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Shape-Changing Carbon Fiber Composite with Tunable Frequency and Damping †

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Abstract: A shape-adaptable Carbon Fiber Reinforced Composite (CFRC) is proposed to derive a material with tunable mechanical properties in order to optimize its response to external excitations. The composite is bi-stable thanks to internal stresses arising in the manufacturing process and is characterized by a built-in heating system that can control the temperature of the material. This approach allows to gradually change the actual curvature of the material as well as tuning its natural frequencies and damping properties.

Keywords: carbon fiber composite; morphing; bistability; tunable mechanical properties

1. Introduction

Morphing materials draw considerable attention in several engineering fields because of the significant enhancement in performance that they can convey to structures.

Recently, major challenges are addressed to morphing materials for load-bearing applications and in particular for carbon fiber composite materials. Large deformations in rigid materials require a significant actuation power. Three key approaches have been proposed in the literature to exploit morphing into carbon fiber composites (CFC): shape memory carbon fiber composites [1]; multistable composites [2]; deployable structures [3]. In particular, the deployable concepts rely on structural aggregations of composite parts. Instead the first and second approaches are truly related to the "material" design in multi-scale response. Several studies and approaches rely on a specific cross-ply lay up of unidirectional fibers, that, thanks to thermal effects leads to multi-stable composites [4–26].

The thermal effect are induced in the curing process and are due mostly to the difference of thermal expansion in the two principal fibers directions (longitudinal and orthogonal). Contrarily to classical lamination theory [6,7], unsymmetric laminates do not exhibit a saddle as room-temperature shape, but two stable cylindrical configurations, while the saddle shape reveals to be unstable [5].

Recently this concept has been expanded into active control via thermal loading [20,21] to obtain controllable stiffness epoxy composites by alternating the plies with a thermoplastic layer [20], as well as by directly coating the fibers with a thermoplastic layer before embedding them into the hosting matrix [21]. The actuation system was modified by applying a controlled force when the configuration change is required (to induce snap-through) or with shape memory alloy wires [22,24] and with piezocomposite actuators [25,26].

In this paper, a novel concept of smart material is proposed: the designed structure is equipped with a system actuators that can actively tune the material stiffness according to the input identified by the embedded sensing system. The above properties are achieved with a simple and reliable multi-scale design of the material which leads to an effective morphing system.

2. Material Concept

The composite consists of multiple cross-ply carbon fiber mats with unsymmetric layup sequence. This give rise to a bi-stable composite with two cylindrical configurations at room temperature, whose curvature is function of the number of layers adopted, the curing temperature and the coefficient of thermal expansion of the adopted resin. During the cooling phase at the end of the manufacturing process, the layers shrink but are constrained by the adjacent layers, this gives rise to internal stresses that lead to a bent shape.

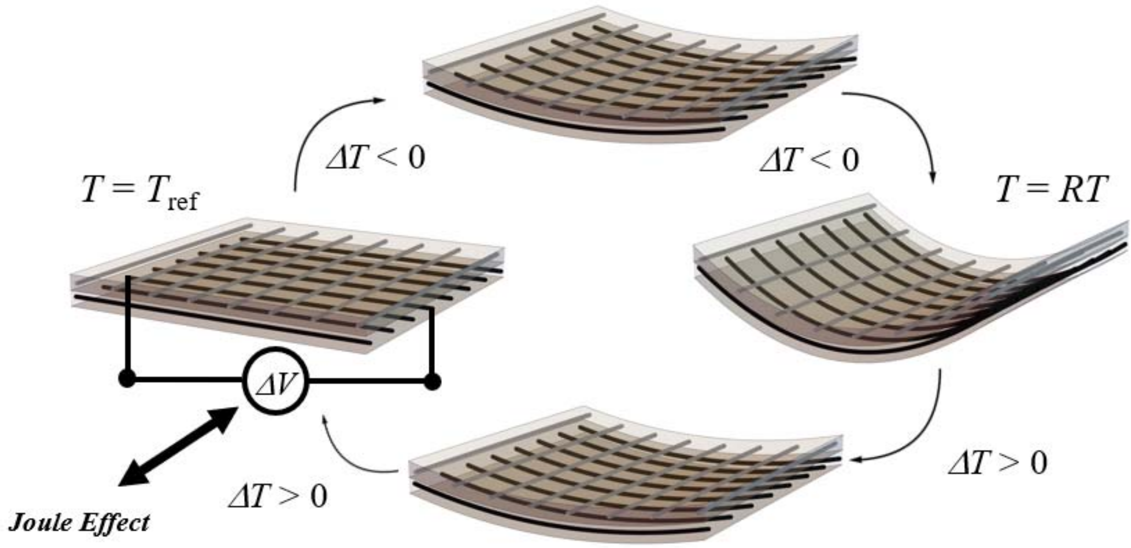

Figure 1. Material concept.

As depicted in Figure 1, while heating the material, the internal stresses are released and the curvature reduces. Moreover, the mechanical properties of the resin are strongly influenced by temperature, thus the overall stiffness of the structure changes.

Moreover, in between the carbon fiber layers, a heating system is introduced. This is composed of a thin copper wire (0.1 mm) distributed all over the surface of the composite. The wire ends are connected to a power generator, thus by applying current to the resistor it is possible to uniformly heat the material.

The approach allows, by governing the applied current, to change the shape of the shell, as well as tune its stiffness, frequency and structural damping.

Such aspect is investigated during unstable phenomenon (snap-through) taking place when the structure experiences the transition between its two stable configurations. It is shown that by controlling and properly tuning the current in the heater it is possible to reduce the critical load, i.e., the activation energy, required to change configuration, as well as to reduce and minimize the vibrations occurring in the snap-through phenomenon. This approach allows to design a structure that can adapt to different situations and can enhance its performance in terms of dynamic response.

3. Results and Discussion

In the following paragraphs, the conducted experimental campaign is illustrated and the obtained results are discussed in order to highlight the main features of the proposed morphing material.

3.1. Structural Characterization

Static tests are conducted by the use of a dynamic mechanical analyzer to characterize the response of the material to simple input. A square bistable plate [0°, 90°] is restrained at the four corners and a cyclic test is performed by imposing a prescribed displacement path. The test is repeated at different temperatures in order to investigate its dependence on thermal effect.

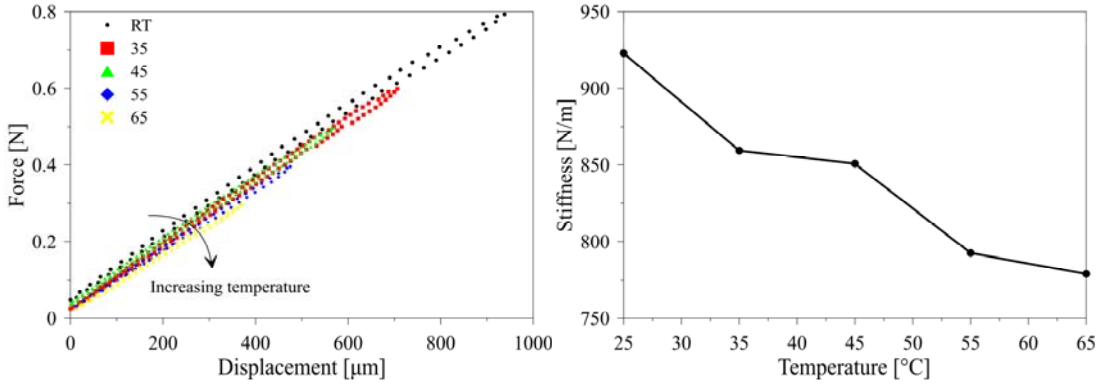

Figure 2. Force-Displacement cycles and stiffness without the instability.

To measure and evaluate such behavior, the linear tangent stiffness is evaluated at the beginning of the cycle in order to compare its variation with temperature. Since the sample is bistable a first set of tests is performed by preventing the snap-through of the structure, thus a simple force-displacement cycle is obtained. The results are illustrated in Figure 2 and are intended to evaluate the effect of thermal stresses within the composite. As expected, as the temperature increases a considerable loss of stiffness is experienced by the structure: from room temperature to 65 °C the stiffness shows a variation up to 16%. This is mainly due to the internal stress that are gradually released, as the temperature increases, the curvature reduces and the geometric stiffness varies.

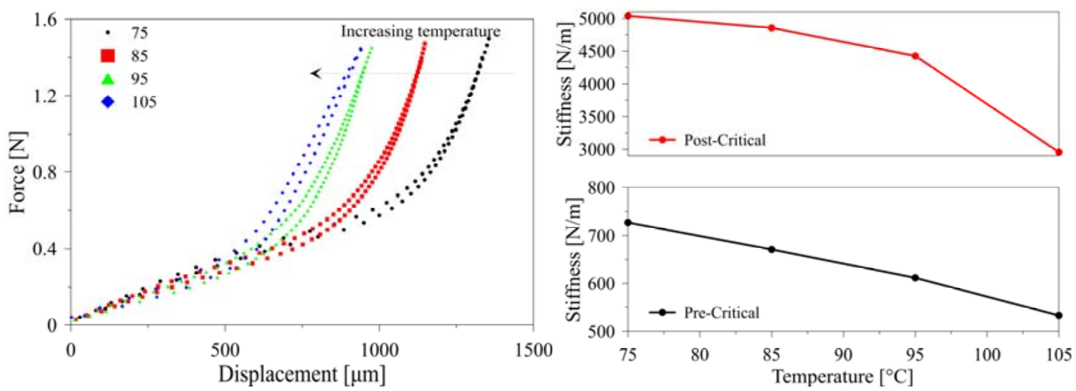

Figure 3. Force-Displacement cycles and stiffness with shape-change.

The same test is pushed at higher temperatures and, as expected, the shape change is well recognizable from the results in terms of force-displacement cycles shown in Figure 3. It can be noticed that the instability does not take place, even though an evident stiffness change is observed at a certain deformation level. The stiffness is evaluated at the beginning of the cycle and also after the shape change. As obvious, the stiffness in the second configuration is much higher.

The snap-through phenomenon was not observed, but the approach shows that it is possible to obtain a configuration change without the instability and those unwanted uncontrolled oscillations. This becomes possible if a suitable temperature control system is embedded within the structure.

3.2. Snap-Through Oscillations

Since the static behavior of the composite was discussed and the influence of temperature well established, a set of dynamic test are performed in order to investigate the oscillation induced during the snap-through. To do this, a square bistable sample [0°$_2$, 90°$_2$] is manufactured and it was coupled to previously described heating system. The structure is fully clamped in the center and the snap-through is mechanically induced, while the corresponding oscillation are acquired by a laser scanner vibrometer. The test is repeated for different values of prescribed current, and the induced temperature is experimentally evaluated (see Figure 4) by the use of a thermo-camera.

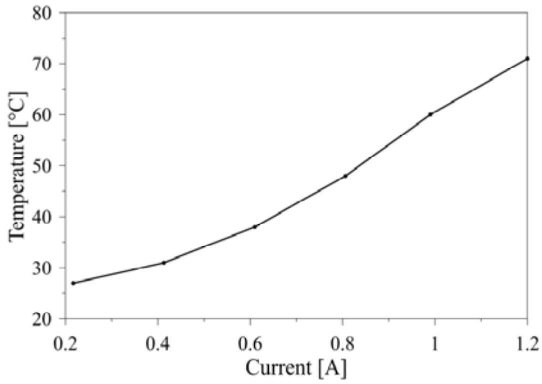

Figure 4. Applied current and derived temperature.

Selected time histories of the acquired signals are illustrated in Figure 5 together with the trend of the maximum amplitude of oscillation measured at every temperature. It can be seen that at room temperature the oscillations induced by the snap-through are characterized by a higher amplitude and the lowest structural damping.

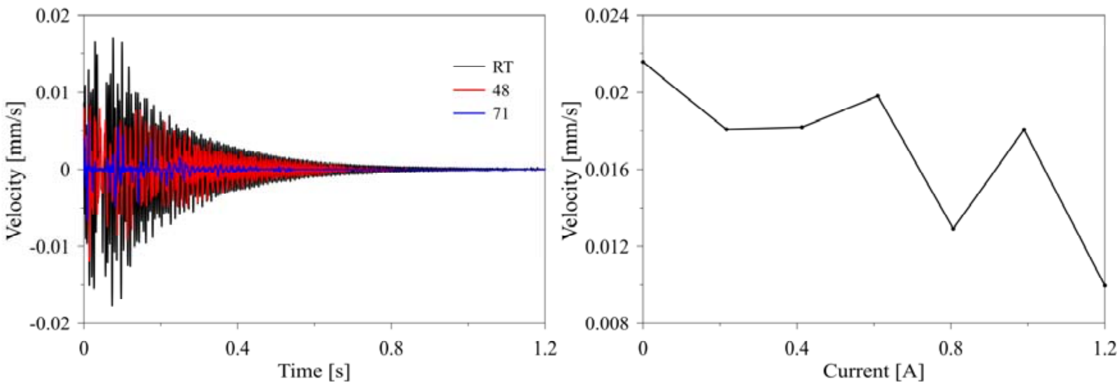

Figure 5. Time history (**left**) and oscillation amplitude with current (**right**).

On the other hand, as current (and thus temperature) increases, the maximum amplitude of oscillation decreases while the damping increases. Though the variation of oscillation amplitude is not monotonic (see right part of Figure 5), which can be due to set up imperfections, the overall trend is clear. In other words, it is possible to appreciate that the proposed approach can control the energy necessary to induce the shape change in such composites and also to reduce the oscillations taking place right after the instability.

From the time histories it is possible to evaluate numerically the corresponding oscillation frequency and equivalent damping. As illustrated in Figure 6, the derived frequencies and damping are reported as a function of the applied current, including also the 0 A case, that represents the room temperature condition.

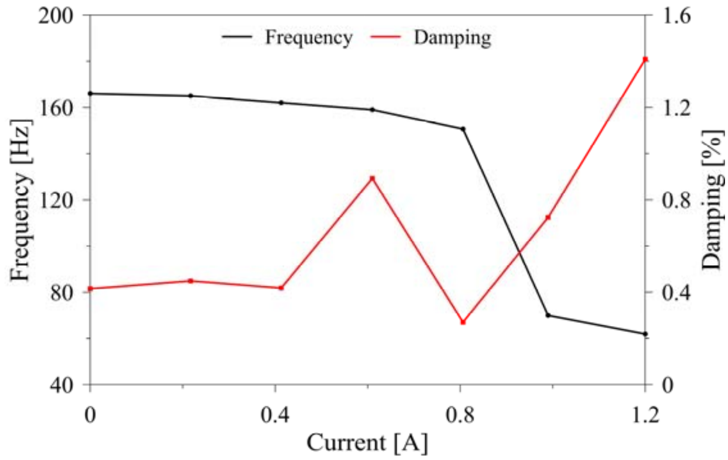

Figure 6. Identified frequency and damping.

The obtained results allow to evaluate the capability of the composite to vary its dynamical properties: the frequency can vary up to 62% while damping go from 0.2% to 1.4% with an equivalent variation of 85%. It is worth to note that the frequency above 0.8 A experiences a sudden drop which it was observed to depend on a global configuration change which takes place around 60 °C.

4. Conclusions

The conducted the experimental campaign was indented to show and discuss the capability of a bistable carbon fiber composite to, not only change shape, but also to gradually vary its property via an active control approach. The resulting behavior allows to govern the shape change process by reducing the activation energy and reducing also the unwanted oscillation taking place after the instability.

The approach described in this work allows to highlight the good capability of the designed composite to act as a morphing structure, that can not only vary its shape according to prescribed input, but can also gradually tune its dynamic properties.

Author Contributions: G.L. conceived and designed the experiments; A.C. performed the experiments and analyzed the data; A.C. and G.L. wrote the paper.

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