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Shape memory composite structures for space debris removal

Loredana Santo, Leandro Iorio*, Fabrizio Quadrini* and Malgorzata Holynska***
**Department of Industrial Engineering, University of Rome Tor Vergata*
Via del Politecnico 1, 00133, Rome, Italy
***ESTEC – European Space Research & Technology Centre, ESA*
NL-2200 AG Noordwijk, The Netherlands

Abstract
A smart composite device for space debris capturing has been manufactured and tested. Shape memory polymer composites (SMPCs) have been used for the production of 4 clamping fingers, consisting of passive carbon fiber reinforced (CFR) laminates joined at their ends by active CFR-SMPC hinges. The shape trigger is provided by heat thanks to the use of flat flexible heaters. Recovery tests have been performed, under different configurations, on the single CFR-SMPC finger to evaluate recovery times and related forces. The final assembled prototype, having the shape of a 1U, is also described with its physical properties.

1. Introduction

Shape memory polymer composites (SMPC) are structural laminates with additional morphing functionalities. Their unique properties make them optimal candidates for Space structures, when structural requirements are combined with self-adapting capabilities or actuation [1]. Best examples are composite booms for solar or drag sails, self-deploying systems, debris capturing devices. In fact, SMPCs are able to freeze a non-equilibrium shape by a thermo-mechanical cycle. The composite structure is softened by heating over a characteristic temperature, deformed, and left to cool below the characteristic temperature, without removing the constraints. After cooling, the constraints can be released, and the frozen shape is preserved with a minimal elastic recovery. In order to recover the initial equilibrium shape, re-heating over the characteristic temperature is necessary in absence of constraints. This SM behaviour is defined “one way”, as a new thermo-mechanical cycle is necessary to freeze again the non-equilibrium shape. Even if two-way actuation systems may be preferred for such uses, there are many important cases where only one shape change is necessary during the operating life of the structure.
A recent innovation has been inserting SMP epoxy interlayers between adjacent carbon-fiber reinforced (CFR) layers to manufacture SMPCs with high mechanical performances [2]. In particular, the SMP epoxy resin is available as uncured powder and inserted between CFR plies during composite lamination [3]. Commercial aeronautical prepregs have been also used for the experimentation [4]. After the one-step molding of the SMPC laminate, a SMP interlayer with 100-150 μm thickness is obtained between plies. SM properties of these laminates have been tested under three-point bending with a new procedure, and remarkable SM properties have been found. Two-ply CFR SMPC laminates are easily 90° folded with low bending radius. However, by increasing the number of CFR plies, the maximum allowable strain during the memory step strongly reduces. Their shape recovery was also evaluated in micro-gravity on the BION-M1 unmanned module, where a 2-ply SMPC laminate was recovered in Space for the first time [5]. Two-ply SMPC laminates were used for first prototypes of actuators [6], space deployable structures [7], antennas [8], and solar sails [9]. Results suggest that these smart materials may be also optimal candidates for space debris capture at least in the case of small debris shape.
The problem of space debris suppression is gaining the scientific interest in the last years, because of the related technical issues and the impact on the society. Many scientific studies discuss possible solutions for debris capturing, also by proposing novel architectures and devices. Lasers can be used for debris de-orbiting by means of an orbiting satellite [10]. An amplified beam enables focusing to distances over 100 km, whereas the reflected light from the debris is collected by a telescope for precise evaluation of its size and velocity. The concept is using this satellite to remove many objects, possibly from different orbits, with the issue of satellite repositioning. This solution avoids

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any contact between the cleaning satellite and the debris to remove. As an alternative, proper devices may be used to capture the debris, including nets and harpoons [11]. These grabbing devices may be designed to capture large objects. In some laboratory studies, the target of the net was an inflated balloon whereas the harpoon was tested on a target which was attached to the same platform of the shooting system. In the case of the harpoon, the possibility of releasing secondary small debris after shooting seems to be a serious issue. The net is probably more effective. In a further study, a 2.25x2.25 m^2 nylon net with 1.59 mm cord diameter and 19.1 mm mesh size, weighing 792 g, was used [12]. A small helium cubic blimp was selected as the object to capture, as it was the largest size that could be completely enveloped by the net. Therefore, the intention of the researchers was proposing a capturing device for large object, and the Stage 2 of Zenit-2 rocket was proposed as case study. It is very hard to scale down this solution for small debris.

A good capturing system should be able to work for any debris shape and rotational energy. For this reason, the number of useful architectures of grabbing devices is limited. Foams can be adopted to put on the debris which increase the area-to-mass ratio and, as a consequence, the natural atmospheric drag and solar pressure [13]. The idea of expandable materials for reducing the time of debris de-orbiting is surely interesting but, for old satellites, these foams should be integrated for mitigation. In other cases, the complexity of the rendezvous phase of the cleaning satellite would suggest to look for faster de-orbiting solutions. The use on small debris is also difficult. According to this state-of-the-art, there is still a big margin to introduce new materials and devices for debris capture, mainly for small sizes, and SMPCs are optimal candidates.

In this study, the use of CFR-SMPCs is discussed for space debris grabbing. A prototype of a 1U device has been designed, in the shape of a “smart composite hand”, and manufactured by using conventional technologies for CFR laminates. This hand has separate fingers, which consist, in turn, of a chain of two main elements, one active (the SMPC hinge) and one passive. This kind of grabbing geometry is able to capture an object of undefined shape, avoiding its escape. Moreover, fragmentation of the debris is prevented thanks to the intrinsic damping behaviour of SMPCs after transition. In fact, SMPCs are soft during shape recovery and object grabbing, and they become rigid only when the debris is fully confined. The passive elements of the smart fingers have been manufactured by compression moulding of commercial aeronautic CFR prepregs. The SMPC hinges have been produced by using the same prepregs with SMP interlayers, which have been inserted in the shape of an uncured SM epoxy resin during composite lamination. Both passive elements and SMPC hinges were 4-ply laminates.

2. Design of the SMPC device

The design of the grabbing system, named β-DREAM (Debris Removal by the European Autonomous Module) is shown in Figure 1. It has a square based pyramid structure to maximize the capture volume. Its size has been chosen to enter the volume of a 1U, and to be mounted on the top of a 1U. The modular approach was chosen to simplify and to optimize the assembly; 4 sub-components, indicated as “fingers” or “arms”, represent the modules of the structure. Each arm is composed of passive parts, carbon fiber reinforced (CFR) laminates, and active parts, the SMPC hinges. Passive parts are responsible for the debris confinement after capture, whereas the active parts switch from the open to the closed configuration by heating.

The single arm is made with trapezoid and triangle CFR laminates (passive elements), and 2 SMPC hinges as active elements. In detail, one hinge, which refers to the “first level”, connects the trapezoid CFR laminate to the top surface of the 1U. The second hinge, which refers to the “second level”, connects the triangle laminate to the trapezoid one. Bolts are used for assembling.

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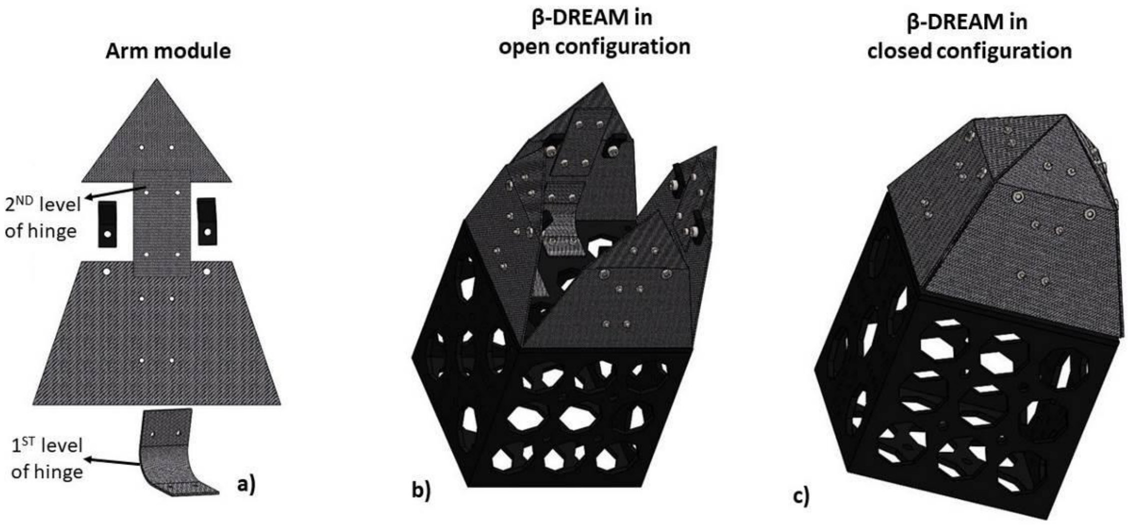

Figure 1: Single arm (a) and full grabbing device in open (b) and closed (c) configuration.

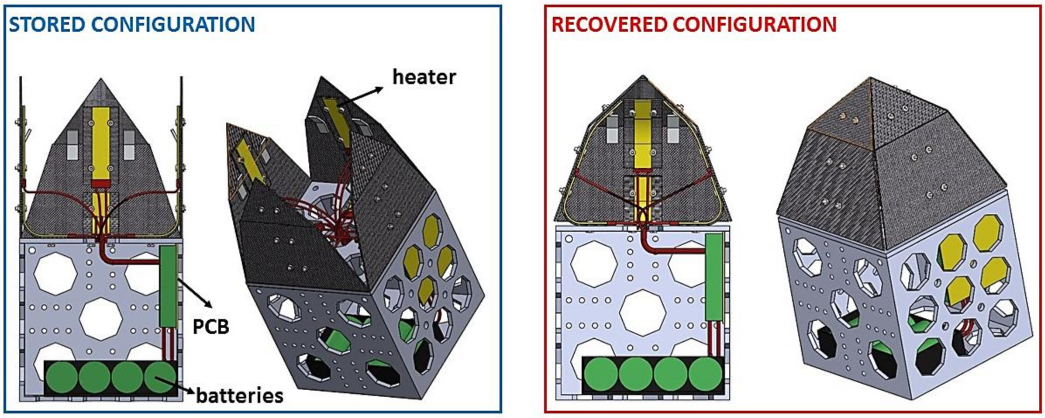

Figure 2: Final assembly of β-DREAM prototype.

The architecture of the SMPC hinge, which is 4-ply with 3 SMP interlayers, has been also selected on the basis of results from durability tests [14]. In particular, 10 memory-recovery cycles have been repeated on laminates with different number of plies (from 2 to 8) in the cantilever configuration. Results show that damages do not occur at low number of cycles if the laminate is deformed in the elastic range at the test temperature.

Shape recovery is activated through external heating devices placed on the intrados of the hinges. The heaters cannot adhere to the SMPC laminate surfaces otherwise they would prevent shape recovery. Sliding is necessary between the heater and the SMPC laminate surface. For this aim, the contact is guaranteed by using thin kapton stripes that tie the heaters with the hinges. Each heater has a resistance of 80 Ω and the maximum operating temperature of about 200°C. In previous studies, the maximum applied voltage for this kind of heater was 24 V at which a temperature of 196°C was reached [15]. In Figure 2, the final assembly of the grabbing module is shown with most of its parts.

2. Manufacturing of the SMPC device

The manufacturing procedure to obtain the DREAM prototype can be divided in 3 phases: the first phase for the active part (SMPC hinges), the second phase for the CFR structural laminates, and the third phase for assembly. The production of passive and active elements is based on compression moulding of CFR prepreg. The same procedure has been applied to CFR laminates and SMPC hinges. Commercial materials were used: Hexply M49/42%/PW CCF-3k prepreg (by Hexcel), and Scotchkote 206N resin (by 3M) as SMP.

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2.1 Active elements

The active elements are the SMPC hinges, which were obtained by pouring the uncured epoxy powder in the form of a thin layer, about 150µm thick (0.2g), between rectangular prepreg stripes, during lamination. As shown in Figure 3, the SMP powder covered almost the entire length of the CFR sheets, apart the ends.

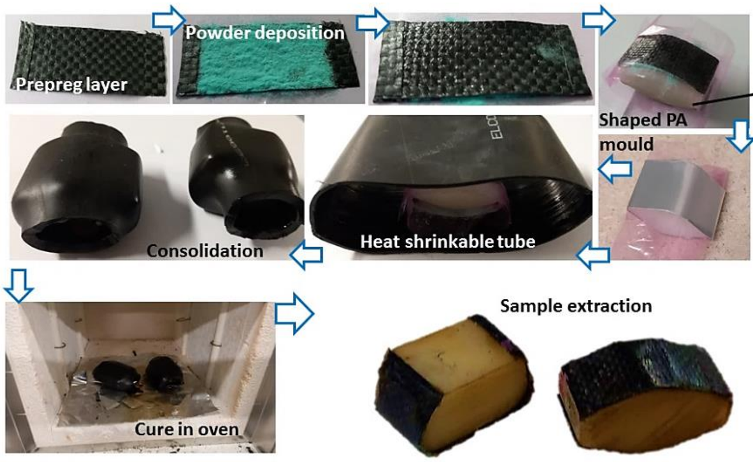

Figure 3: Manufacturing procedure of active elements (SMPC hinges).

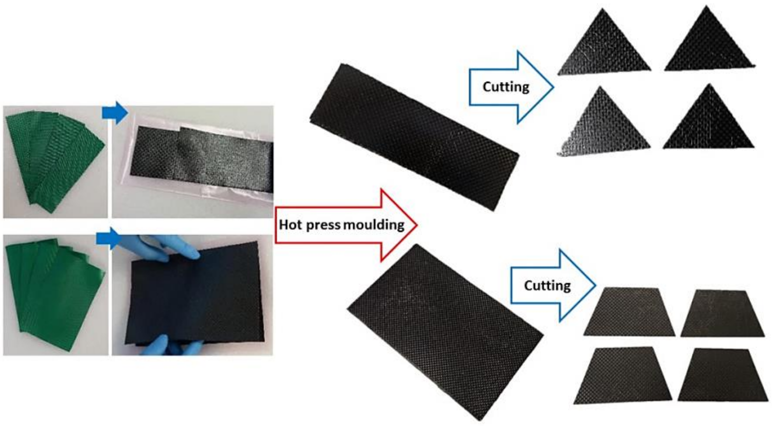

Figure 4: Manufacturing procedure of passive elements.

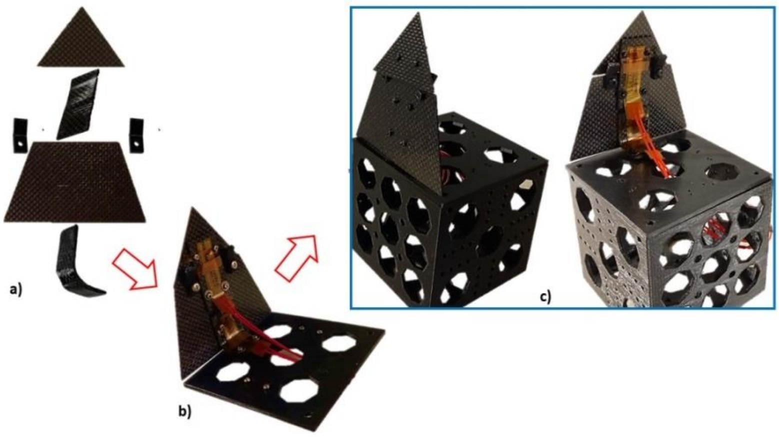

Figure 5: Assembly phase of a single smart arm.

The lamination sequence consisted of 4 CFR prepreg plies, and 3 SMP interlayers. Small prepreg stripes, 5x22 mm^2 in size, were also placed at the ends of the deposited SMP interlayers to confine the powder during the following shaping and agglomeration steps. In order to provide the initial curvature of the hinge, in the equilibrium configuration, the uncured SMPC laminates were placed on shaped PA moulds. Thin release films were also used between the moulds and the laminated composites to avoid adhesion during cure. In the end of the lamination procedure, aluminium foils were also inserted on the external skin to have smooth moulded surfaces. The required molding pressure was achieved by heat-shrinkable tube (by ElconMegarad, Italy). The tube recovers its shape in oven thus applying a consolidation pressure to the laminate. The initial diameter of the tube was 85mm, and it reaches 22mm upon heating in free conditions. The entity of the agglomeration pressure by the heat-shrinkable tubes was also estimated, ranging between 0.06 and 0.15bar. Cure was made in oven at 200°C for 1h. Finally, SMPC hinges were extracted from moulds, and the excess of resin, due to edge bleeding, was removed. The average weight is 2.23g for the first level of hinges, and 2.42g for the second level.

2.2 Passive elements

Passive elements were manufactured by using 4 CFR plies with the procedure of Figure 4. Initially, rectangular laminates were compression moulded on a heater plate at 200°C for 1h. The applied pressure of 15kPa was sufficient to reach the expected laminate consolidation. CFR triangles and trapezoids were cut from 50x160mm^2 and 125x210mm^2 rectangular panels, respectively.

2.3 Assembly

The assembly stage was divided in two main sub-steps, first the assembly of the single arms and, subsequently, their insertion on the 1U of the "β-DREAM" device. The single arm is obtained by combining 2 passive elements (one CFR trapezoid laminate and 1 CFR triangle) and 1 SMPC hinge. In Figure 5, the assembly of a single arm is shown.

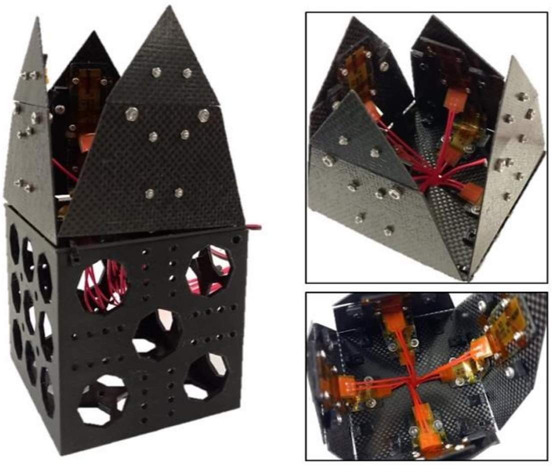

Figure 6: Final assembly of the SMPC grabbing device.

In the open configuration, the shape of the full arm is a triangle. The flexible heaters are also shown at the intrados of the SMPC hinges. All the manufactured smart fingers have been assembled by mechanical joints on the 1U, as shown in Figure 6. The weight of the assembly (consisting in the top plate, the fingers, he heaters and all the connecting wires and joints) is only 130.56 g. All the heaters have been connected in parallel, and the whole electric resistance have reached the value of 10 Ω, according to the manufacturer's data sheet. The grabbing device is confined in a 1U volume, both in the open and closed configuration. In fact, the maximum height in the open configuration is about 98 mm.

2. Testing functionalities of the smart fingers

The functionality of the single arm has been evaluated by free and constrained recovery tests. Under constraints, the recovery load was also evaluated. The first tests were made to evaluate the ability of the arm of the β-Dream prototype to close correctly. On the basis of previous experimentation, and by considering technical limitations due to the adopted flexible heaters, the maximum voltage of 24V was applied. Heaters were connected in parallel to the electric supply.

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In Figure 7 the sequence of shape recovery is shown. During the test, the current intensity of 0.55A was measured, thus generating a power of 13.2W. As a result of the free test, the full shape recovery was achieved. The flexible heaters did not detach from the SMPC hinge surfaces during sliding. Recovery tests were repeated with the same configuration. Results showed that SMPC hinges with high number of plies can undergo several memory-recovery cycles if the memory angle is small (less than 45°). Full shape recovery of the smart arm was always achieved in about 4 min. Generally the first 2min are required to reach the maximum temperature at the applied voltage.

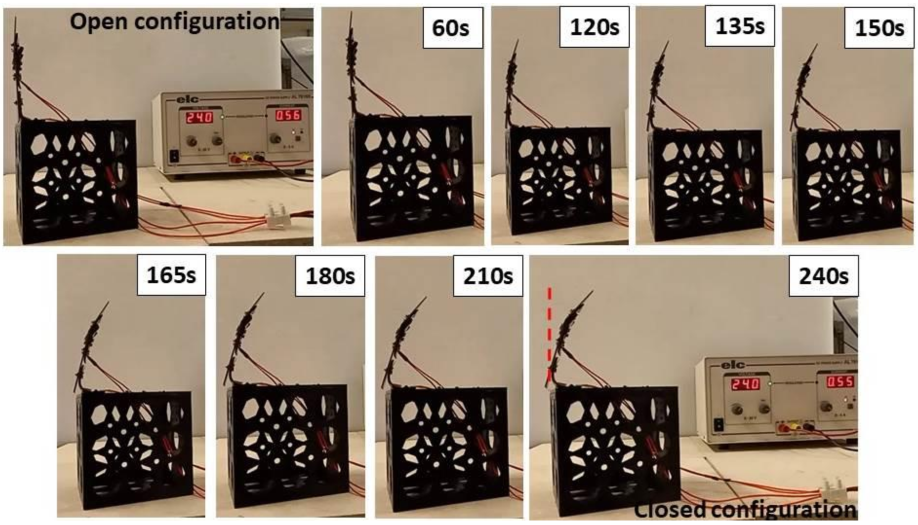

Figure 7: Recovery test of the SMPC finger.

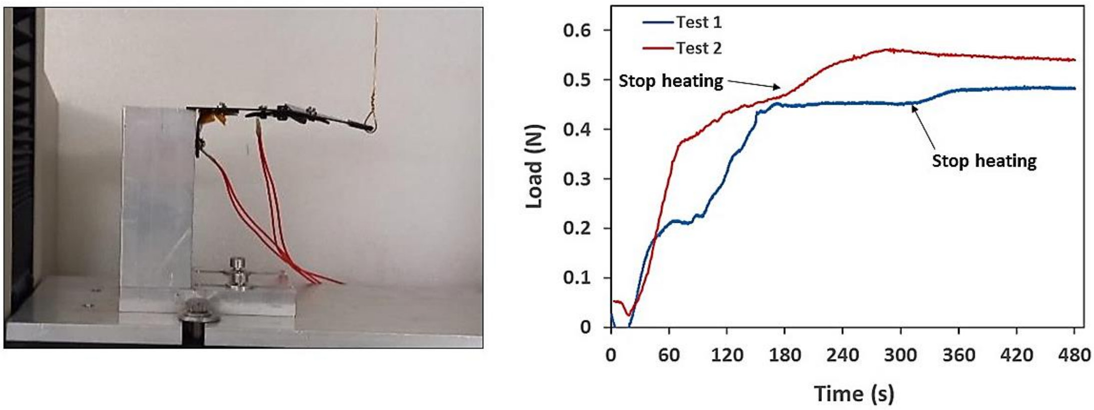

Figure 8: Configuration and results from recovery load measurements of the smart finger.

The second test typology for the single arm was made by constraining its free end, as shown in Figure 8. These tests aimed at evaluating the recovery load of the arm upon recovery, and were performed on a universal material testing machine (MTS Insight 5). During the test, the machine crosshead was fixed, and the free end of the smart arm was connected to it by a metal wire. A minimum preload was applied to have the wire in tension. Heating-cooling cycles were performed at the same voltage of 24V, with a current of 0.55A and a power of 13.2W, as well as for the free recovery tests. Similar recovery loads were measured, about 0.45N for both tests. During cooling, a load increase was found, up to 0.48N for the first test, and 0.54N for the second.

3. Conclusion

A first prototype of a SMPC grabbing device (called β-DREAM, Debris Removal by the European Autonomous Module) has been manufactured and tested under several memory-recovery cycles without evident damages. A limit for the maximum number of cycles has not been found yet, but previous studies allowed testing SMPC samples under 10 consecutive memory-recovery cycles without failures. The prototype of the grabbing device is fully in composite, without mechanical parts apart from screws and bolts. The β-DREAM prototype is about 130 g in weight, and their single fingers have been operated at the voltage of 24 V and the power of 13.2 W, leading to a recovery time lower than 4 min. Next step is testing the functionality of the full device in debris capturing tests. From the manufacturing point of view, some improvements are necessary, by reducing hand operations and inserting automatic procedures for composite moulding and assembly.

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