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Shape memory composite antennas for space applications

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Abstract. Future space missions will require large space infrastructures in order to achieve scientific and technological objectives characterized by an intrinsic complexity. In this study, the development of shape memory composite structures for aerospace applications is described. In particular, the structure of a small-scale self-deployable mast has been prototyped as a proof of concept for its feasibility. The mast structure is made by interlocking two shape memory polymer composite (SMPC) strips, each one made of two layers of carbon fiber fabric with a shape memory (SM) epoxy resin interlayer. A complete deployment of the SMC structure was achieved. The versatility of this technology has been also demonstrated in previous studies, in which small scale deploying solar panels were fabricated. Obtained results are very promising in terms of manufacturing technology, and shape recovery of manufactured parts.

1. Introduction

Deployable structures are largely used for space applications and infrastructures. Generally, solar panels, antennas, radars and masts of the satellites are deployable to save space during launch. At the same time, it is very important that such structures are as light as possible and they require good stability in the deployed configuration to support structural loads and to resist external disturbances. Most conventional deployable structures are highly complex structures making use of numerous mechanical components such as linkages, hinges, motors and energy storage devices [1]. However, the large-sized mechanisms and complex assembly processes of these kinds of devices could involve problems like heavy weights, complexity of mechanisms and high costs [2]. Some of these structures as the able deployable articulated mast (ADAM) and the large deployable antennas (LDAs) use complex linkage mechanisms resulting in a large structural mass in order to obtain a good performance during deployment [3,4]. For example, deployable masts have been studied as telescopic booms which deploy via a series concentric prismatic joints [5]. Recently, masts with box bellows are constructed from flat rectangular panels joined by hinges [6], but generally the use of articulated trusses is very widespread [7,8]. However, recent advances in smart materials and structures that are easy to control, light weight, inexpensive, and capable of continuous deformations have opened new possibilities to design compact deployable structures. Shape memory polymers (SMPs) are polymeric smart materials that have the ability of recovering from a deformed shape to their original shape induced through the application of an external stimulus. SMP-based bending actuators and hinges for foldable and deployable structures have been studied and developed in the last few years [9-12]. Instead, SMPCs combine structural properties of continuous-fibre polymer-matrix composites with functional behaviour of shape memory polymers. In previous studies, the authors have developed and prototyped some self-deploying configuration structures by using SMPCs. A first result was obtained in the production of composite laminates with shape memory properties. Composite sheets consisted of two layers of carbon fibre fabric with a shape memory epoxy resin interlayer. Carbon fibre prepregs can be also used: an optimal adhesion between the different layers was achieved thanks to the compatibility of the prepreg matrix and the shape memory material [13]. SMC sandwiches, having a SM foam core and fibre reinforced skins, were also produced [14]. Among several applications it can be cited truss structures, solar reflectors, space station's modules, antennas and solar sails [15]. The shape recovery of a bent thin sheet of such composites was also tested for the first time in microgravity conditions during the BION-M1 mission of the Soyuz spacecraft (20th of April 2013) [16]. Interesting results were achieved in terms of shape recovery and the effect of microgravity in the case of small samples is found negligible if compared with recovery forces. Instead, microgravity strongly affects performances of heating devices and it has to be taken into account for designing of self-deployable structures in future space applications. Recently, also other studies on SMPCs application with higher strength and elastic modulus have been studied to fabricate a deployable truss which can unfold and has a low stiffness after being deployed [1]. Moreover, conceptual design of small-scale structures was prototyped with the aim to define several configurations which are able to self-deploy. In particular, the SMC prototypes were manufactured to represent two examples of self-deployable devices for de-orbiting systems: a composite cross without sail and a dual sail structure with composite frames and kapton sails [17].

In the current study, the acquired knowledge about SMPCs' technology is used to develop and prototype a different SMPC deployable structure for space applications. In fact this technology offers a new foldable/deployable lightweight structure that can be scaled to large antenna dishes or similar deployable structures. In particular, a prototype of space deployable articulated mast is developed. Deployable masts have been used in space extensively for deploying and support space operations. The basic idea is to mould the composite structure in the elongated (opened) configuration and subsequently shift to a shortened (closed) shape in the memory step. The composite structure would recover the opened configuration by heating. Obtained results are very promising in terms of manufacturing technology, and shape recovery of manufactured parts. Thus, as a result of heating, initial configuration can be successfully recovered without failures. In laboratory tests, composite heating was provided by a hot air gun. Commercially available materials have been used in the experimentation for both composite layers and SMP interlayer.

2. Materials and methods

2.1. Materials

Commercially available materials have been used for prototyping SMPC structures. The thermosetting carbon fibre reinforced (CFR) prepregs utilized are Hexcel Carbon/Epoxy prepreg composite. HexPly® M49/42%/200T2X2/CHS-3K is a woven high strength carbon epoxy prepreg, whereby M49 is the resin type; 42% is the resin content by weight; 200T2X2 is the reinforcement reference and CHS-3K refers to high strength carbon fiber. This kind of prepreg is a 0/90 fabric typically used for aeronautical applications: the epoxy matrix shows high stiffness and strength without any shape memory behavior. The SMP interlayer was an uncured epoxy resin (3M Scotchkote 206 N) which was available as a green powder, and was a one-part, heat curable, thermosetting epoxy coating.

2.2. SMPC production

Two shape memory composite strips were produced by using a sandwich structure in a laboratory scale procedure. These two strips properly combined and memorized are going to form the mast structure. The prepreg sheet was cut into four strips of 15x400 mm^2. Two prepreg strips were used as the outer skins of the sandwich structure and between them an interlayer SMP of about 0.1 mm thick was deposited (Figure 1a). The behavior of the SMPC structures was relatively complex because of the presence of two epoxy systems with different glass transitions temperatures. It has been observed that their transition range were comparable [13] and accordingly 150°C has been considered as an appropriate temperature for material forming whereas higher temperatures could lead to degradation. Therefore, the two sandwich strips were placed between two sheets of thermoplastic film (used for mold-release) and finally formed by hot pressing in a hydro-pneumatic press (by ATS FAAR). The applied pressure was 1.3 MPa, the moulding temperature 150°C, and the holding time 15 min.

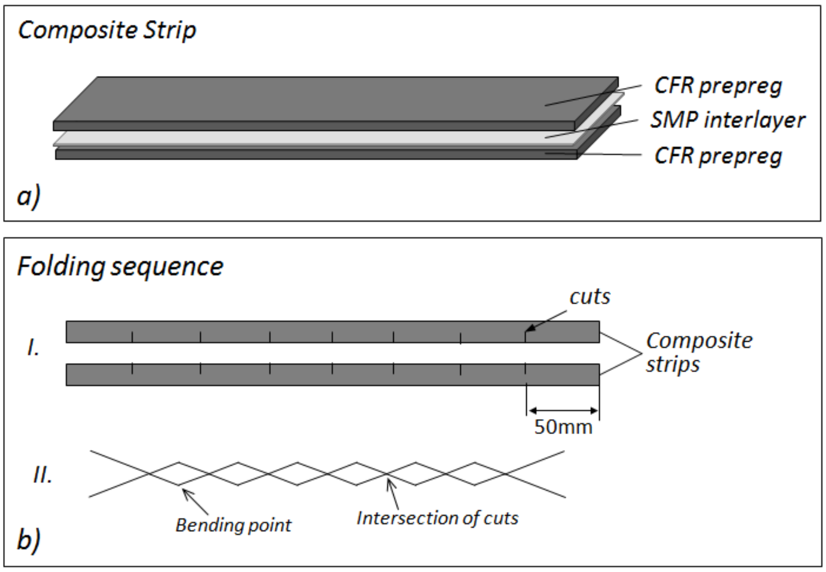

Figure 1: a) Scheme of the composite strip; b) Scheme of the sequence of combination and folding of the composite strips.

2.3. Memory and recovery step
The initial shape of the strips after forming was a flat configuration. The two sandwiches were combined and shaped as showed in Figure 1b. On each sandwich structure, a horizontal cut of 7 mm was made every 50 mm, in order to obtain 7 cuts on each strip.

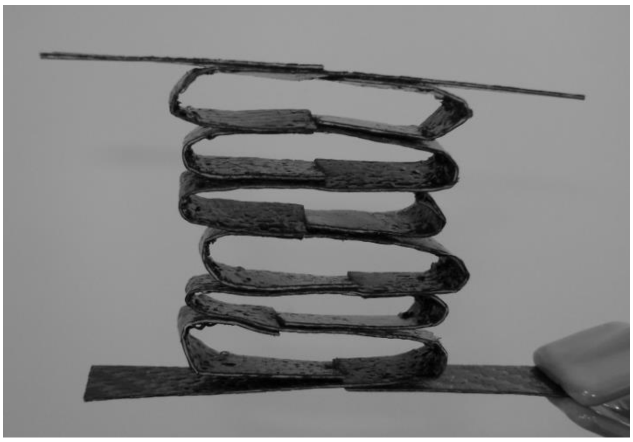

Figure 2: Final configuration of the mast after memorizing step.

During memory step, the two strips were heated and combined intersecting two homologous cuts and bending of about 180° the centre portion of strip between two consecutive cuts. This operation has been performed for six times, in order to fold and close the structure. A hot gun was used to provide 150 °C for the memory phases. The final memorized configuration was showed in Figure 2. After manufacturing, the SMPC mast was tested with several memory-recovery cycles. Shape recovery was obtained using a hot gun. The aspect of the reduction of the total length and so the folding sequence is fundamental for the correct deployment that is also function of the heating source. In particular, heating must promote the correct sequence of deployment avoiding the uncontrolled recovery of parts.

3. Results and discussion

The main design criteria in deployable structures are the compactness of the stored configuration, dimensional tolerances, light weight, ease of deployment, durability and endurance. In this study, it has been assessed the possibility to optimize the design and the configuration deployment of shape memory mast. The SMPC mast was memorized with a configuration which reduces the initial length of 7 times. Thus, it is possible to deploy a mast of an initial length (memorized) of 57.3 mm to a final length of 400 mm. The deployment of the mast has been achieved only by exploiting the shape recovery properties of the structure and no telescopic booms, switching mechanisms or rigid joints are used. The memory-recovery process is very easy and rapid both in the memory and recovery phases. After identifying the optimal folding design and memorizing the SMPC structures, it was possible to deploy the SMPC mast by heating with a hot air gun. In order to test the performances of the SMC prototypes, simple memory-recovery cycles have been carried out. In particular the initial configuration and the phases of the recovery are showed in Figure 3. The SMC mast folded configuration recovered its initial flat shape (Figure 4).

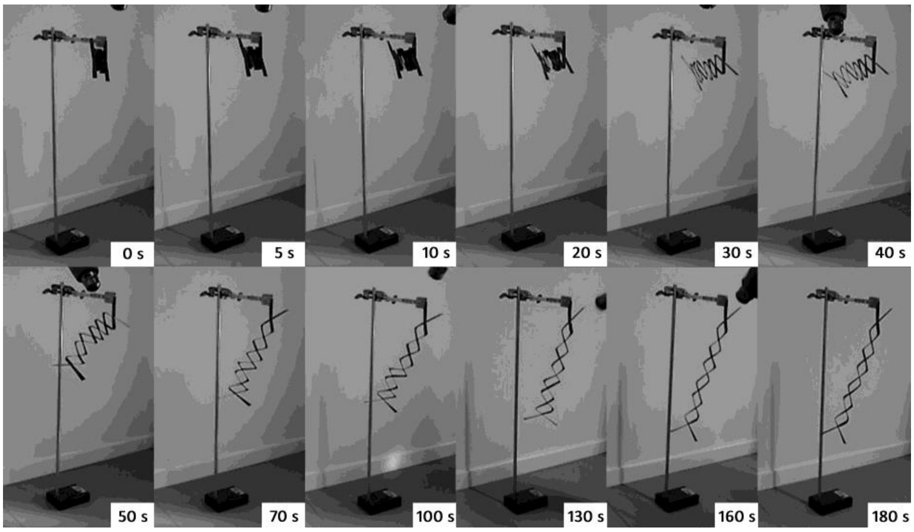

Figure 3: Recovery sequence of the composite mast.

During tests the composite mast was fixed on a metallic support. The SMC mast deployed smoothly without problems achieving the final shape (the elongated one), demonstrating multiple folding and related deployment of the two strips without issues. About 200 s were necessary for a full recovery of the SMC mast, due to the greater extension of the structure and to the localized heat source used.

Accordingly, the SMPC mast unfolds correctly six times for single strip, demonstrating the deployment of a mast with a reduced length of seven times.

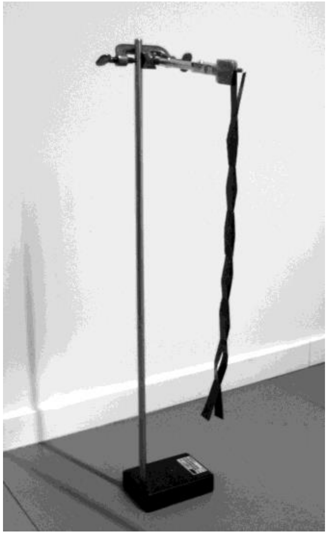

Figure 4: Deployed SMPC mast.

An important achievement was that no damages or evident cracks in the bending zones, or the surrounding areas, were found.

In the laboratory tests, a localized heat source as a hot air gun was chosen to memorize and recovery the SMC shape due to the limited sizes of the laboratory prototypes. In final applications, higher sizes are expected and local heating could be easily embedded to control shape recovery. Embedding the heaters could also help in differential deployment along different unfolding axis.

Starting from these results, the possibility to scale-up the prototypes could be furtherly investigated. Additionally, in order to deepen the present work, some aspects should be more thoroughly investigated, such as: the damage during and after the memory stage, the residual stiffness of the SMC, the final geometry to evaluate possible defects, etc.

4. Conclusion

In this study, a SMPC mast was prototyped in a laboratory scale process and its memory-recovery properties were assessed. SMPC structures can be easily produced by placing a SMP interlayer between composite layers. In particular, the proposed SMPC mast prototype was designed and produced so that the structure can deploy stretching six-fold compared to the initial memorized size. The experimental results showed that SMPC mast can successfully self-deploy following the desired design constraints and recovering the original flatness without noticeable damages. Obtained results are very promising in terms of manufacturing technology for producing SMPC slender structures, of compactness of the stored configuration and of ease of deployment. The presented results are expected to represent a first step to understand and study the SMPC mast structure for space applications. Further studies will be performed to quantitatively evaluate the rigidity of the deployed configuration, the durability and endurance of the system, the amount of recovery and of damages.

References

[1] Zhang, R., Guo, X., Liu, Y. & Leng, J. (2014). “Theoretical analysis and experiments of a space deployable truss structure“. Compos. Struct. 112, 226–230

[2] Huang, H., Deng, Z., Li, B. (2012). “Mobile Assemblies of Large Deployable Mechanisms“. J. Space Eng. 5, 1–14

[3] Gross, D. & Messner, D. (1999). “The able deployable articulated mast–enabling technology for

the shuttle radar topography mission". In Proc. of the 33rd Aerospace Mechanisms Symp. Pasadena

[4] Meguro, A., Shintate, K., Usui, M. & Tsujihata, A. (2009). "In-orbit deployment characteristics of large deployable antenna reflector onboard Engineering Test Satellite VIII". Acta Astronaut. 65, 1306–1316

[5] D. S. H. Chae, D. J. Rohweller, M. W. Thomson, (1994).US Patent 5135795

[6] F. Jensen, and S. Pellegrino, (2001). "Arm development – review of existing technologies, Tech. Rep. CUED/D-STRUCT/TR198", Department of Engineering, University of Cambridge, Cambridge, UK.

[7] H. Guo, R. Liu, and Z. Deng, (2008). "Preliminary design method study for the space deployable articulated mast," Proc. 1st Int. Conf. on Intelligent Robotics and Applications, Vuhan, China, pp. 322-331

[8] L. R. Adams, (1988). "The X-beam as a deployable boom for the space station," Proc. 22nd Aerospace Mechanisms Sym., California, US, , pp. 59-66

[9] Lee, Y., Lee, H., Hwang, T., Lee, J. & Cho, M. (2015). "Sequential Folding using Light-activated Polystyrene Sheet". Sci. Rep. 5, 16544

[10] Xiao, X. et al. (2015). "Shape memory polymers with high and low temperature resistant properties". Sci. Rep. 5, 14137

[11] Mao, Y. et al. (2015). "Sequential Self-Folding Structures by 3D Printed Digital Shape", Memory Polymers. Sci. Rep., 5, 13616

[12] Felton, S., Tolley, M., Demaine, E., Rus, D. & Wood, R. (2014)."A method for building self-folding machines Science", 345, 644–646

[13] Quadrini, F. (2014). "Polymer matrix composites with shape memory properties." Advanced Materials Research, 783-786, pp.2509-2516.

[14] Santo, L., F. Quadrini, and L. De Chiffre (2013). "Forming of shape memory composite structures." Key Engineering Materials, 554-557, pp.1930-1937.

[15] Accettura, A., L. Santo, and F. Quadrini (2012). "Space mission opportunities using shape memory composites." Proceedings of "63rd International Astronautical Congress" IAC 2012.

[16] Loredana Santo, Fabrizio Quadrini, Pier Luigi Ganga, Valfredo Zolesi (2015). Mission BION-M1: Results of Ribes/Foam2 experiment on shape memory polymer foams and composites, Aerospace Science and Technology, 40, pp. 109-114.

[17] Santo L., Quadrini F., Bellisario D., Accettura A.G, "Conceptual prototypes of composite structures for aerospace", Proceedings of the 2016 Manufacturing Science and Engineering Conference, MSEC2016, June 27 to July 1, 2016, Virginia Tech, Blacksburg, VA, USA.