# Self-Activated Morphing Carbon Fiber Composites via Cyclic Internal Stresses

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## ABSTRACT

An innovative concept to exploit self-activated morphing composite materials is presented and demonstrated experimentally. In this design, shape changes of a carbon fiber composite are achieved by combining two key ingredients: fibers orientation and temperature-sensitive epoxy resin. When the fibers are properly oriented in each layer, internal stresses can be induced or gradually released by hardening or softening, respectively, the hosting epoxy resin. The epoxy resin stiffness is controlled with the help of internal heaters (e.g. the carbon fibers as demonstrated in this paper). The proposed mechanism results in a large scale and cyclic shape-changing capability which, together with the corresponding tunable stiffness, represent the fundamental features of morphing structural materials.

***Keywords***: morphing, carbon fibre composite, tunable stiffness

## 1 INTRODUCTION

The interest in morphing materials is rapidly increasing because of the significant enhancement in performance that structures or devices would gain with their usage. Morphing materials typically imply the capability to change shape by exploiting different principles: shape memory effect, sensitivity to environment conditions (e.g. humidity, chemical agents, Ph), internal stresses that give rise to multiple stable configurations, integration of active devices.

All of the the above principles are ingenious in their essence but are affected by critical disadvantages: polymers have a slow response and are unsuitable for load-bearing applications, while composites are usually faster but require a large energy to be activated.

For these reasons, major challenges are faced in the development of morphing materials for load-bearing applications and in particular for carbon fiber composite materials [1, 2]. In particular, several studies rely on a specific cross-ply lay up of unidirectional fibers, that, thanks to thermal effects leads to multi-stable composites that can snap from one configuration to the other (thus changing shape) as a consequence to an applied external load [3, 8]. Such thermal effects are induced in the curing process and mostly are due to the difference of thermal expansion in the two principal fibers directions (longitudinal and orthogonal). Contrarily to classical lamination theory, unsymmetric laminates do not exhibit a saddle as room-temperature shape, but two stable cylindrical configurations, while the saddle shape reveals to be unstable [9].

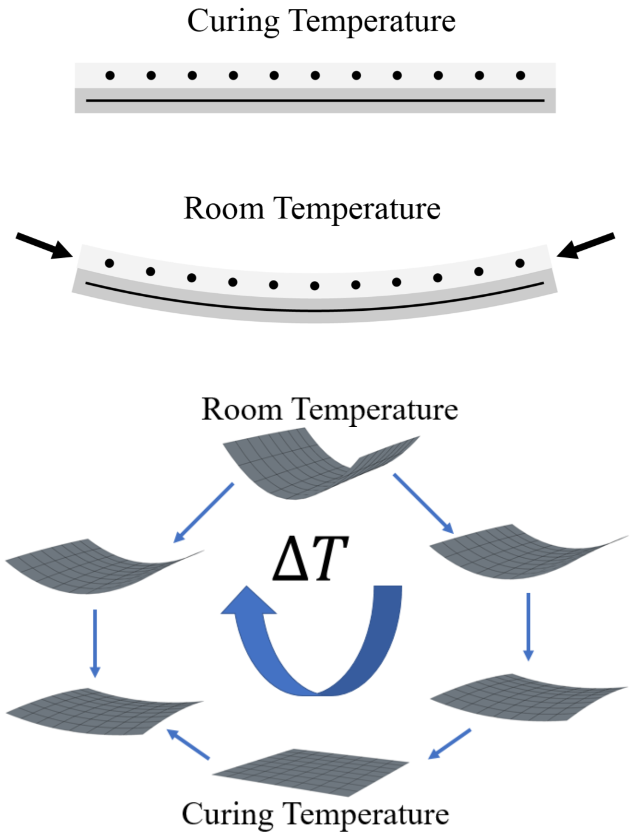

Figure 1: Working principle of the morphing composite.

Recently this concept has been expanded into active control via thermal loading [10, 11] to obtain controllable stiffness epoxy composites by alternating the plies with a thermoplastic layer [10], as well as by directly coating the fibers with a thermoplastic layer before embedding them into the hosting matrix [11].

The actuation system was modified by applying a controlled force when the configuration change is required (to induce snap-through), this was achieved with shape memory alloy wires [12] and with piezocomposite actuators [13].

In this paper, a novel concept is proposed to realize self-activated carbon fiber morphing composite materials that can provide: large-scale morphing, fast response, load-bearing capability and stiffness variation. 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 key concept of the designed material is shown in Fig. 1. Multiple layers of 0°/90° carbon fiber mats are embedded into a high temperature-sensitive resin. The adopted unidirectional carbon fibers tows (T300 from Torayca®) have a Young's Modulus of 230 GPa and an average diameter of 7 $\mu$m, while an epoxy resin based on bisphenol-A is adopted as hosting matrix.

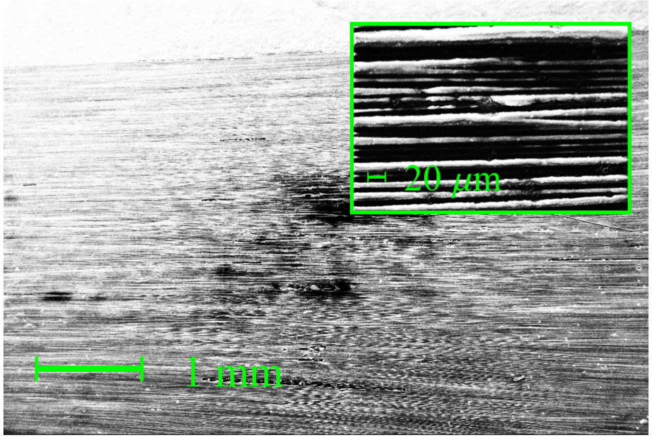

Figure 2: SEM images of the fabricated composite.

A thermal contraction descending from the cooling phase at the end of the fabrication process takes place in the direction denoted by the black arrows in the upper part of Fig. 1. The 0°/90° layers starts interacting and, due to the different coefficient of thermal expansion along the longitudinal and transverse direction, strong internal thermal stresses arise. This interaction leads to a curved shape at room temperature (see Fig. 1).

By inducing thermal gradients into the material it is possible to prescribe stiffness variations, that, thanks to the high temperature-sensitivity of the matrix, can reach several orders of magnitude. This induces a loss of internal stresses activating a shape change of the composite which goes from an initial curved shape (room-temperature) to a flat shape. In other words, the plate is capable to switch gradually and cyclically from a curved shape to a planar shape, as illustrated in the lower part of Fig. 1, making this design interesting for morphing applications.

In the proposed approach, the carbon fibers work in the material system, not only as reinforcing element, but also as thermal heaters. To let the fibers act as heaters, an ad hoc procedure was developed to provide suitable electrodes that would not affect the overall stiffness of the composite but allow to uniformly contact all the fibers. Such procedure had to be included during the manufacturing process, since the epoxy can cover all the fibers, thus causing electrical insulation. To avoid this, the fibers tips are first coated with a conductive paste and are connected to an aluminum foil which becomes the actual electrode. Thanks to the fibers electrical conductivity, it is possible to connect them to a current generator and thus uniformly heat the plate at prescribed temperatures.

## 3 RESULTS AND DISCUSSION

Figure 2 shows the SEM images of the top view and a cross section of a two-layer sample. The images show that there are no appreciable voids within the composite and that the fibers are well aligned. The material morphology at the microscale was also investigated with an optical microscope comparing images before and after the heating process. This analysis showed that the fibers alignment is not affected by the resin softening.

Since the presence of voids and other particles is negligible, the overall quality of the obtained laminates is consistent with the adopted manufacturing process and, moreover, is appropriate for the present study, whose main focus is to investigate the possibility to exploit such material in shape/stiffness control for morphing applications.

### 3.1 Mechanical characterization of the composite

The mechanical properties of the manufactured composite are derived from the Voigt/Reuss model [14]. It delivers the Young's moduli of a single layer laminate, under the assumption of perfectly longitudinally aligned fibers and perfect bonding between fibers ad matrix. The model is also known as the rule of mixtures and its inverse, which are based on the knowledge of the fibers volume fraction and the Young's modulus of the fibers and the matrix alone. The first one is retained as a constant, while the second is evaluated experimentally (see Tab. 1).

Table 1: Polymer Young's Modulus versus Temperature

| °C | 25 | 40 | 50 | 60 | 70 | 80 | 90 |
|---|---|---|---|---|---|---|---|
| MPa | 3125 | 2912 | 2637 | 2127 | 1219 | 341 | 50 |

The derived Young's modulus of the epoxy resin reveals the strong dependence of the material properties on temperature. Thanks to this feature, the composite is characterized by a high capability to change its stiffness and thus its shape when the temperature varies.

According to the results illustrated in Fig. 3, the longitudinal and transverse moduli of the composite are obtained by assuming an average fibers volume fraction of $\phi = 60\%$, that is in agreement with the literature values for composites fabricated with the same process. As expected, the Young's modulus in the longitudinal direction, $E_1$, is not considerably affected by temperature variations, since it mostly depends on the fibers properties. On the other hand, in the transverse direction the temperature strongly influences the actual value of the Young's modulus, $E_2$, in particular, it resembles the behavior of the epoxy resin showing a sudden drop of the mechanical properties around $T = 80°\text{C}$.

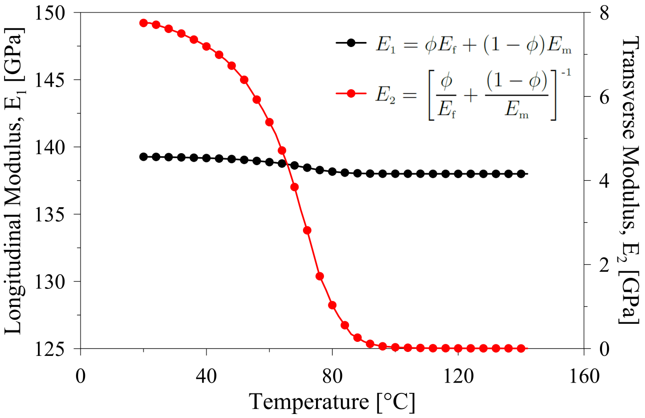

Figure 3: Longitudinal and transverse moduli of the composite with $\phi = 60\%$ and $T = 20 \div 150\,°\text{C}$.

This peculiar behavior confers to the material great shape changing capabilities, since the internal stresses that govern the curved shape of the composite are strongly dependent of temperature.

## 3.2 Shape Control via Temperature

The morphing capability of the material is first investigated by a passive control of temperature (hot plate). This set up allows to evaluate the shape variations of the curved laminate, since the material response is only related to its intrinsic properties while being unaffected by the performance of the heating system. The sample is placed on a hot plate in order to control the temperature according to a prescribed path ($20 < T < 150°\text{C}$) and the actual temperature of the sample is constantly monitored by a thermo-camera whereas the curvature is derived by a digital image correlation approach.

The collected data are represented in the plot of Fig. 4 in terms of curvature against the sample average temperature. The room temperature shape of the laminate has a specific known curvature that decreases as the temperature increases reaching a flat shape when $T \simeq 150°\text{C}$. The obtained behavior is in agreement with typical literature results [9], but it is worth to note that, when the temperature approaches the value $T \simeq 70°\text{C}$, the curvature experiences a more intense decrease and this is due to the peculiar behavior of the adopted epoxy resin (see Fig. 3).

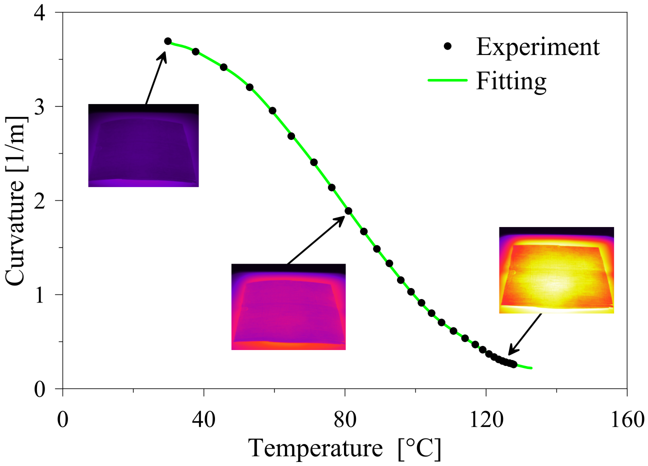

Figure 4: Laminate curvature against the imposed temperature.

The conducted experiments showed that the this process is reversible, thus it is possible to govern the shape changing of the material if the temperature is suitably controlled.

## 3.3 Active Shape Control

As previously mentioned, the self-actuation capability of the curved composite is achieved by using an internal heating system. In this case, carbon fibers are used as embedded heaters. This is possible thanks to the Joule effect that is activated when current is forced to pass in the fibers. By properly tuning the applied current, temperature gradients are achieved and the composite changes its shape accordingly, as shown in Fig. 4, but it also changes its stiffness.

A Dynamic Mechanical Analyzer is adopted to prescribe a displacement path to a square composite: the sample is simply supported at the four corners and the displacement is applied in its center. Moreover, the sample is equipped with proper electrodes as described before. The resulting force exerted by the sample is then measured along the displacement path and a power supply is adopted to apply current to the sample, while the resulting temperature is monitored with a thermo-camera. The obtained force-displacement curves are shown in Fig. 5 where the mechanical test is performed at three different current values, that are 0.5 A, 1.0 A and 1.5 A, while in Tab. 2 the main results are given.

It can be noted that as the temperature increases the actual stiffness of the sample reduces. When the current

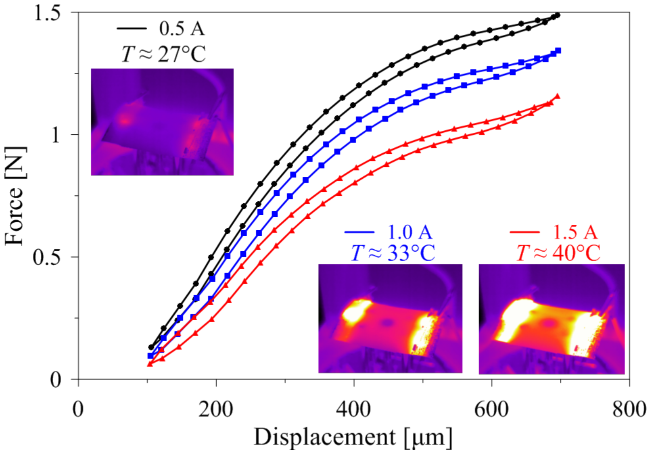

Figure 5: Force-Displacement cycles at different temperatures (self-heating).

reaches 1.5 A the temperature is $T \simeq 40$°C. The initial tangent stiffness is reported for the three values of applied current and the corresponding temperature. The obtained results show that the designed composite can vary its stiffness up to 27%, thus it is possible to tune the structural composite in a wide range, making the proposed approach interesting for morphing applications.

Table 2: Experiment Results

| Current | A | 0.5 | 1.0 | 1.5 |
|---|---|---|---|---|
| Temperature | °C | 27 | 33 | 40 |
| Stiffness | N/m | 4133 | 3639 | 3035 |

## 4 Conclusions

In this paper, an innovative approach to develop self-activated shape adaptable carbon fiber composite materials was proposed. The active control of temperature via the application of voltage to the material reveals to be a reliable method to govern the shape of composites. The conducted experimental campaign showed the capability of the composite to change shape according to prescribed temperatures. Moreover, an ad hoc treatment was proposed to let the fibers act as suitable internal heaters, and the results showed the great capability of the designed heating system to uniformly heat the material. The proposed approach can thus be adopted to develop morphing structures with an embedded actuation system that allows shape/stiffness tuning.

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