

Article

Soft Actuation in Space Environment Through Autoclave-Molded Shape Memory Polymer Composites with Embedded Heater

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Abstract

Telecommunication, energy generation, defense and research are just a few of the sectors that need to deploy structures in the space environment. Traditional systems are complex and expensive and, as a result, there is a critical need for new solutions. Shape memory polymer composites (SMPCs) have the potential to be used in such systems, since they can provide an actuation load during shape recovery. In this paper, an SMPC device with an embedded heat source, used to trigger the shape change, was manufactured by hand lamination and autoclave molding. A thermo-mechanical cycle was applied to investigate the SM ability. Tests were performed by powering the heat source from 20 V to 24 V. Recovery angle and recovery speed were evaluated at 24 V. Microscopy showed that a good level of agglomeration was reached thanks to autoclave molding, with the functional interlayer being uniformly distributed. SM tests underlined that the recovery load was not affected by the memory temperature and, regardless of the activation temperature, it always reached the same plateau value. Finally, the SMPC device was integrated into a 1U CubeSat and used to deploy one of its sides; an opening of 28 deg was obtained in only 45 s.

Keywords: soft actuation; shape memory polymer composites; carbon fiber reinforced composite; autoclave molding; space



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1. Introduction

Shape memory polymer composites (SMPCs) are stimuli-responsive materials which react to external changes by varying their shape. They can be deformed into a temporary configuration by means of a trigger that permits the transition between the two states. The material is able to recover its initial shape once the same stimulus is reapplied. Typical triggers are light, pH variation, magnetism and temperature [1]. An example was provided by a 4D-printed spine bone that was successfully deployed with the action of a magnetic field [2]. Also, SM behavior can be activated by an electric field, but SMPs should be doped with conductive materials [3]. Several studies showed that epoxy resins are characterized by good SM ability. Epoxy-based SMPCs are generally activated by temperature changes, which unlock the cross-linked molecular structure, ensuring the mobility of the polymeric chains. Molecular mobility increases when the glass transition temperature (T_g) of the polymer is exceeded; under these conditions, the composite is easily deformed and stores

a certain amount of energy, which is released during shape recovery. The SM effect is commonly investigated by theories based on thermodynamic constitutive models, working on a macroscopic or microscopic level. The former is based on rheological properties, while the latter is based on phase transition [4]. When dealing with SMPCs, SM behavior is also influenced by fiber arrangement; for example, the satin texture exhibits higher capabilities than twill and weave [5]. The presence of the fibers guarantees structural performance, while the SMPs provide multifunctionality. Furthermore, SMPCs are lightweight and have high specific strength, which makes them particularly promising for space applications. In such a sector, they can be used as hinges [6], trusses and booms for solar sails, grabbing devices, solar arrays and antennas [7,8], and eventually inflatable lunar habitats [9]. These challenging systems require a new generation of aerospace materials for thermal protection, shielding from ionizing radiation and resistance to atomic oxygen erosion [10]. SMPCs can withstand several thermo-mechanical cycles without showing any damage [11] and can resist moisture, aging, UV light and lubricants for a long period [12]. However, prolonged isothermal exposure at high and low temperatures, as well as thermal cycling, slows down the shape recovery response [13]. SMPCs can also be obtained in the form of aerogels; polyimide-based ones were manufactured by including 2 wt% of amino-functionalized carbon nanotubes, which showed very good SM behavior, with a shape fixity ratio of 98.8% and a shape recovery ratio of 97.2% [14].

Unlike hold-down release mechanisms (HDRMs), which permit a rapid release of stored energy for structure unfolding [15], SMPCs and some shape memory alloys (SMAs) can behave as Non-Explosive Actuators (NEAs) [16]. In particular, SMAs have been used as spring actuators for a non-explosive ball-type pin puller, with the material releasing a ball-lock mechanism [17]. SMAs were also used to enable rapid in situ reprogramming in response to an external stimulus [18]. However, soft actuation has the potential to limit the risk of premature damage and failure during deployment [19]. The most used low-shock connection and separation devices are segmented nut mechanisms, flywheel nut mechanisms, steel ball mechanisms and notched bolt mechanisms [20], with the main non-pyrotechnic sources of actuation being based on electrical and magnetic energy, gases, SMAs and thermal knives. Nevertheless, SMPs are preferred for applications in which density reduction and high flexibility are design parameters [21]. A further weight reduction could be achieved by using SMP porous materials, which allow tailoring the performance of the structure to the specific application [22].

The use of smart polymer composites in advanced sectors such as aeronautics and aerospace is strictly influenced by manufacturing. Epoxy-based composites with SM properties have already been produced with traditional technologies of composite laminate fabrication such as vacuum-assisted resin transfer molding (VARTM) [23,24], pultrusion [25] and filament winding [26]. In this context, L-shaped SMPCs were manufactured by VARTM as panel and wire hinges based on their width; it was shown that the former configuration allowed a higher deployment accuracy and an increment of 43.1% in the deployment speed [27]. Furthermore, SMPCs with good SM ability have been obtained by additive manufacturing [28]. Also, compression molding was used to manufacture SMPCs; a novel class of smart composites has been developed by depositing an SM epoxy interlayer between adjacent layers of carbon fiber-reinforced (CFR) prepreg [29]. These SMPCs have been studied for soft actuation and for self-deploying systems [30] and have been validated in the space environment during the MISSE-9 experimental campaign [31]. It was shown that a heat source can be integrated into these SMPC structures, favoring the use of such materials in complex systems [32].

The present study aims to take a step forward in the actual implementation of SMPCs in space structures, providing a deeper understanding of the effect of both manufacturing

and memorization on the SM behavior of composite laminates. Manufacturing by autoclave molding instead of traditional compression molding represents a major innovation compared to previous studies, with this advanced technology establishing a strong link with the industrial world. In addition, this work highlights the correlation between the SM activation temperature and resulting actuation load, providing a robust basis for the design of actual deployable systems. For this purpose, an autonomous SMPC device was prototyped and tested. SM ability was evaluated by memory, constrained-recovery and free-recovery cycles, with the experimental campaign being conducted in such a way as to identify the correlation between the deformation method and the available actuation load. Finally, the SMPC device has been connected to a standard 1U CubeSat and used as a smart actuator to open one of its sides.

2. Materials and Methods

2.1. Supplied Materials

A 2-ply CFR-SMPC with an embedded heating system was manufactured in 3 main steps: hand lamination, vacuum bagging and cure in an autoclave. Commercially available materials were used for this purpose. A CFR prepreg commonly used in the aeronautic industry CC202 ER450 39% T300 3k by Composites Materials (Legnano, Italy) and designed for autoclave molding was used to obtain the external plies of the composite structure. The prepreg was made of CFs arranged in a plain weave and impregnated with a high-performance epoxy resin having a curing range between 80 °C and 180 °C. The SM interlayer consisted of an uncured epoxy powder Scotchkote 206N (3M, St. Paul, MN, USA), which was deposited between prepreg plies. The flexible heater KHLVA-0504/10 (OMEGA, Engineering Ltd., Manchester, UK) worked as a heat source; it had a nominal thickness of 150 µm and a surface area of $13 \times 90 \text{ mm}^2$. The heater was made of an etched copper circuit with a nominal resistance of 40 Ω encapsulated between 2 layers of polyimide film.

2.2. Manufacturing of the Smart Composite Device

Prepreg plies of size $20 \times 150 \text{ mm}^2$ were extracted from the supplied roll by cutting. The SM interlayer was deposited on the surface of one ply with a nominal thickness of 150 µm before positioning the flexible heater. On top, an SM layer was placed, followed by the second composite ply.

The uncured laminate was positioned on a large aluminum plate and covered with a 1 mm thick aluminum caul plate to obtain a smooth surface. A 50 µm thick fluorinated ethylene propylene (FEP) release film was used to avoid adhesion between the prepreg and external aluminum plates. The Airweave® N10 breather (Airtech International Inc., Huntington Beach, CA, USA) was placed at the top of the assembly and covered the bottom aluminum plate. Finally, a nylon bag was stuck over the supporting plate with tacky tape AT 200Y (Airtech International Inc., Huntington Beach, CA, USA)). The whole procedure is shown in Figure 1.

An initial vacuum of 0.5 bar was applied for 1 h, according to the CFR prepreg datasheet. Then, consolidation was carried out in an autoclave at 130 °C and 3.2 bar for 100 min with heating and cooling rates of 2.5 °C/min and 1.0 °C/min, respectively.

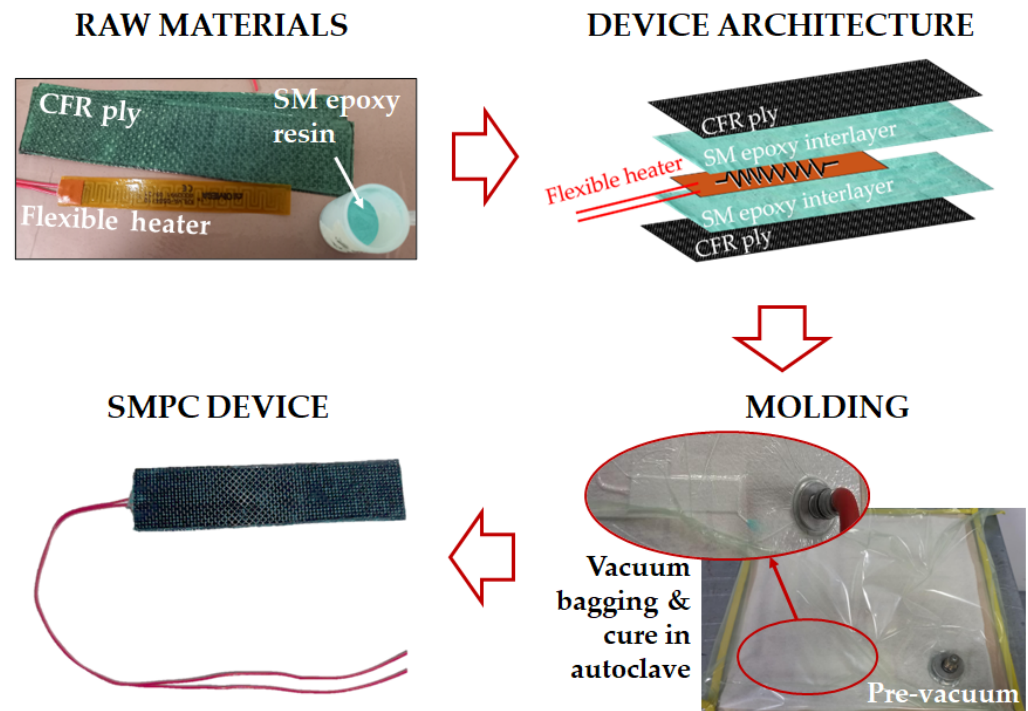


Figure 1. Manufacturing of the SMPC device.

2.3. Device Characterization and SM Testing

Physical properties of the manufactured SMPC device were measured after molding. Optical observations were carried out with a stereomicroscope Leica S9i (Leica Microsystems Ltd., Heerbrugg, Switzerland) to investigate the homogeneous distribution of the SM interlayer as well as the presence of voids and cracks.

Before SM testing, preliminary measurements were performed to identify the correlation between the voltage of the heater and the resulting temperature. The SMPC activation temperature was 120 °C, and thus, it had to be exceeded to trigger the shape change [30]. To investigate this aspect, the SMPC device was positioned on a support and powered from 20 V to 24 V with a step of 1 V; temperature changes were recorded by a thermo-camera Testo 883-1 (Testo SE & Co. KGaA, Titisee-Neustadt, Germany). At 20 V, the device reached 141 °C, while 182 °C was obtained during the test at 24 V; it was observed that the composite temperature increased with the applied voltage.

SM tests were conducted using a universal material testing machine MTS Insight 5 (MTS Systems Corporation, Eden Prairie, MN, USA) equipped with 3-point bending fixtures. A thermo-mechanical cycle, which included memory, constrained-recovery and free-recovery tests, was performed to evaluate both SM and mechanical performance. The memory test was performed at 10 mm/min with a span length of 90 mm and a maximum displacement of 10 mm. The device was deformed to the selected displacement at room temperature. Then, the heater was powered for 3 min; the load decreased until a plateau was reached. The same voltages as in the temperature tests were used, which corresponded to a power ranging from 10 W to 14.4 W and a current between 0.5 A and 0.6 A. Subsequently, the device cooled to room temperature for 4 min, after which the constraint was removed. In this way, the temporary shape was fixed. A representative curve is reported in Figure 2a; the load corresponding to the maximum inflection was the applied memory load (L_a), whereas the loads of the 2 plateaus were the memory load (L_m) and the residual memory load (L_{mr}), respectively. During the subsequent constrained recovery tests, the 3-point bending configuration was maintained with the device being initially subject to a preload of 1 N. The heater was powered for 4 min, after which the composite

was left to cool for an additional 4 min. In the first step, the load rapidly increased until a plateau was reached, while, as the SMPC cooled, the load decreased to a second plateau value. In Figure 2b, the load–time curve is shown. In the load recovery curve, the load of the hot plateau was the recovery load (L_r), and that of the cold plateau was the residual recovery load (L_{rr}).

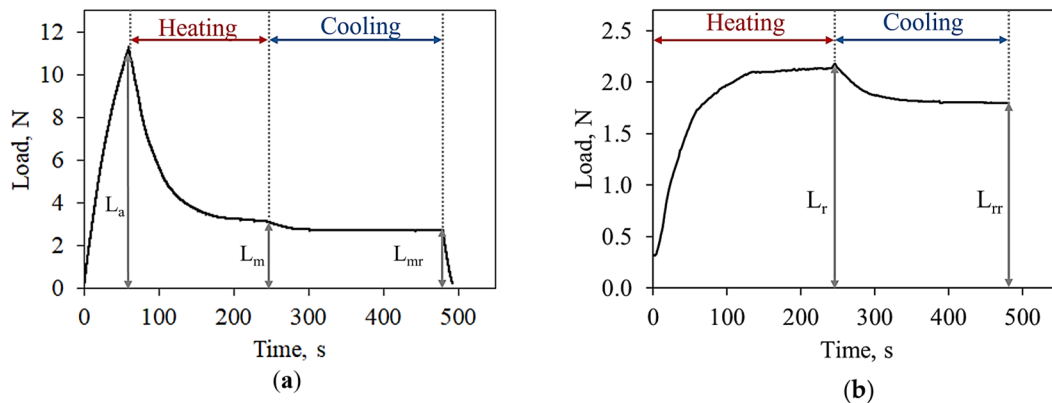


Figure 2. Shape memory tests at 22 V: (a) load–time curve during memory test, (b) load–time curve during constrained recovery.

Finally, free recovery was carried out with the sample being heated without any constraint in such a way that the initial shape was recovered.

The SM performance was evaluated by the shape fixity ratio (R_f), the material's ability to fix a deformed configuration, and the shape recovery ratio (R_r), the SMPC's ability to restore the undeformed configuration. They were calculated by Equations (1) and (2), respectively, where ε_u was the true applied strain after load removal, ε_e was the recovered strain calculated as the difference between the maximum applied strain in the memory test (ε_m) and the final residual strain after the free recovery test (ε_p). The recovery rate was obtained by image elaboration since the SMPC device was not removed from the supports during testing.

$$R_f = \frac{\varepsilon_u}{\varepsilon_m} \times 100 \quad (1)$$

$$R_r = \frac{\varepsilon_e}{\varepsilon_m} \times 100 \quad (2)$$

2.4. Prototype Testing

In this section, the part of the experimental campaign which was designed considering the actual implementation of such SMPCs is described. The SMPC was deformed into an L-shape and fixed on an aluminum plate in a cantilever configuration with the material testing machine punch applying a preload of 0.05 N. The testing setup is shown in Figure 3a. The composite was powered at 24 V, recovering part of the applied deformation when the machine punch was removed; thus, the following tests were conducted by positioning the punch at 1 mm from the device top surface. The load provided during shape recovery, L_r , was evaluated as the vertical load (L_{rv}) divided by the cosine of the angle (θ), which was formed by the initial flat side of the L-shaped composite and the final shape obtained after testing, as reported in Figure 3b. A total of 6 recovered angular positions were evaluated.

In the end, the SMPC device was memorized again in an L-shape with a radius of curvature of 17.5 mm and joined to the vertical wall of a standard 1U CubeSat by heat-resistant glue. The opposite side was fastened to a composite plate which served as the 6th wall of the 1U structure. The CubeSat was made of polyethylene terephthalate glycol (PETG) and manufactured through fused deposition modeling (FDM) using the Prusa i3

MK3 (Prusa Research a.s., Prague, Czech Republic), with 5 out of 6 walls being printed. The final system is shown in Figure 4. The smart actuator was supplied with 24 V to test its ability to deploy the top plate.

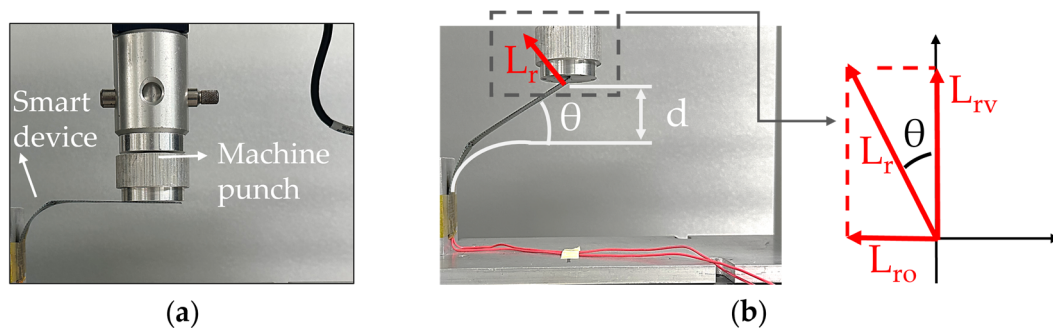


Figure 3. (a) L-shaped deformed configuration before test starting; (b) intermediate deformed configuration after elastic recovery at the end of test.

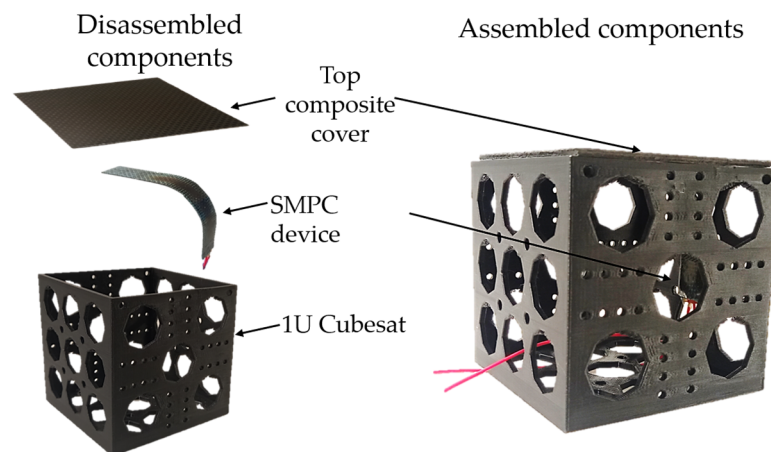


Figure 4. Prototype of a 1U CubeSat with the installed SMPC device.

3. Results

The manufactured SMPC device had a mass of 9.3 g and a nominal size of $150 \times 20 \text{ mm}^2$. The thickness was not uniform because of the presence of the embedded heater; indeed, it was $0.93 \pm 0.21 \text{ mm}$ in the areas that included the heat source and $0.67 \pm 0.07 \text{ mm}$ in the other regions. A good level of agglomeration was achieved by autoclave molding, as shown by microscopy in Figure 5. The distribution of the SM interlayer was uniform, and voids were not visible. The appearance of the device surface was characterized by the presence of blue areas at the intersection between the warp and weft directions of the CFs; this was due to the surfacing SM interlayer, which had the same color.

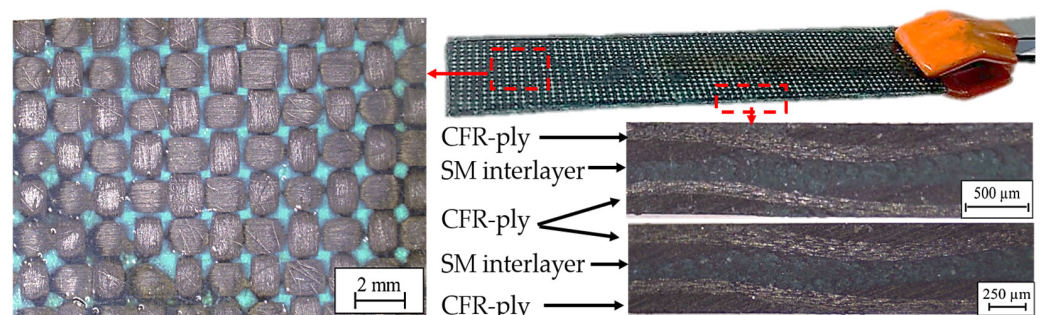


Figure 5. Microscopy of the interface and of the top surface of the SMPC device.

Before SM testing, the temperature of the SMPC device was measured at different voltages. Figure 6 shows the thermography of the SMPC at different voltages, highlighting the maximum temperature achieved during each test.

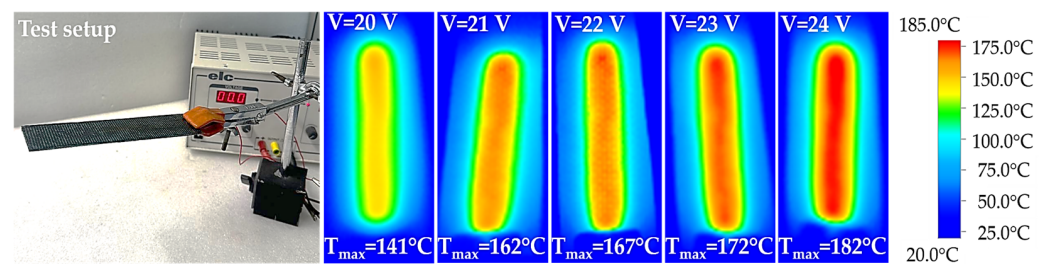


Figure 6. Temperature evaluation at different voltages.

In terms of mechanical properties, the SM device stiffness was 2.2 N/mm, and its bending modulus was 27.9 GPa; these data were extracted from the loading step of memory tests which were carried out at room temperature.

A thermo-mechanical cycle was designed to trigger SM behavior. The device was tested only once for each voltage to provide evidence of the different trends. However, repeatability is a critical factor for the actual implementation of these devices, and it will be further explored in future studies. The behavior of the SMPC device during each step of the thermo-mechanical cycle is shown in Figure 7. The reference loads, which were identified in Figure 2, are reported in Table 1 for each applied voltage. Both L_m and L_{mr} decreased with increasing voltage, while a correlation between L_r and L_{rr} and the electric potential was not found, since very small variations were observed. In particular, L_r and L_{rr} were 2.1 ± 0.02 N and 1.8 ± 0.04 N, respectively. An evaluation of the SM behavior was provided in terms of R_f and R_r . The R_f increased from 52% to 76%, which were obtained during the tests at 20 V and 24 V, respectively. The increment was almost linear, but data scattering was noticed at 21 V and 22 V, with the latter being slightly smaller than the former. A very high R_r was recorded in all the tests, with the smallest value being 94%, obtained at 24 V, and the greatest being 100%, obtained at 22 V.

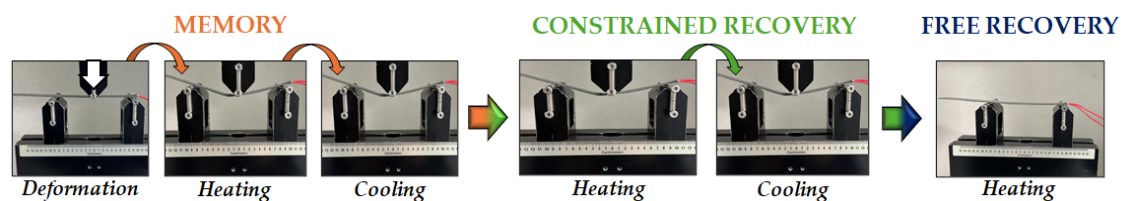


Figure 7. SMPC device shape changes during the thermo-mechanical cycle.

Table 1. Shape memory properties extracted from the thermo-mechanical cycles.

Voltage, V	Memory Load, N	Residual Memory Load, N	Recovery Load, N	Residual Recovery Load, N	Shape Fixity Ratio, %	Shape Recovery Ratio, %
20	3.9	3.5	2.1	1.8	52	99
21	3.4	3.0	2.2	1.8	63	99
22	3.1	2.7	2.1	1.8	58	100
23	2.9	2.5	2.1	1.8	71	96
24	2.8	2.2	2.2	1.7	76	94

Subsequently, the device was deformed into the L-shape according to the testing setup shown in Figure 3; the SMPC actuator was fixed on an aluminum support, and its free edge was in contact with the machine punch. Results of constrained recovery tests are shown in Figure 8, with all angular positions and corresponding recovery loads being reported. At the end of each test, the SMPC device partially recovered the deformed shape (Figure 8a) because of the thermal cycling. The recovery angle was 8.5 deg after the first test and 48 deg after the last one; on average, the specimen recovered 10 deg during each cycle. The recovery load was maximum during the first test, having a magnitude of 0.58 N, and then an average value of 0.24 ± 0.02 N was obtained (Figure 8b).

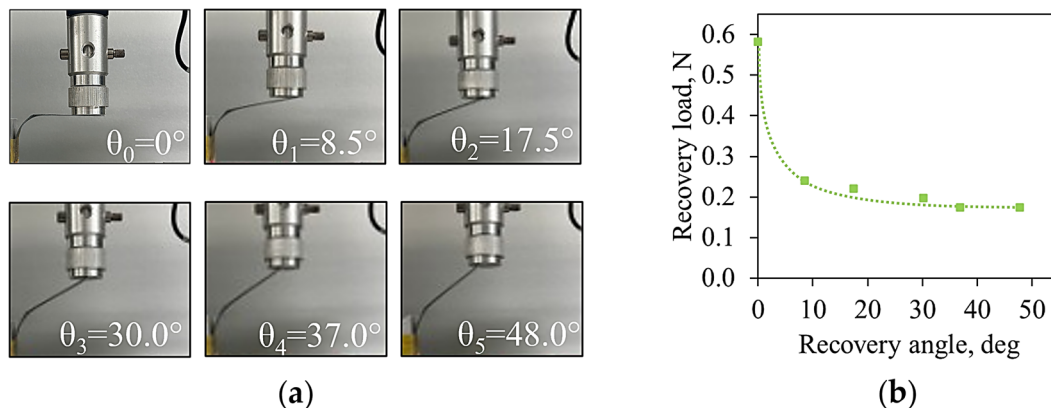


Figure 8. (a) Evaluation of recovery angle at 24 V; (b) recovery load as a function of the recovery angle.

Finally, the SMPC device was used as a soft actuator for deploying the CFR composite plate of the 1U CubeSat, with results reported in Figure 9. During testing, the SMPC device recovered about 28° in 45 s, which was 31% of the applied deformation. The test did not proceed until the full opening was reached because the high temperature caused the softening of the polymeric CubeSat, which was made of PETG, and distortions were observed. The average angular recovery speed was 0.62 deg/s.



Figure 9. Opening of the top composite cover of a standard 1U polymeric CubeSat.

4. Discussion

A large variety of orbiting structures require deployment in the space environment, with typical examples being reflector antennas, booms, solar sails and arrays. Actuation can be provided by motors, inflatable devices and both explosive and non-explosive systems. These solutions are valid, but the high weight and the complexity of the apparatus are great constraints, especially considering the increasing number of space missions. In this frame, SMPCs represent a suitable alternative to traditional deploying systems, since they can provide an actuation load during shape change.

The choice to use commercially available raw materials as well as industrial-scale manufacturing processes, such as autoclave molding, was made with the aim of providing

a point of contact between research and industry, favoring technology transfer. Materials and technologies that are already close to the industrial background are now seen from a different point of view, being used for innovative and high-value applications through a deep redesign and re-engineering of components.

In this work, the SMPC device was deformed at room temperature, and the new configuration was stored by heating and further cooling under constraint. This procedure was developed to ensure that the SMPC would not fail because of the applied deformation; however, hot programming and subsequent cooling represent a viable alternative. At the end of the cooling step, the constraint was removed and the measured load returned to 0 N, as shown in Figure 10, with the actual stored load being the difference between L_a and L_{mr} . Ideally, the SMPCs should be able to store the entire applied load (i.e., $L_{mr} = 0$ N), but the viscoelastic nature of the polymer and the presence of stiff constituents such as CFs did not permit reaching this condition. When the composite was heated, the molecular chains of the epoxy resins began to move, and stresses were relaxed; consequently, a portion of the applied energy was spent for this purpose and could not be stored in the laminate. On the other hand, CFs had high stiffness and excellent mechanical properties, which were fundamental for the structural performance of the composite laminates; however, they provided a resistive force toward deformation, and a certain amount of energy was spent to overcome this force. Consequently, the stored load was only a portion of the L_a . Experimental tests showed that changes in the stored load depended on temperature; it ranged between 65% and 88% of the L_a with increasing applied voltage.

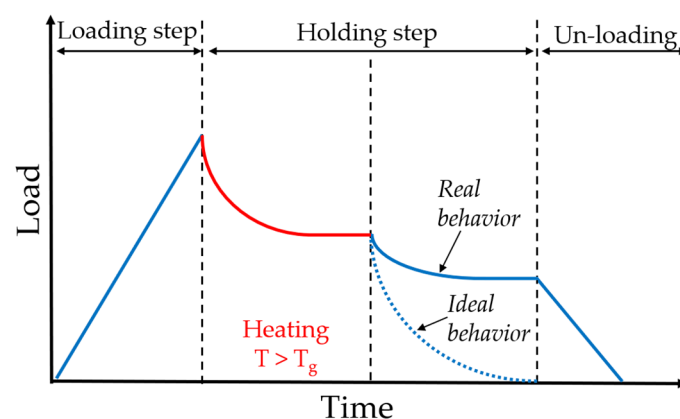


Figure 10. Comparison of the actual thermo-mechanical cycle used for SMPC memorization with the ideal cycle.

This effect was also visible by normalizing the L_a with respect to L_{mr} , Figure 11a, with the load decreasing with increasing temperature. Nevertheless, the increase in memory temperature did not affect the resulting recovery load, which was 2.1 N on average. In Figure 11b, the changes of L_r over time are reported; depending on the applied voltage, different trends were recorded, but after 180 s of heating, all the curves converged toward the same load. This result demonstrated that, regardless of how the SMPC was memorized, the available L_r remained unchanged. On the other hand, both R_f and R_r changed with the applied voltage and, in turn, the activation temperature. In particular, R_f generally grew with the temperature, from 52% to 76%. In shape memory composites, CFs exhibit perfect elastic behavior over the full transition range, reducing the maximum achievable deformation that can be stored. Also, the matrix can exhibit elastic behavior, much higher at lower temperatures, further reducing the attainable stored deformation. On the other hand, lower values of R_r were observed at higher temperatures, but this datum is probably affected by the measurement procedure, as hot samples are more sensitive to their weight and manipulation conditions. In real applications, these SMPC devices are supposed to

work as actuators in deployable systems, with their ability to provide an actuation load to a certain extent. The L_r measured in the 3-point bending configuration quantifies only the initial actuation load, since the fixed punch stopped the device from shape recovery. To investigate the ability of the composite device to behave as an actuator, a new experimental test was designed with the composite being deformed into an L-shape.

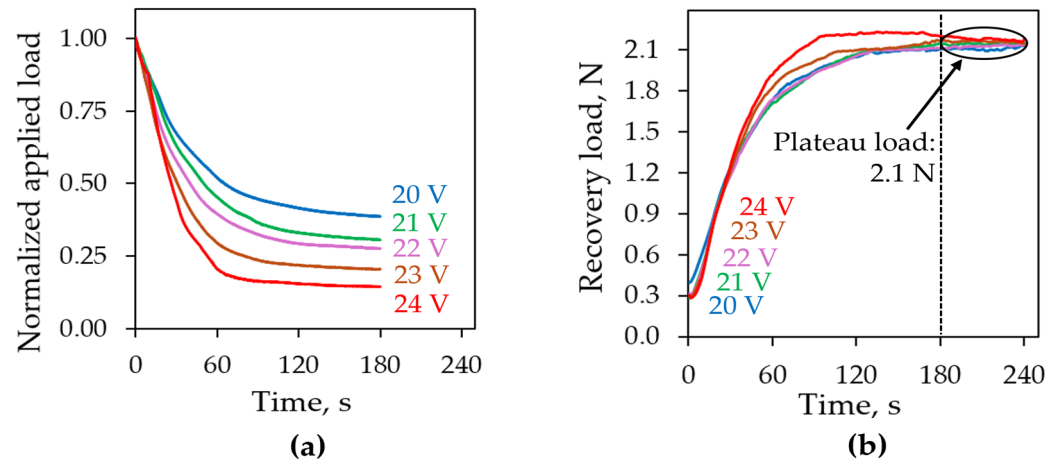


Figure 11. (a) Normalized applied load at different voltages; (b) recovery load curves for all the applied voltages.

Using an embedded heat source allowed for a uniform temperature increase in the laminate structure, which was heated from its core. The presence of this element created an interface between the SMP and the polyimide film of the heater itself. Such an interface could cause poor adhesion between the different polymer layers; however, microscopy in Figure 5 highlights that a good level of agglomeration was achieved thanks to the proposed manufacturing strategy.

The recovery speed during free recovery was evaluated at 24 V by means of the inflection. When the device was powered on, the SMPC had a maximum inflection of 7.6 mm; this deformation was recovered in less than 2 min, with the material showing a residual inflection of 0.4 mm. The trend of the curve was like an inverse sigmoid, whose flex point was at 60 s. The speed, which is the derivative of the inflection in time, exhibited a starting value of 0 mm/s, reached a peak of 0.15 mm/s and then decreased to 0.01 mm/s. Both the inflection and the speed curves are reported in Figure 12. After 60 s of heating, the SMPC device reached both the maximum recovery load of 2.2 N and the maximum recovery speed of 0.15 mm/s.

Furthermore, measurements of the recovery angle showed that the recovery load was maximum when the SMPC device had the maximum deformation, but a plateau was rapidly reached; in particular, the recovery load ranged between 0.22 N and 0.26 N for a recovery angle between 8.5 deg and 47.7 deg. When the SMPC device was connected to the 1U CubeSat to deploy one of its sides, it was able to open 28 deg in less than a minute before the test was stopped. This promising result underlined the capabilities of this class of materials and the possibility of integrating them into complex space structures. Nevertheless, additional tests are required prior to implementation since the current study was conducted under laboratory conditions and not in a simulated or real space environment, which may partially affect the behavior of the SMPC device.

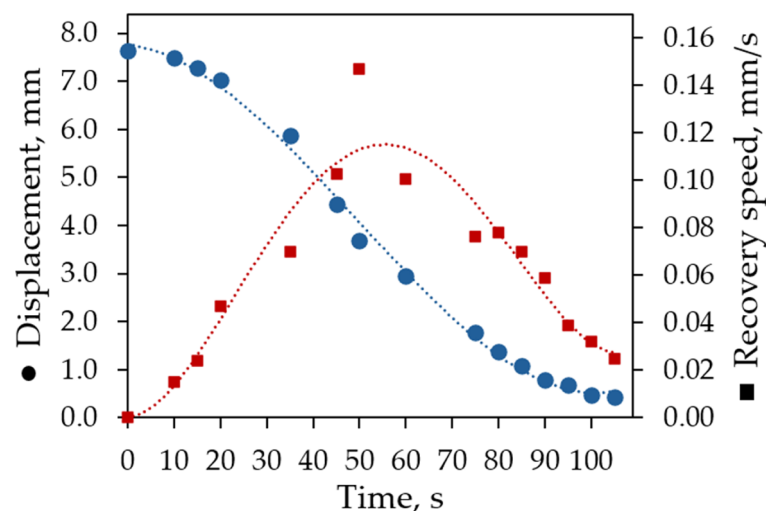


Figure 12. Evaluation of the recovered inflection and of the mean recovery speed during the free recovery test.

5. Conclusions

SMPCs have several properties that make them suitable for high-value applications such as the deployment of space structures. When heated, they become soft and can be shaped into a temporary configuration which is maintained after cooling, with the laminates recovering their initial stiffness. By reheating, they return to their original shape with an actuation load being available for use.

Until now, SMPCs have been manufactured mainly by lab-scale processes, but to foster their actual implementation, it is fundamental to use technologies that belong to the know-how of industries. For this reason, the novelty of this study regards the manufacturing procedures that were followed to obtain the SMPC device. The stacking sequence of the composite laminate included a functional interlayer between prepreg plies, which imparted the SM ability, and embedded the heat source that drove the shape change. Consolidation was performed by autoclave molding, which is largely used in the aerospace sector to manufacture composite components with excellent structural properties.

Experimental tests conducted at different voltages showed that the magnitude of the L_r was independent of the temperature at which the composite was memorized. At all temperatures, R_r was very high, with the minimum value being 94%. R_f increased with temperature, and thus, the maximum value of 76% was obtained during the test at 24 V. This voltage was selected for the following free recovery test; it was shown that after 60 s, the SMPC device reached the maximum recovery load of 2.2 N and the maximum recovery speed of 0.15 mm/s.

Finally, the ability of the composite device to deploy a composite laminate representing the cover of a 1U CubeSat was investigated, with promising results being recorded.

Author Contributions: Conceptualization, F.Q. and L.S.; methodology, F.Q.; software, L.I.; validation, A.P. and D.N.; formal analysis, L.I. and A.P.; investigation, F.Q.; resources, L.S.; data curation, L.I., A.P. and D.N.; writing—original draft preparation, A.P.; writing—review and editing, F.Q. and L.I.; visualization, D.N.; supervision, F.Q.; project administration, L.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

SMPCs	Shape Memory Polymer Composites.
CFR	Carbon Fiber Reinforced.
SMAs	Shape Memory Alloys.
HDRMs	Hold-Down Release Mechanisms.
NEAs	Non-Explosive Actuators.
L_a	Applied Memory Load.
L_m	Memory Load.
L_{mr}	Residual Memory Load.
L_r	Recovery Load.
L_{rr}	Residual Recovery Load.
R_f	Shape Fixity Ratio.
R_r	Shape Recovery Ratio.
ε_m	Maximum Applied Strain.
ε_u	True Applied Strain.
ε_e	Recovered Strain.
ε_p	Final Residual Strain.
PETG	Polyethylene Terephthalate Glycol.
FDM	Fused Deposition Modeling.

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