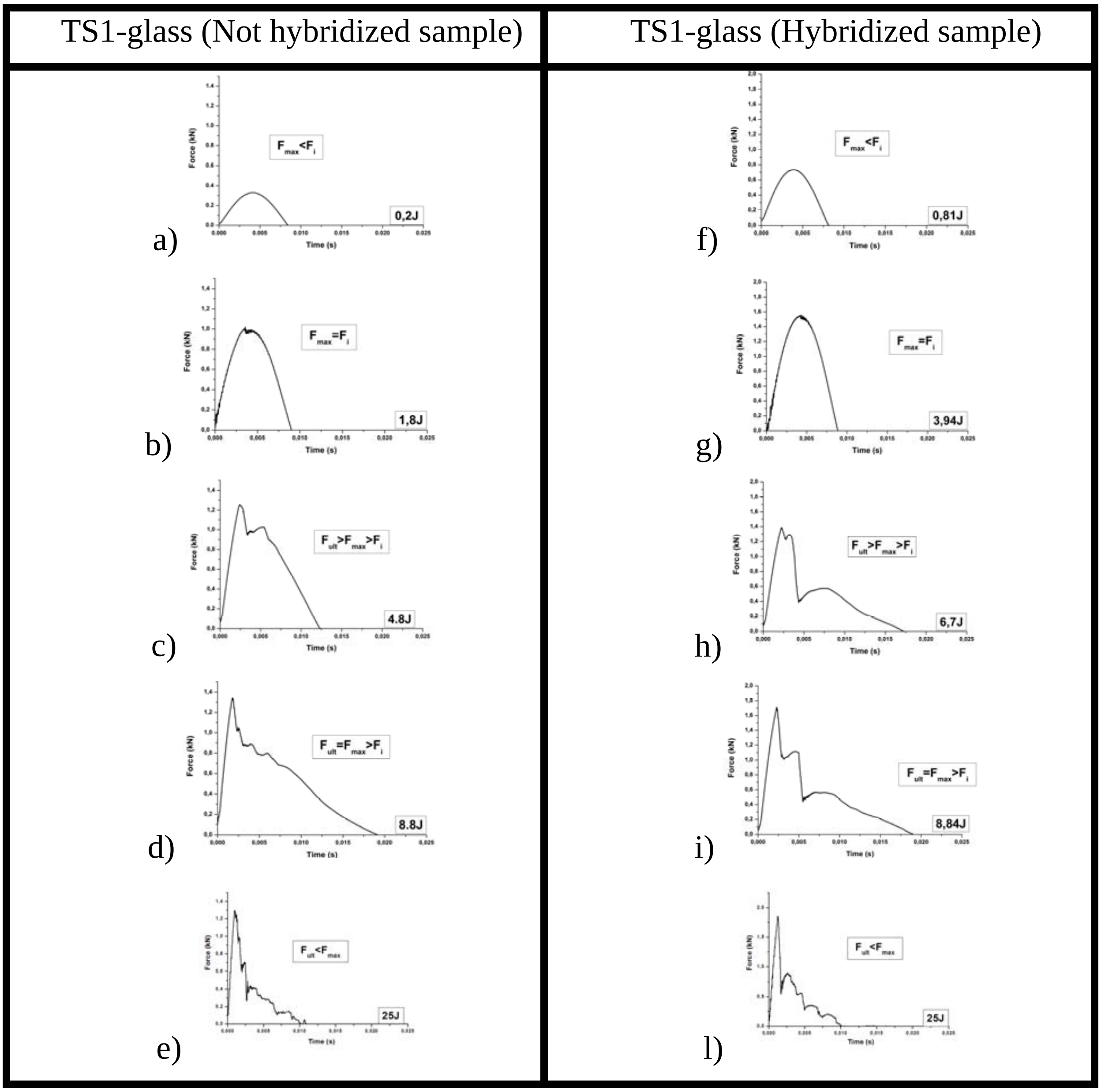


Figure 3: impact response of samples subjected to previous impacts at different energies of hammer (TS1-glass laminate).

Impact fatigue was performed at energies much lower than 8.84 J, the minimum energy to break both samples (1.80 J, 2.43 J and 3.14 J). F_{max} measured during the fatigue impact experiments are shown in Figure 4 for different energy levels for TS1-glass specimens. Non-hybridized specimens follow the typical fatigue behavior shown in figure 2 at 1.80 J and 2.43 J. The three regions of damage initiation, damage propagation and delamination followed by sample breakage are clearly detected in Figure 4 for non–hybridized samples. On the other hand, at lower impact energies, the curves F_{max} vs N of hybridized laminates are characterized by an initial plateau indicating that the damage initiation is delayed when SMA wires are used. Moreover, a damage initiation region is not evident when an energy of 1.80 J is used. Hybridization is responsible of a shift of the impact fatigue curve at a higher number of impacts resulting in an increases the fatigue life of the composite between 1.5 to 2 folds. At the highest energy level (3.14 J) this effect is not anymore evident and the curves shown in Figure 4c are characterized by the same shape, even if hybridized sample presents an impact fatigue life higher of more than 50%.

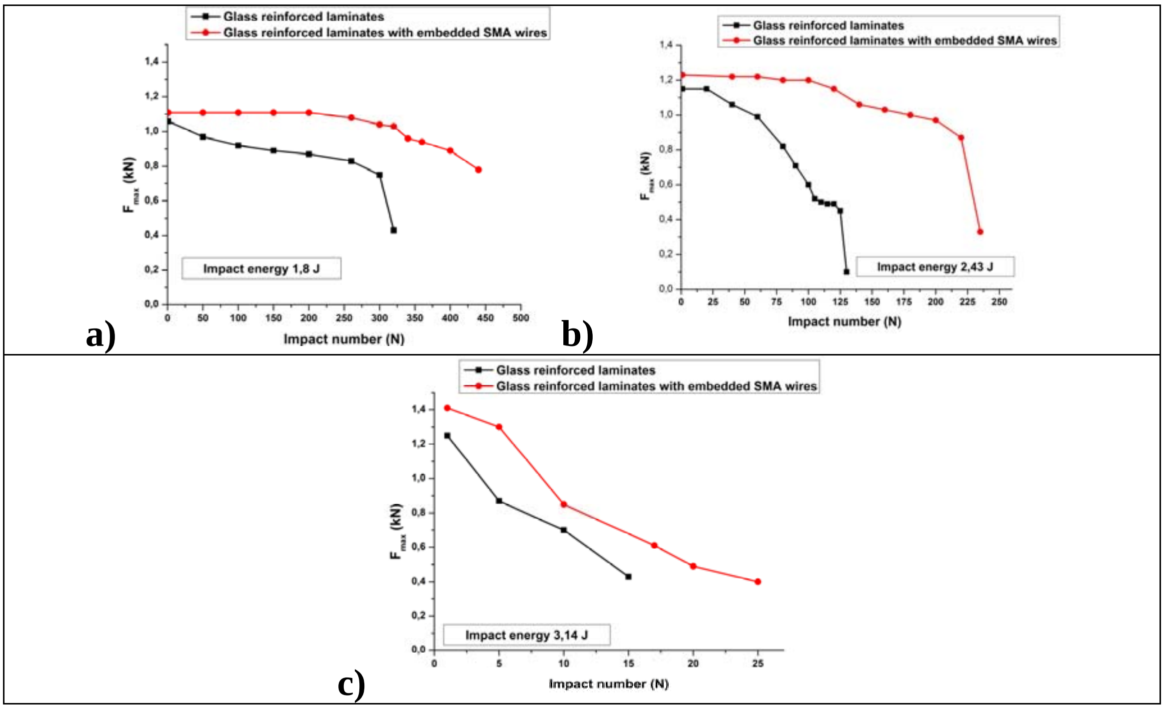


Figure 4: variations of F_{max} during the impact fatigue experiments (TS1-glass laminate).

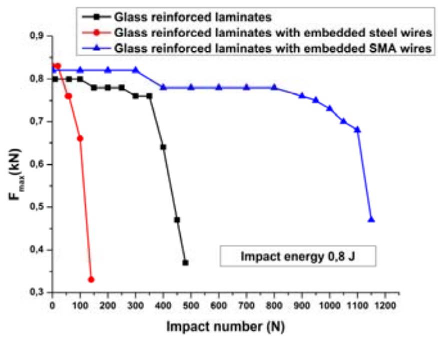


Figure 5: variations of F_{max} during the impact fatigue experiments (TS2-glass laminate).

In order to gain a deeper insight into the reasons of the positive effect of superelastic wires on the impact properties of glass fiber reinforced composites, a laminate, the TS2-glass, was fabricated embedding in different regions SMA or steel wires. F_{max} values during the fatigue impact experiments are reported for 0.8 J impact energy in Figure 5, while the impact fatigue curves are shown in Figure 6. SMA hybridized samples displays the highest damage tolerance, while steel hybridized samples breaks for a number of impacts even lower than those of the non-hybridized sample. This can be attributed to the very high difference between steel and E-glass moduli. Taking into account that a very low amount of metallic wire is used (1% v/v), it can be concluded that at the beginning steel wires takes most of the load reaching the break very soon but also significantly damaging the composite.

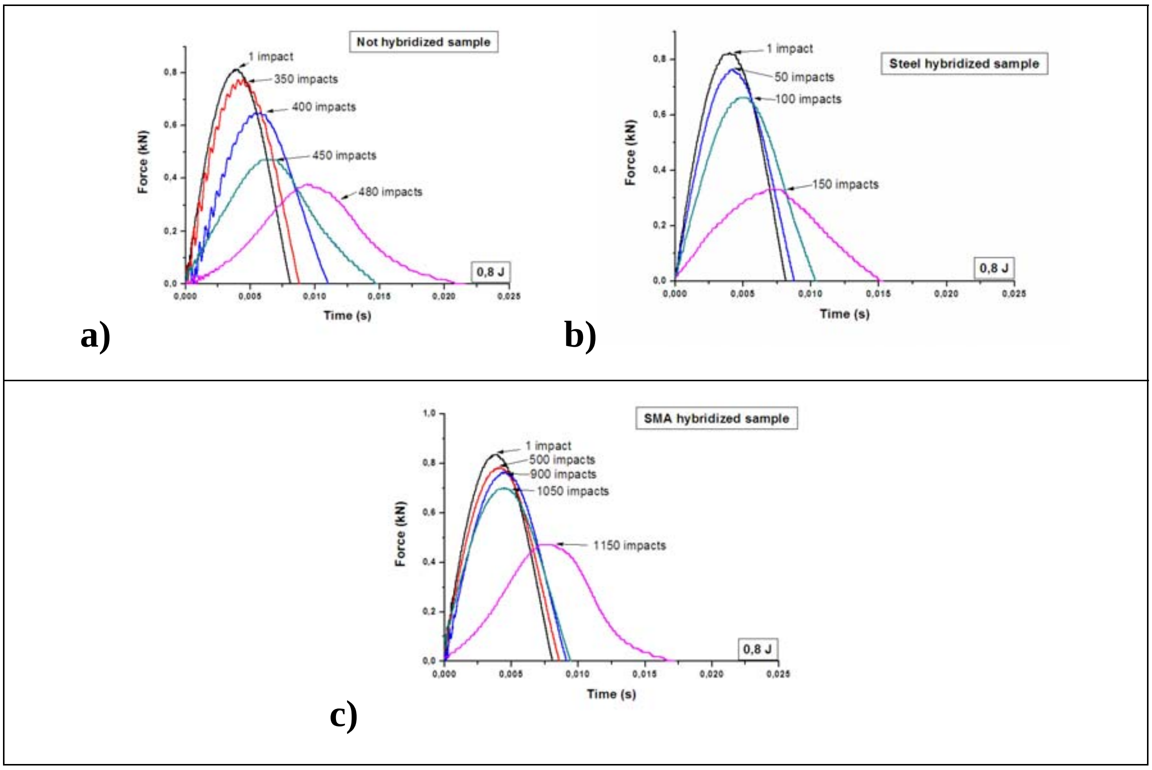


Figure 6: impact fatigue curves for 0,8J energy level (TS2-glass laminate).

Finally superelastic and steel wires were embedded into a carbon fiber reinforced laminate (TS3-carbon in Figure 1). F_{max} evolution during the fatigue impact experiments are reported in Figure 7 for 0.46 and 0.8 J impact energies. In this case SMA wires effect on the damage tolerance of the composite is detrimental, while steel wires show a little positive effect.

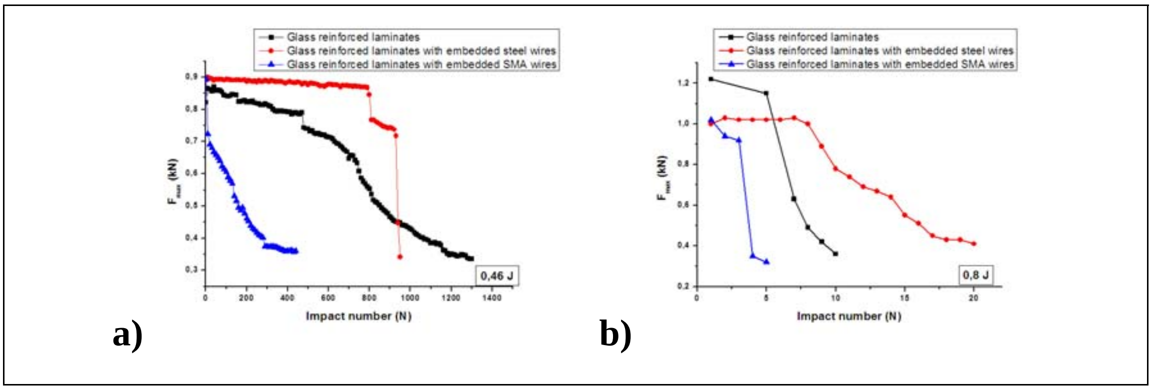


Figure 7: variations of $F_{\max}$ during the impact fatigue experiments (TS2-glass laminate).

The high difference between SMA wires and carbon fiber moduli and the lower difference between steel wires and carbon fiber moduli can be again the reason of these effects. In the first case SMA wires acting as weak inclusions, takes only a limited portion of the load, as also evidenced by the correponding low initial value of Fmax in Figure 7. In the second case steel wires share the load with carbon fibers, delaying the final rupture thanks to their plastic deformation and hardening.

6. CONCLUSIONS

In this work the influence of hybridization with SMA and steel wires on the damage tolerance of glass and carbon fiber reinforced composites has been investigated. As reported before, SMA wires have a significant effect on the damage tolerance of glass reinforced laminates, while they have a detrimental effect on carbon reinforced laminate. On the other hand steel wires better perform when are embedded in carbon reinforced laminates, giving a longer impact fatigue life to these composites.

In order to explain these effects, it is to be considered that embedding metallic wires into a composite structure implies the introduction of an inhomogeneity. It is well known that inhomogeneities have a great influence on laminate response to cyclic loading, and that from the behavioural standpoint, they present a dichotomy [10]. In many respects, they are the most important factors contributing to the generally superior resistance of laminated composite materials to fatigue damage development, because they limit the crack growing. At the same time, they are almost certainly the greatest contributing factors in the initiation of damage at the micro-level. For these reasons SMA wires make the glass reinforced laminates more resistant to the growth of the cracks, because they have a very good effect on limiting this growth. On the other hand SMA wires cause inhomogeneous deformations in carbon reinforced laminates, since their modulus is much lower than that of carbon fiber modulus, promoting cracks initiation. For the same reason steel wires decreases the damage tolerance of glass reinforced composites, because their higher modulus promote the cracks initiation. This effect is inverted for carbon reinforced laminates, because the modulus of carbon fibers is higher than the elastic modulus of SMA wires, while it is closer to that of steel. However in this case the positive effect of steel wires is less significant, being carbon laminates more resistant to the crack growth during cyclic loads.

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