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Embedding of Superelastic SMA Wires into Composite Structures: Evaluation of Impact Properties

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Shape memory alloy (SMA) represents the most versatile way to realize smart materials with sensing, controlling, and actuating functions. Due to their unique mechanical and thermodynamic properties and to the possibility to obtain SMA wires with very small diameters, they are used as smart components embedded into the conventional resins or composites, obtaining active abilities, tunable properties, self-healing properties, and damping capacity. Moreover, superelastic SMAs are used to increase the impact resistance properties of composite materials. In this study, the influence of the integration of thin super-elastic wires to suppress propagating damage of composite structures has been investigated. Superelastic SMAs have 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. NiTi superelastic wires ($A_f = -15$ °C fully annealed) of 0.10 mm in diameter have been produced and characterized by SAES Getters. The straight annealed wire shows the typical flag stress-strain behavior. The measured loading plateau is about 450 MPa at ambient temperature with a recoverable elastic strain of more than 6%. 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 paper, the improvement of composite laminates impact properties by embedding SMA wires is evaluated and indications for design and manufacturing of SMA composites with high-impact properties are also given.

Keywords advanced characterization, aerospace, mechanical testing, structural plastics

1. Introduction

Composite structures often present small damages and defects resulting either from the manufacturing process or from accidental impacts occurring during their use. These small impacts may result in initial deformations and reduce the strength and the lifetime of composite material. In fields where the event of an impact needs to be considered, such as aerospace and transportation, 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 has to resist to the static and fatigue loads and 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 their weights and compromising other mechanical properties.

Shape memory alloys (SMA) represent the most versatile way to fabricate smart materials with sensing, controlling, and actuating functions (Ref 1-4). Due to their unique mechanical and thermodynamic properties, and to the possibility to obtain SMA wires with very small diameters (down to 20-30 μm diameter), they are used as smart components embedded into conventional composites, obtaining active abilities, tunable properties, self-healing properties, and damping capacity. Moreover, SMA superelastic properties can be exploited to increase the impact properties of composite materials. SMA presents a very high strain to failure and a large recoverable elastic strain, thanks 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, with a nearly constant stress level.

In this study, the increasing of impact properties of fiber reinforced polymer composites by the integration of thin superelastic SMA wires has been investigated. Other authors have already investigated the impact damage behavior of SMA composites, showing that for low-velocity impacts, embedding SMA wires increases the impact properties (Ref 5-10). For this reason, SMA wires of small diameter (100 μm) are embedded in glass and carbon reinforced composite laminates, in order to understand how the impact properties of composite materials change with this hybridization, and to find out some indications for the design of SMA/carbon or SMA/glass hybrid composites with improved impact properties. These results will be applied to new energy-absorbing structures for the aerospace and transportation industries and for the individual protection industry.

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In order to discriminate the influence of the martensitic transformation from the simple introduction of metallic wires into the polymeric matrix, preliminary tests were carried out on composite panels embedding steel wires of the same diameter of the SMA ones.

The hybrid laminates were tested by Charpy pendulum, using a hammer equipped with a piezoelectric sensor for the measurement of force-time and force-displacement curves during the impact test. Moreover, glass and carbon reinforced samples were subjected to repeated low-velocity impacts up to fracture, in order to evaluate the influence of this hybridization on the damage tolerance of the composite. Results of repeated impact loads were plotted as peak load (F_{max}) versus repeated impact number, as in a traditional fatigue plot, thus providing preliminary design rules. In addition, a quasi-static analysis was performed, according to ASTM D790, to compare the failure mechanisms at different strain rates.

2. Materials and Methods

2.1 Materials

A SAES Getters SMA wire made of superelastic 56.00 wt.% Ni balance Ti alloy straight annealed was used. The superelastic wires have 100 μm diameter, transformation temperature $A_f = -15$ °C as measured on finished wires, upper plateau load (at 4% strain) ≅ 400 MPa, lower plateau load (at 4% strain) ≅ 100 MPa. In Fig. 1 the results of tensile test on these wires are reported. Moreover, steel wires made of AISI 304L alloy with 100 μm diameter, 700 MPa break load and 5% break deformation, provided by COMAR S.r.l., were embedded in the composite laminates to make the comparison with equivalent SMA composites.

To embed SMA wires into the composite layers, special frames were designed for a proper wire spacing into the matrix, obtaining a 1 mm distance between the wires and alignment in the principal direction of the sample. Four layers of wires were embedded into the composites at different distances from the neutral axis, near the external surfaces of the specimen. The volume percentage of the SMA and steel wires embedded into

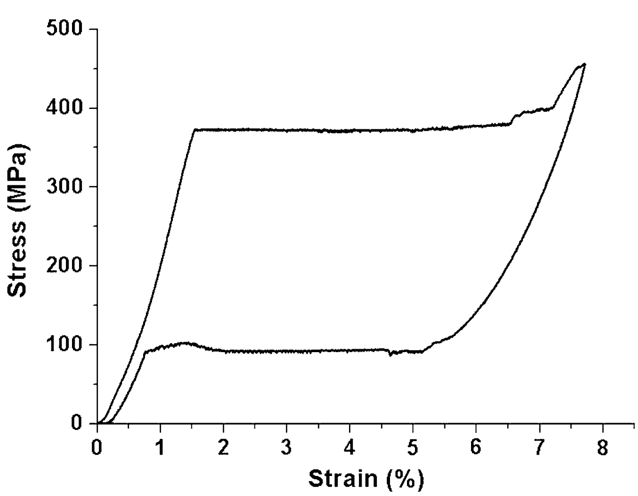


Fig. 1 Tensile stress-strain curve for a SAES Getter shape memory superelastic wire

the composites is about 1%. The laminates were realized by vacuum-assisted resin infusion process.

In Table 1 materials and stacking sequences of the composite laminates in which SMA and steel wires were embedded are reported, and in Table 2 their main mechanical characteristics are represented.

2.2 Experimental Methods

Three kinds of specimens were obtained from each laminates for impact characterization: specimens without any metallic wires and hybrid specimens embedding steel and SMA wires.

Impact tests were performed according to the Charpy test method (ASTM D256 (Ref 11)) by an instrumented impact tester. A schematization of sample geometry, positioning, and testing procedure is represented in Fig. 2. The pendulum hammer was equipped with an ICP® Dynamic Force Sensor provided by PCB Piezoelectronics for the measurement of 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 with a single hit. Moreover, the samples were hit with less energy, regulating the pendulum holding and releasing mechanism so to start the swing from a minor vertical height. Using such energy levels the specimens do not break with a single hit and so they were repeatedly impacted up to fracture. Results of repeated impact loads were represented as peak load (F_{max}) versus repeated impacts number, as in a traditional fatigue plot.

Static flexural tests were performed by three-point bend procedure (ASTM D790 (Ref 12)): the results are an average of 15 specimens of each type.

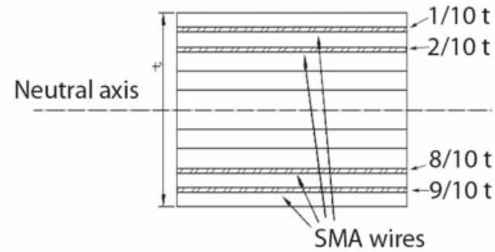
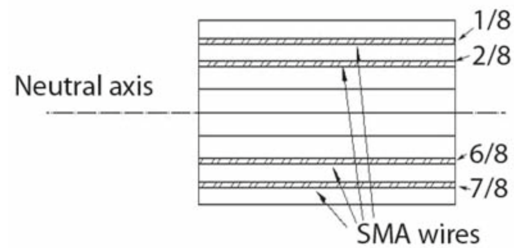
3. Approach

A typical damage sequence in Charpy laminate specimens under increasing low-velocity impacts is represented in Table 3, where F_{max} is the maximum in the force-time curve, F_i the force at the onset of delamination, and F_{ult} is the breaking load for the composite.

For low-energy impacts (Table 3a), localized matrix cracking occurred in the contact area before the onset of delaminations, but it was insufficient to have a noticeable effect on the impact response curve that remains symmetric. When the onset of delamination took place, there was an initial drop as indicated in Table 3b. For higher energy impacts, this load drop increased for the ply shear-out. By further increasing the energy impacts, ply shear continued through the thickness, resulting in the growth of a truncated pyramid of shear-out material. Ultimately this pyramid forced the remaining plies, to fracture with an explosive bang as illustrated in Table 3e.

In Fig. 3 a schematic representation of the development of damage during the fatigue life of a composite laminate is reported. Composite laminate was assumed to experience a flexural load history and to include plies with different orientations with respect to a principle load direction (0° direction). It can be observed that the changes in F_{max} values take place in three regions (Ref 13-16). At first region, F_{max} values decrease gradually and this diminution is associated to primary crack formation and multiplication. In the second region, there is a plateau (or crack saturation) region, where crack coupling, interfacial debonding, and fiber breaking take

Table 1 Materials and stacking sequences of the composite laminates in which SMA superelastic wires have been embedded

<table>
<tr><th>Laminate</th><th>Material</th><th>Stacking sequences</th><th>Side views</th></tr>
<tr><td>TS-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>TS-carb</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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</table>

W indicates the metallic wires

Table 2 Main mechanical characteristics of the composite laminates in which SMA wires have been embedded

Laminate code	Fiber content, wt.%	Thickness, mm	E_1, GPa	E_2, GPa	ε_1, %	ε_2, %	σ_1, MPa	σ_2, MPa
TS-glass	70	3	16.8	16.8	4.2	4.2	650	650
TS-carbon	70	3.2	32.5	32.5	2	2	530	530

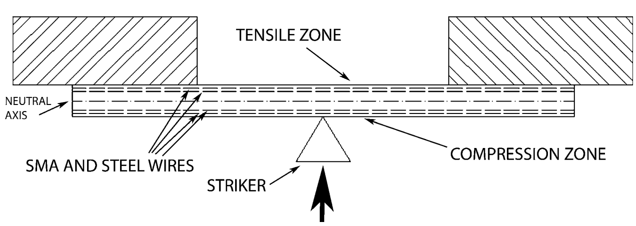


Fig. 2 Schematization of sample geometry, positioning, and testing procedure

place. At last in the third region, an acceleration of the damage takes place and F_{max} values decrease sharply due to delamination growth till the sample breaks.

Another important aspect to be considered is the increase of absorbed energy as a consequence of the possible stiffness increase associated with addition of the SMA (or steel) wires. An important parameter that can be used to measure the effect of wire embedding is the ductility index D (Ref 13), which is the ratio between the propagation energy E_p and the initiation energy E_i:

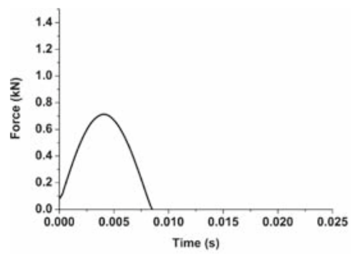
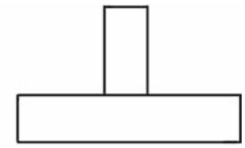
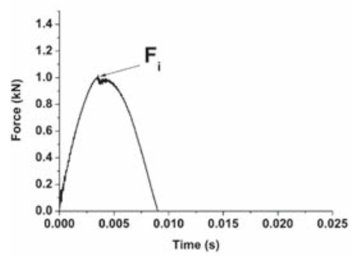
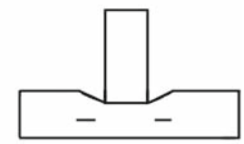
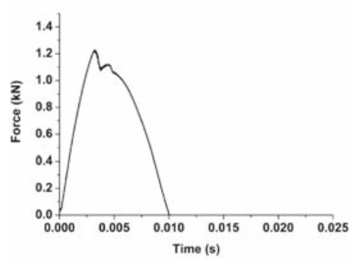
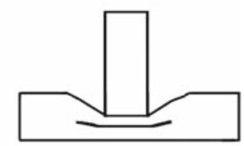
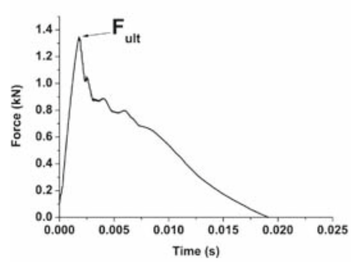
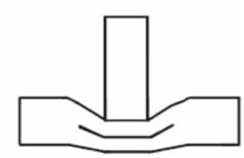
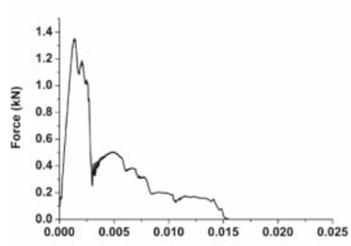
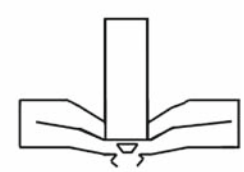
$$D = \frac{E_p}{E_i}$$

where E_i is the area up to the maximum load under the force-displacement curve and E_p is the area from the force peak until the end of the test. The hybridization with SMA wires is more effective if it increases the parameter D, otherwise it can be considered as a brittle reinforcement of the material behaving like the other reinforcement. The effect of hybridization can be also observed from the stress-strain curves obtained in a static flexural experiment.

4. Experimental Results

A synthesis of the Charpy and static flexural results is reported in Table 4 and 5. The average force and displacements impact curves for the three types of specimens for each composite are shown in Fig. 4 and 5. As visible in Table 4, SMA hybridization has a little positive effect on the impact energy for TS-glass (+1%), while for TS-carbon it is more considerable (+9.1%): this behavior is due to the smaller break deformation of carbon reinforced composite, which is more brittle than glass reinforced one. Moreover, for steel hybridization, impact energy of TS-glass composite decreases (−4.6%), while for TS-carbon there is an increase of impact energy smaller than for SMA hybridization (+5%). It is interesting to observe the behavior of ductility index D: it sensibly increases for TS-glass hybrid laminate. This is principally due to the decrease of mechanical properties of glass reinforced laminate as a consequence of hybridization: this is responsible for a sensitive decrease of E_i, reflected by an increase of D (see results of static flexural characterization in Table 5).

Table 3 Damage sequence in Charpy laminate specimens under increasing low-velocity impacts

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

We can conclude that the impact energy is marginally affected by SMA wires in the lay-up; however, to have a more sensitive increase of impact energy, more wires have to be embedded into the composite structures, even if this is not technologically easy.

For this reason the samples were hit with less energy, for a more general investigation of the effect of SMA hybridization on composite damage tolerance. So the specimens did not break with a single hit and they were repeatedly impacted up to fracture.

In Fig. 6 the force-time (F-t) curves of impacts at energy levels lower than 25 J are illustrated for non-hybrid (a-d), SMA-hybrid (e-h), and steel-hybrid (i-l) TS-glass samples. In this case, the hammer struck each sample only once and the samples were preserved from additional strikes. As Fig. 6 shows, for SMA-hybrid samples up to 3.94 J, total elastic deformations were observed (symmetrical F-t curves), while for non-hybrid samples the energy value for the onset of visible damages was lower (equal to 1.8 J). Even for steel-hybrid samples the onset of visible damages was 3.94 J, but in this case a higher sudden drop in F value was measured. Moreover, hybrid samples reach higher F_{max} and F_{ult} values than non-hybrid ones.

Starting from these first results, impact fatigue tests on TS-glass samples have been carried out. The composite samples were positioned on the sample holder and hit by Charpy hammer repeatedly. The composite samples were subjected to single impacts repeatedly up to fracture at each impact energy level. In Fig. 7 the F_{max} values during the fatigue impact experiments on TS-glass specimens are reported for 0.8 J impact energy, and in Fig. 8 the impact fatigue curves are shown. As Fig. 7 shows, embedding SMA wires increases the damage tolerance of the composite laminate. In fact, SMA samples fractured after nearly 1200 impacts, so much later than

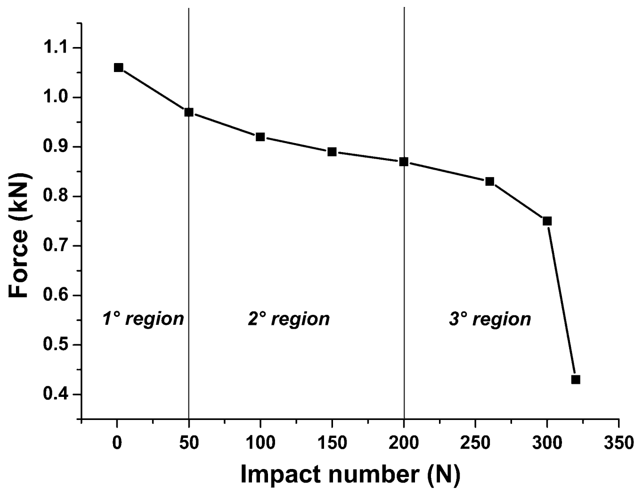


Fig. 3 Peak load (F_{max}) vs. repeated impact number curves during the impact fatigue experiments

Table 5 Synthesis of static flexural characterization results and evaluation of the changes in mechanical properties of the composite due to hybridization

Laminate	E_c, GPa	ε_r, %	σ_r, MPa
TS-glass			
No wires	16.8	4.2	650
Steel wires	17.8	4.2	541
	+6%		−17%
SMA wires	15.5	4	513
	−8%	−5%	−21%
TS-carbon			
No wires	32.5	1.99	528
Steel wires	35	1.66	471
	+7.7%	−16.6%	−10.8%
SMA wires	32.5	1.89	451
	//	−5%	−15%

The increases are referred to the absorbed energy of the samples without metallic wires

E_c = longitudinal flexural modulus, ε_r = longitudinal flexural strain, σ_r = longitudinal flexural strength

Table 4 Summary of the average impact energies to fracture not hybridized and steel and SMA hybridized samples and ductility index values measured in Charpy tests

Laminate	Energy, J No wires	Energy, J Steel wires	Energy, J SMA wires	*D* No wires	*D* Steel wires	*D* SMA wires
TS-glass	8.7	8.3	8.8	1.1	1.4	1.5
		−4.6%	+1%		+27%	+37%
TS-carbon	12	12.6	13.1	8.9	9.5	9.13
		+5%	+9.2%		+2.5%	+2.5%

The increases are referred to the absorbed energy of the samples without metallic wires

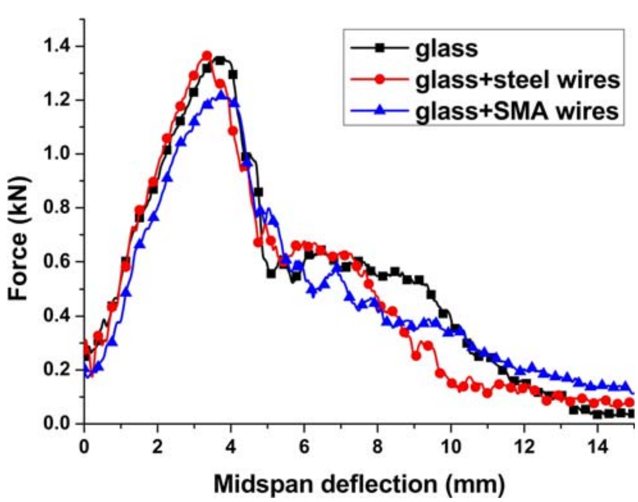


Fig. 4 Average force and displacements impact curves for the three types of specimens for TS-glass composite

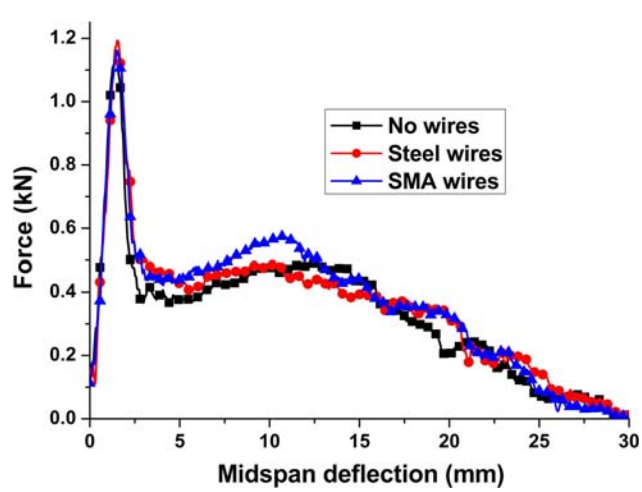


Fig. 5 Average force and displacements impact curves for the three types of specimens for TS-carbon composite

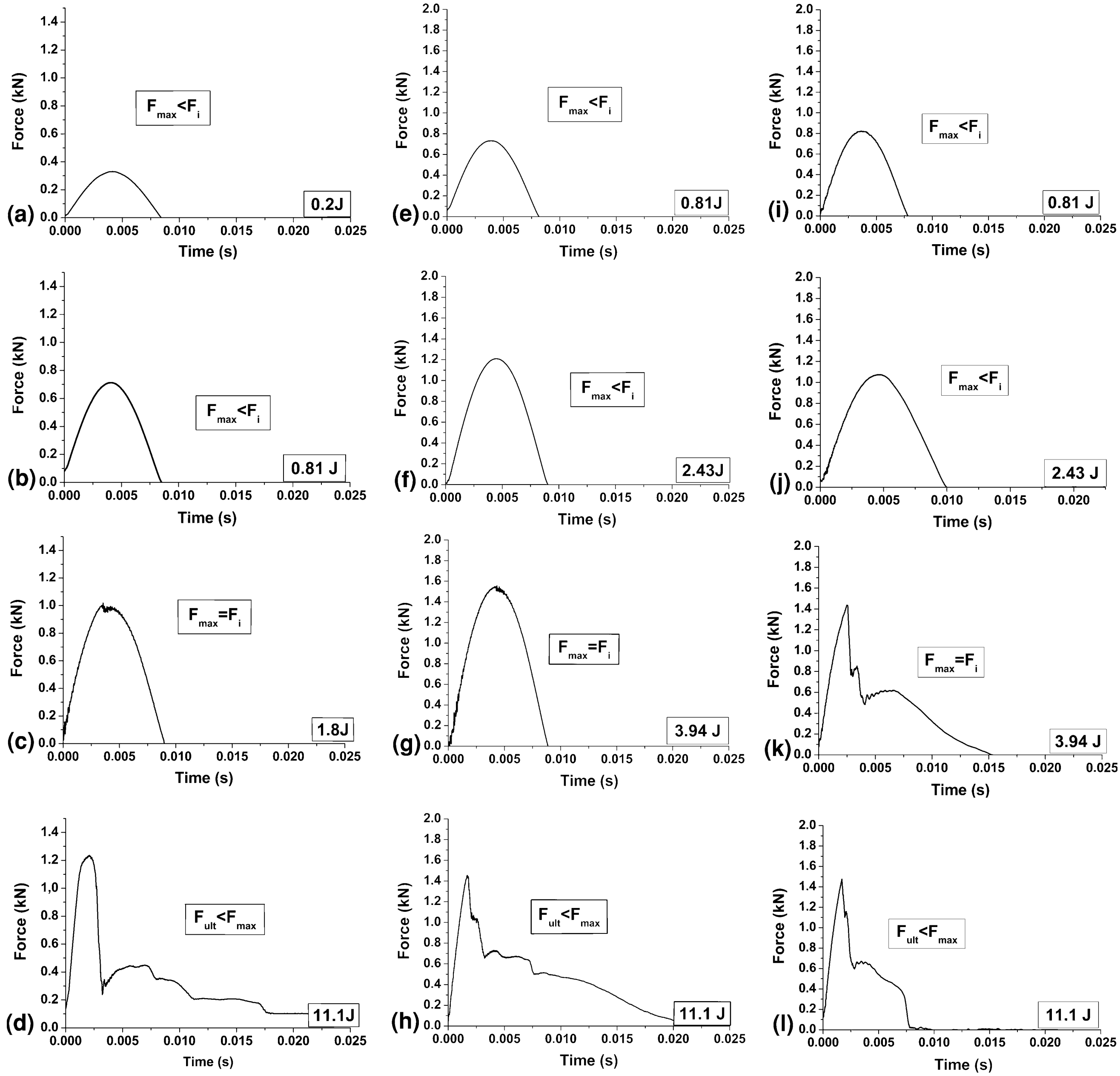


Fig. 6 Force-time (F-t) curves of impacts at energy levels lower than 25 J for non-hybrid (a-d), SMA-hybrid (e-h) and steel-hybrid (i-l) TS-glass samples

non-hybrid samples, which fracture after about 500 impacts. Instead, for steel hybrid samples, there is a worsening of fatigue impact properties (fracture after about 170 impacts). Moreover, for SMA-hybrid samples a lower "slope" in F_{max}-N curve can be observed.

This effect was observed for different impact energies, even if it becomes less sensitive for higher energy levels. Moreover, as for low energy levels, steel hybridization shows a negative effect on the damage tolerance of TS-glass composite for higher energy levels too. In Fig. 9 the results of fatigue impact experiments have been reported for TS-glass and TS-glass SMA specimens for 1.8, 2.43, and 3.14 J energy levels.

Finally, impact fatigue tests were performed on specimens obtained from the carbon reinforced laminate: in Fig. 10 the F_{max} values during the fatigue impact experiments are reported for 0.46 and 0.8 J impact energies. In this case, SMA influence on the damage tolerance of the composite is negative: in fact, for hybrid samples, there is no plateau region and fracture takes place before non-hybrid sample. Instead, steel wires have a little positive effect both on the slope curve and impacts number; however, this effect is not so sensitive as for SMA wires for TS-glass laminate.

5. Conclusions

In this work, the influence of hybridization by means of SMA and steel wires on the damage tolerance of glass and carbon fiber reinforced composites was investigated. Initially,

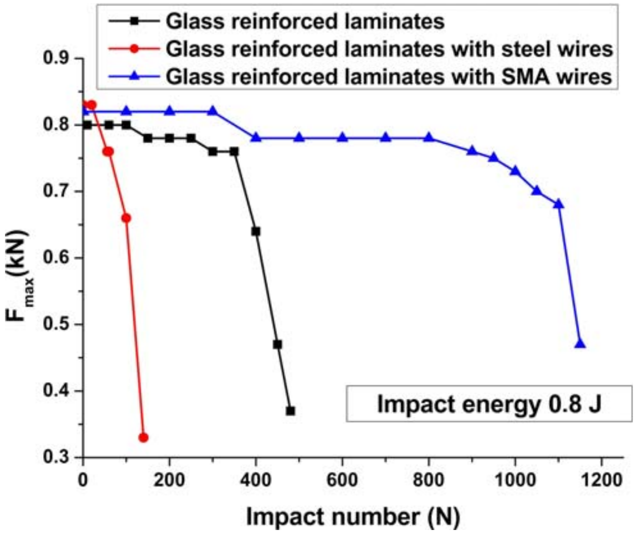


Fig. 7 Variations of F_{max} vs. repeated impact number for non-hybridized and steel and SMA hybridized samples during the impact fatigue experiments (TS-glass laminate)

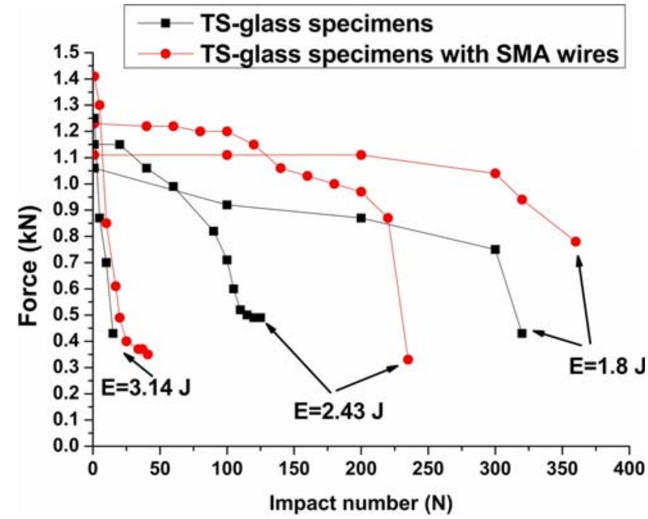


Fig. 9 Variations of F_{max} vs. repeated impact number during the impact fatigue experiments for 1.8, 2.43, and 3.14 J impact energies for steel and SMA hybridized samples (TS-glass laminate)

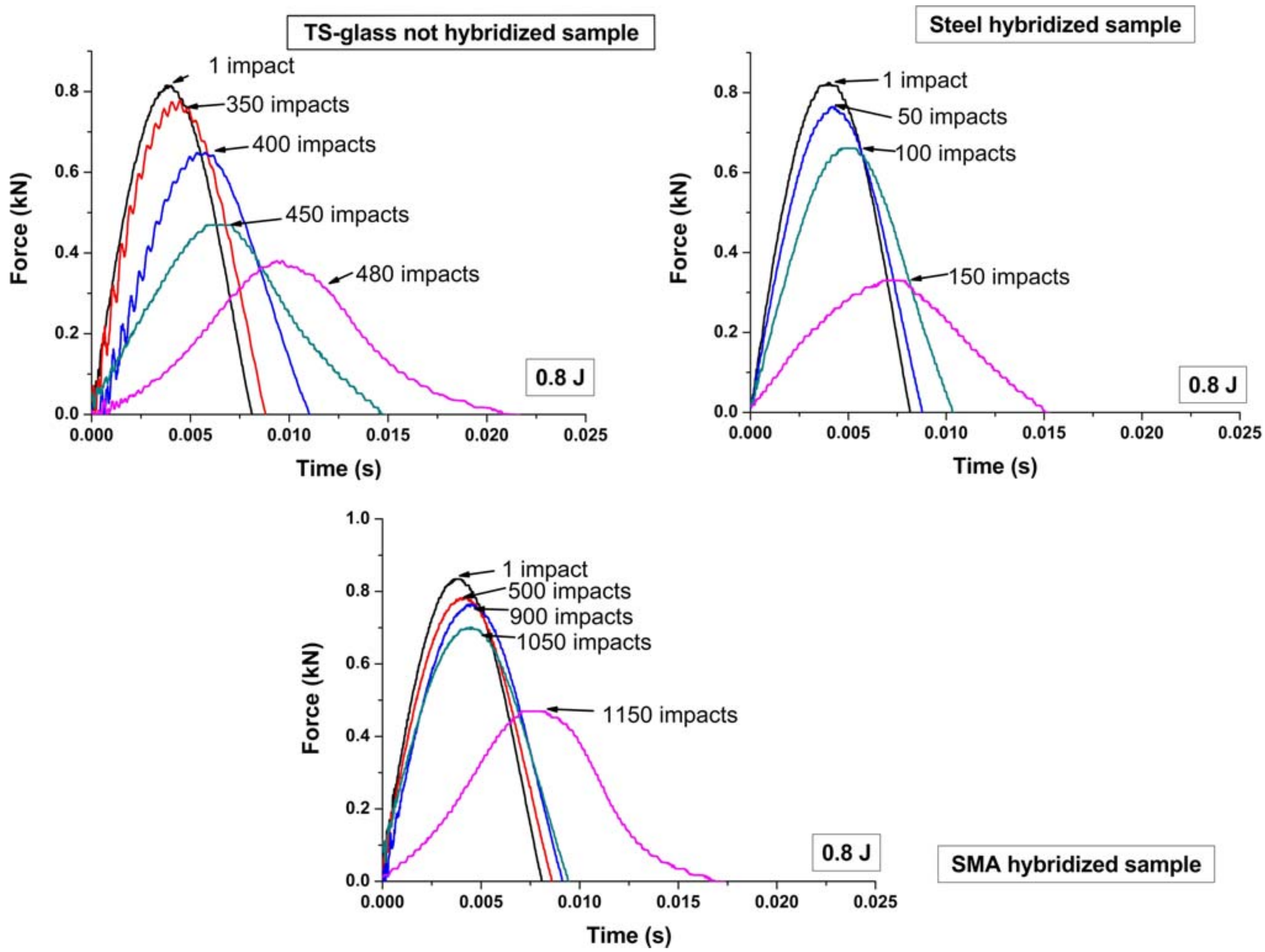


Fig. 8 Force-time (F-t) curves of impacts for 0.8 J energy level for non-hybridized and steel and SMA hybridized samples (TS-glass laminate)

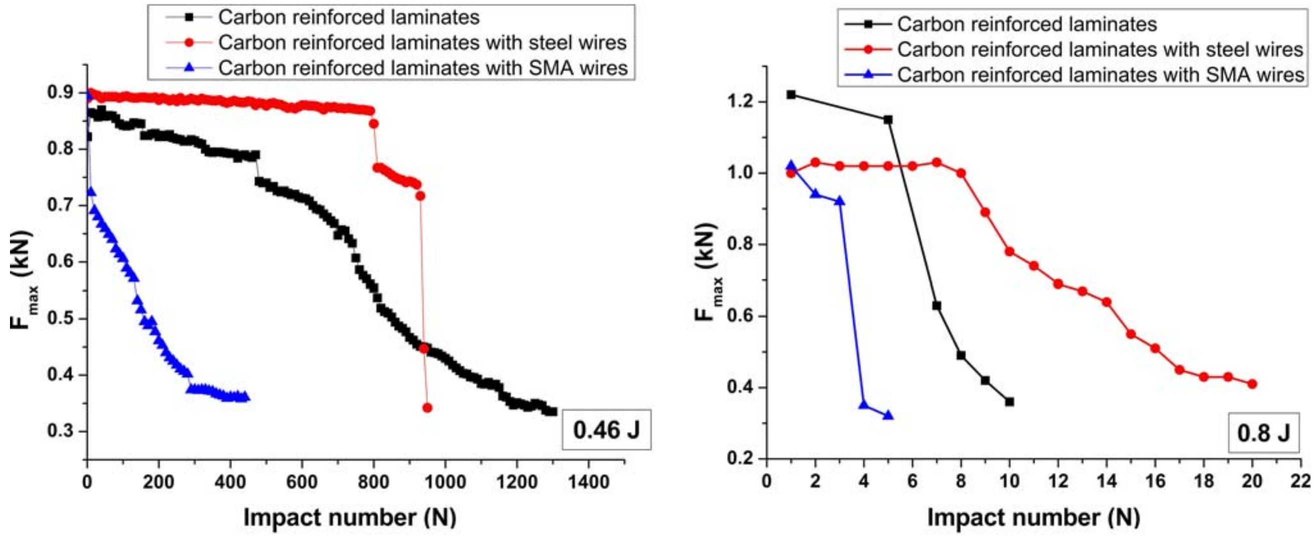


Fig. 10 Variations of F_{max} vs. repeated impact number during the impact fatigue experiments for 0.46 and 0.8 J impact energies for non-hybridized and steel and SMA hybridized samples (TS-carbon laminate)

the possibility to increase the energy to break standard Charpy samples by SMA and steel hybridization was studied. By the use of SMA hybridization a little increase of impact energy was observed, while with steel wires the increase is absent or less sensitive. This is probably due to the small amount of metallic wires embedded into the composite structures. Further tests are to be performed trying to increase the total amount of SMA wires to be embedded.

Subsequently, the samples were repeatedly impacted with less energy up to fracture, to investigate more generally the damage tolerance of hybrid composite. As reported before, SMA wires have a sensitive effect on the improving of the damage tolerance of glass reinforced laminates, while they have a worsening effect for carbon reinforced laminate. Steel wires influence is bad for glass reinforced laminate, while they have a little positive effect for carbon reinforced ones.

To understand 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 behavioral standpoint, they present a dichotomy (Ref 13). 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 obstruct 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 glass reinforced laminates more resistant to the growth of the cracks, thanks to their very good effect on obstructing this growth. Instead, in carbon reinforced laminates, they cause inhomogeneous deformations in the material, since their modulus is very lower than carbon fiber modulus and so they promote the cracks initiation. For the same reason steel wires decrease the damage tolerance of glass reinforced composites, because their higher modulus promote the cracks initiation. This effect is inverted for carbon reinforced laminates: the modulus of carbon fibers is higher than the elastic modulus of SMA wires, while it is closer to the steel modulus. However, in this case, the positive effect of steel wires is less sensitive, because carbon laminates are generally more resistant to the crack growth during cyclic loading.

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