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SELF-ACTUATED MORPHING COMPOSITE WITH TUNABLE FREQUENCY AND DAMPING

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ABSTRACT

In this paper, an innovative approach is proposed to realize a morphing material with load-bearing capability that can self-activate with temperature. In particular the material can provide large-scale shape changes with fast response that can be induced with tuneable energy levels. The above properties are achieved with a simple and reliable multi-scale design of the material which leads to an effective morphing system.

Keywords: multi-stability, morphing, carbon fibre composites.

INTRODUCTION

It is well known that in multiple engineering fields structural systems encounter different working conditions, this aspect leads to specific requirements that a traditional structure cannot fulfill with high performance. This is why morphing materials are increasingly becoming a key object of several research studies, thanks to their characteristics that can lead to significant enhancement in the overall structural system. Morphing materials should have the capability to change shape and this is achieved by exploiting different principles. Typically, they rely on the use of shape memory polymers (Zhao, 2016), environment-sensitive (e.g. humidity, chemical agents, Ph) materials (De Haan, 2014), composite prestressed structures allowing multiple stable configurations (Daynes, 2008) and deployable structures with external actuators (Sickinger, 2006).

It was demonstrated that the above principles have some drawbacks. Polymer-based approaches have a slow response and are not applicable for load bearing applications. On the other hand, composite-based approaches have faster response, but the energy required to change shape is generally too high for cost-effective applications. For these reasons, the focus of this work is the study a carbon fiber composite morphing material with lower activation energy and fast response.

Several key approaches have been proposed in the literature to exploit morphing into carbon fiber composites (CFC). In (Tupper, 2001), the conventional epoxy resin, adopted to manufacture the composite, was replaced by a shape memory polymer. These materials are characterized by the capability of providing large shape changes, but, being the matrix of a shape memory nature, the resulting composite is affected by the same limitations of shape memory polymers.

The second approach relies on a specific cross-ply lay up of unidirectional fibers, that, thanks to thermal effects leads to multi-stable composites (Hufenbach and Gude, 2002) that can snap from one configuration to the other (thus changing shape) as a consequence to an applied external load (Hyer, 1998; Jones, 1999). Early studies on such approach were presented in (Hyer, 1981) where a nonlinear mechanical model was proposed to evaluate the curvature of the manufactured composite.

On the other hand, in (Schlecht, 2003; Gigliotti, 2001) a finite element approach was proposed to evaluate the response of unsymmetric cross-ply composites with high accuracy and especially the room-temperature configurations. The problem was also extended to general fiber orientation and not only the 0°/90° case (Dano, 1998).

Not only cross-ply laminates were investigated, but also different fiber orientation have been considered to derive morphing composites, that exploit residual thermal stresses to develop multi-stability. A piecewise variation of the laminate layup sequence was investigated in (Mattioni, 2008) via a finite element approach. On the other hand, a Rayleigh-Ritz approach was adopted in (Mostafavi, 2016) to study the room temperature shape of multi-connected curved laminates; the analyses revealed to be in good agreement with experimental results. The multi-stable shell design and modeling aspects are treated in (Hamouche, 2016) to provide general guidelines to obtain shells with prescribed stability properties.

Numerical model can hardly predict the effect of the manufacturing process and material degradation, in fact in (Hufenbach *et al.*, 2002) particular attention was dedicated to the design process, while in (Gigliotti, 2003; Wisnom, 2006) the conducted experimental campaign investigated the effect of thermal fatigue and distortion during manufacturing. Microscopy characterization was performed to identify the material imperfections (Giddings, 2010) in order to suitably optimize the finite element modeling. On the other hand, in (Betts, 2010) an intense experimental campaign was dedicated to study the influence of imperfections on the final cured shape of laminates.

The accuracy in evaluating the room-temperature shapes of cross-ply laminates has been object of several studies (Eckstein, 2013; Eckstein, 2014) by taking into account dependency on temperature of the adopted materials. Whereas, a theoretical study (Zhang, 2015) investigated the possibility to control the deformation of bistable composites.

Recently, this concept has been expanded into active control via thermal loading to obtain controllable stiffness epoxy composites by alternating the plies with a thermoplastic layer (Tridech, 2013), as well as by directly coating the fibers with a thermoplastic layer before embedding them into the hosting matrix (Tridech, 2014).

On the other hand, several studies regarded the shape change of bistable composites and the induced snap-though (Dano, 2002; Dano, 2003; Cantera, 2015). Particular attention was dedicated to the system required to activate the snap-through: shape-memory alloy wires in (Hyer, 2003) and piezocomposite actuators in (Hyer, 2006; Schultz, 2006; Giddings, 2011), were proposed.

In this paper, a novel concept is proposed to realize self-activated carbon fiber morphing composite materials that can provide load-bearing capability and tunable mechanical properties (stiffness). The approach relies on a simple and reliable multi-scale design of the material which leads to an effective morphing system.

MATERIAL CONCEPT

As illustrated in Figure 1, the shape changing capability of the material is based on its thermal behavior: its actual shape is strictly related to the temperature. This behavior is obtained by adopting the typical unsymmetric lay-up sequence based on multiple 0°/90° unidirectional fiber plies. Moreover, the shape and stiffness change are considerably enhanced by adopting a hosting matrix that exhibits elevated temperature sensitivity. In particular, the adopted carbon fibers (T300, Torayca) have an average diameter of 7 μm and a Young's modulus of 230 GPa, while the matrix is a bisphenol-A based epoxy resin whose thermo-mechanical characteristics are derived experimentally. Results are illustrated in Figure 2, where it is possible to appreciate the high temperature sensitivity of the resin that has a glass transition temperature T_g~72°C and above that its stiffness is almost negligible.

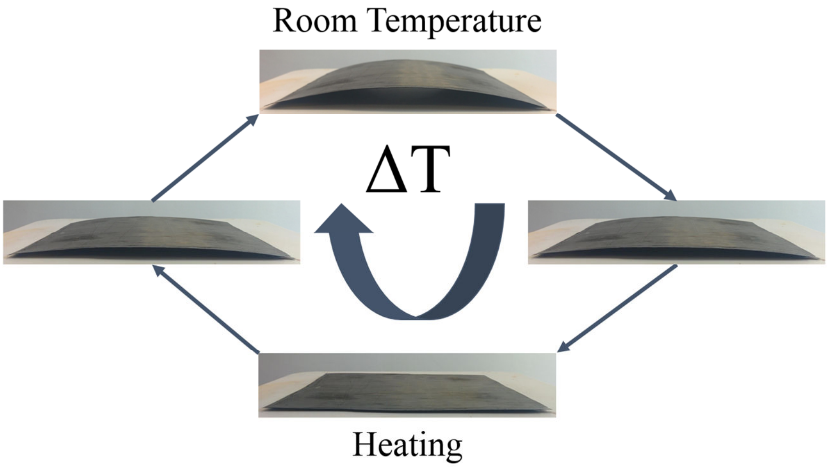


Fig. 1 - the shape changing capability of the material is based on its thermal behavior

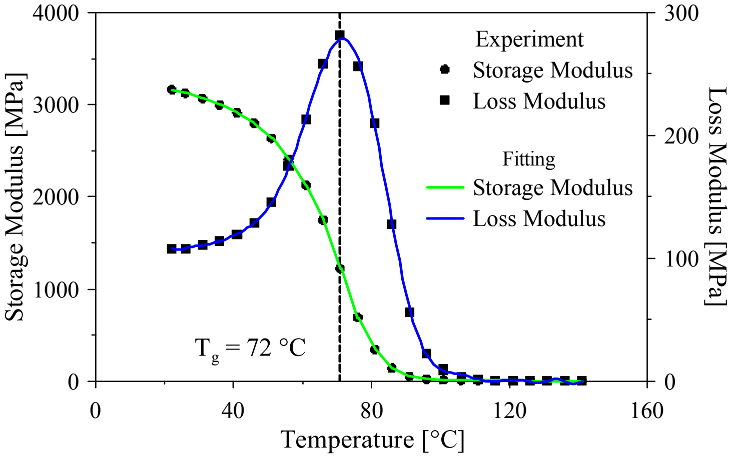


Fig. 2 - Storage and loss moduli of the adopted epoxy resin

Typically, unsymmetric cross-ply composites are characterized by the presence of considerable internal stresses due to the interaction of adjacent layers. This interaction is generated by the differential shrinkage in the two orthogonal direction arising in the cooling phase of the manufacturing process. Such stresses cause a bending in the composites that leads to a curved shape at room temperature, in particular the obtained composites show cylindrical shapes that are multistable.

In this paper the focus is on one of the cylindrical shapes and its shape changes with temperature. As illustrated in Figure 1, the manufactured composite can gradually switch from its cylindrical configuration to a perfect flat shape according to the prescribed temperature. This is due to the fact that the internal stresses are released as temperature increases and are then recovered with cooling.

As previously mentioned, the shape changes can be considerably enhanced by the adopted epoxy (see Figure 2). Thus, if it is possible to actively control the material temperature, it is possible to gradually and cyclically tune the composite properties and govern its shape.

Automatic temperature control is achieved by integrating the composite with an embedded heating system whose performance is here investigated. In particular, heat is produced by exploiting the Joule effect in a resistor. Such resistor consists of a simple copper wire with a diameter of 0.1 mm that is embedded within the composite layer, as illustrated in Fig.

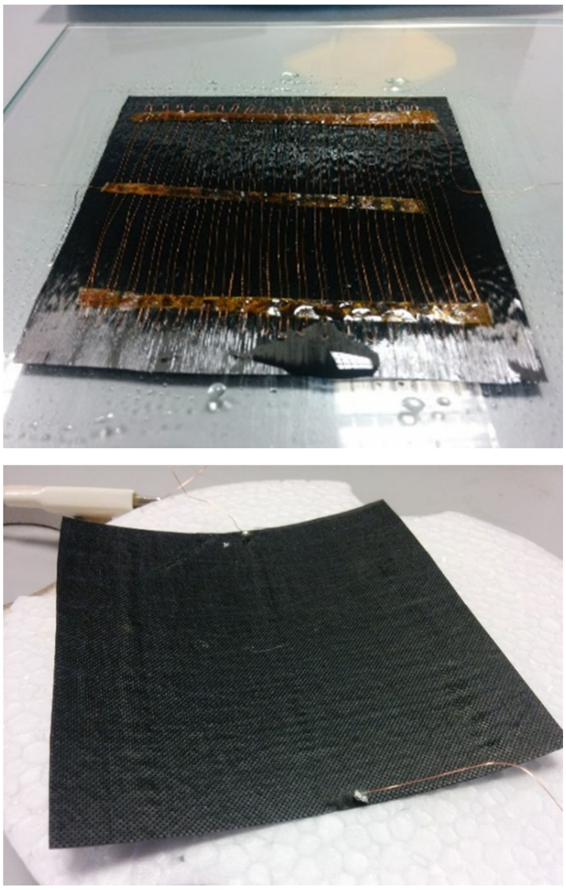


Fig. 3 - Integrated heating system**.**

The wire is coiled between two adjacent layers of the composite during the wet lay-up phase of the manufacturing process. The wire ends are then left outside the composite and the curing process is completed. The obtained structure is shown in the right part of Fig. The overall length of the resistor is 4.1 m and the resulting resistance is R=9.19 Ω (copper resistivity 1.76×10^{-8} Ωm). A power generator is used to induce current into the resistor and thus heat the material. In order to investigate the performance of the heating system, the obtained temperature is monitored by a thermo-camera up to a value of T=150°C that is reached with a current of 0.96 A (8.5 W).

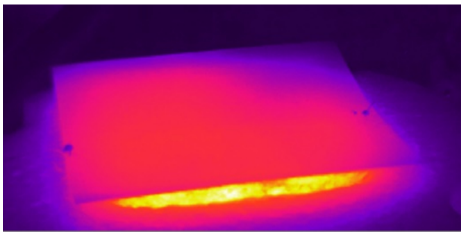
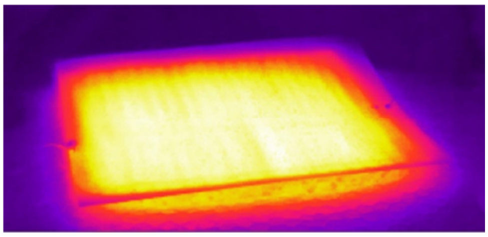
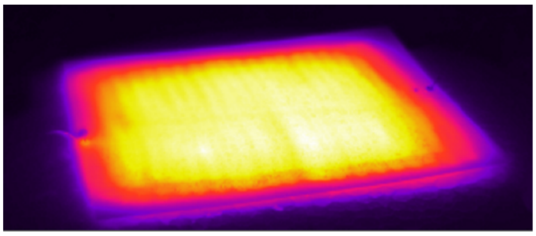
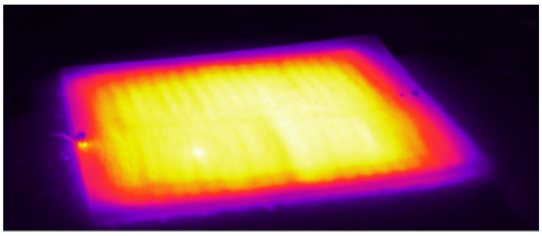
T_{max} = 30 °C	T_{max} = 60 °C
	
T_{max} = 100 °C	T_{max} = 150 °C
	

Fig. 4 - Thermal images of the heating system performance test.

The results are shown in Figure 4 where thermal images are reported together with the corresponding maximum temperature reached by the material as the applied current is increased. The investigations clearly show that the designed heating system not only can accurately control the composite temperature, but also a uniform and well distributed heating is achieved. Moreover, it is also possible to appreciate the curvature variations induced in the material as temperature increases.

The proposed strategy represents a promising approach to develop a morphing material with variable curvature that can actively be controlled according to prescribed inputs. In other words, the plate is capable to switch gradually and cyclically from a curved shape to a planar shape, by simply applying voltage within the plate, making this design interesting for morphing applications.

STIFFNESS VARIATIONS

It is of great interest to investigate, together with the shape change, the capability of the material to vary its stiffness to an external excitation. Here, the case of a prescribed displacement is investigated with the help of a Dynamic Mechanical Analyzer (DMA) test set-up that is shown in Figure 5. A square composite plate is trimmed in order to fit the internal dimensions of the DMA furnace. The plate is simply supported in its four corners, while the displacement is applied in the center. The DMA allows to vary the temperature inside a controlled furnace, thus it is possible to perform mechanical tests at different temperatures.

In particular, a displacement ramp is applied to the sample at five temperatures directly using the DMA furnace and the force exerted by the plate is continuously measured along the displacement path.

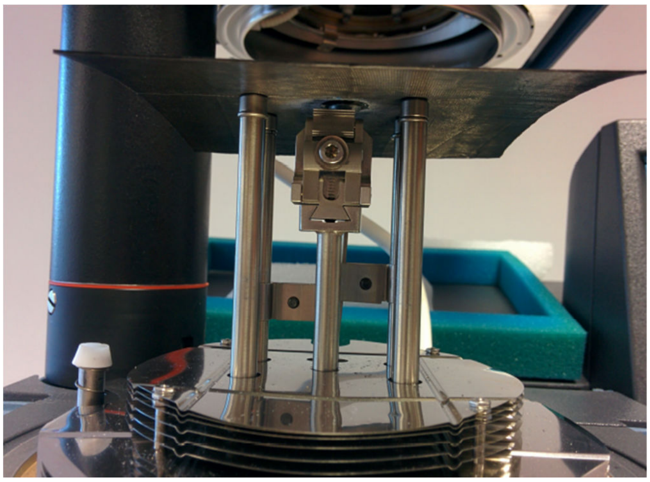
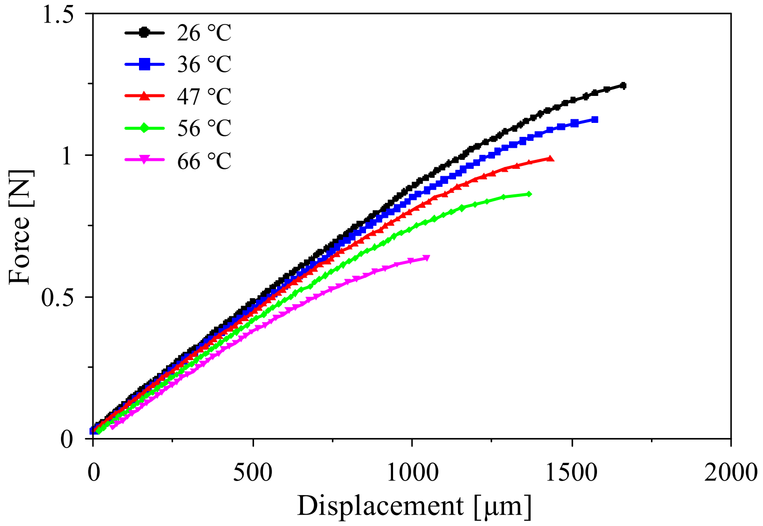


Fig. 5 - DMA set up.



Fig, 6 - Force-Displacement paths at different temperatures prescribed by DMA furnace.

The results in terms of force-displacement diagrams are illustrated in Fig, where the displacement ramp is represented at 5 different temperature levels (25< T< 70°C). The maximum displacement is adjusted at each temperature to avoid the instability of the composite, since the here conducted test is intended to evaluate only the linear stiffness variations.

As the temperature increases, the stiffness decreases, but also the shape of the structure is changing since the curvature is decreasing. In particular, the curvature experiences a maximum variation of 31% (see Table1 - Curvature and stiffness variations with temperature.) above which the composite becomes almost flat, since it is approaching the glass transition temperature of the matrix and the residual thermal stresses are negligible.

On the other hand, the linear stiffness, that is represented by the slope of the curves shown in Fig, is considerably reducing. As illustrated in Table1 - Curvature and stiffness variations with temperature., it is possible to appreciate its large variations: when the temperature is around 47°C (that are obtained with a current of 0.45 A) the stiffness has already a 10% reduction, that goes up to almost 50% at 66°C (0.57A).

Table1 - Curvature and stiffness variations with temperature.

Temperature [°C]	26	36	47	56	66
Curvature [1/m]	14.67	13.83	12.78	11.83	10.14
	Loss [%]	-6	-13	-19	-31
Stiffness [N/m]	1.25	1.13	0.99	0.86	0.64
	Loss [%]	-10	-21	-31	-49

As previously mentioned, the procedure can be cyclically repeated, thus the strategy can be suitably adopted to tune the structural stiffness and adapt its response to external excitations.

TUNING SNAP-THROUGH ENERGY

The same set up described in the previous section is adopted to investigate the snap-through phenomenon that describes the dynamic instability taking place when the bistable composite is forced to switch from one configuration to another.

Such aspect is investigated during unstable phenomenon (snap-through) taking place when the material experiences the transition between its two stable configurations (Schultz M.R. 2006, Zhang Z. 2015). In this case, the prescribed displacement is increased until the plate undergoes the snap-through. A further displacement increase is observed and allows to study the pre- and post-instability behavior of the material.

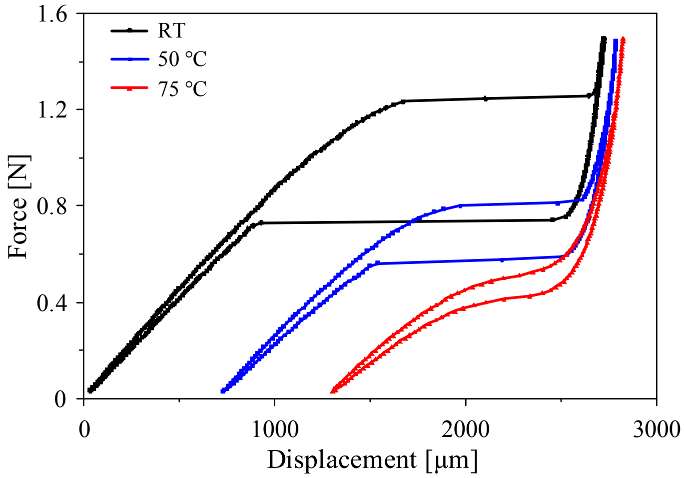


Fig. 7 - Force-Displacement paths with induced snap-through at different temperatures prescribed by DMA furnace.

The results are illustrated in Figure 7: Force-Displacement paths with induced snap-through at different temperatures prescribed by DMA furnace. where the response of the structure is reported in terms of force-displacement diagrams at the different selected temperatures. The black solid line represents the structure at room temperature and it is possible to observe the onset of the snap-through when the force approaches 1.2 N; then, a sudden increase of displacement is observed, while the force remains constant until the second configuration is reached. At that point, the material recovers stiffness and its value is much higher than that in the first configuration. This is mainly due to the fact that the material in this case is almost in a pure tensile state. When the versus of the imposed displacement is inverted the snap-through takes place at a much lower load level, thus a considerable hysteresis cycle is obtained.

By increasing temperature, the material loses curvature and this can be clearly identified by the initial displacement of the force displacement cycle (blue and red lines). When the temperature reaches 50°C (blue line), the critical load that activates the snap-through is around 0.8 N, but the overall behavior resembles the room-temperature cycle (black line).

On the other hand, when the temperature reaches 75°C (that is higher than the polymer T_g) the snap-through phenomenon disappears and the structure goes gradually from the first configuration to the second.

These results imply that by heating the material, the shape change can be obtained with different energy levels that can be actively tuned. Moreover, above a certain temperature threshold, the change in configuration can be performed gradually without undesired (because uncontrollable) instabilities.

FREQUENCY AND DAMPING VARIATIONS

The results illustrated in the previous sections, show that the proposed approach can well be adopted to actively control the properties and the shape changing capability of the manufactured morphing material. The snap-through phenomenon described in the previous section was obtained by passively controlling the material temperature, i.e. an external furnace was adopted.

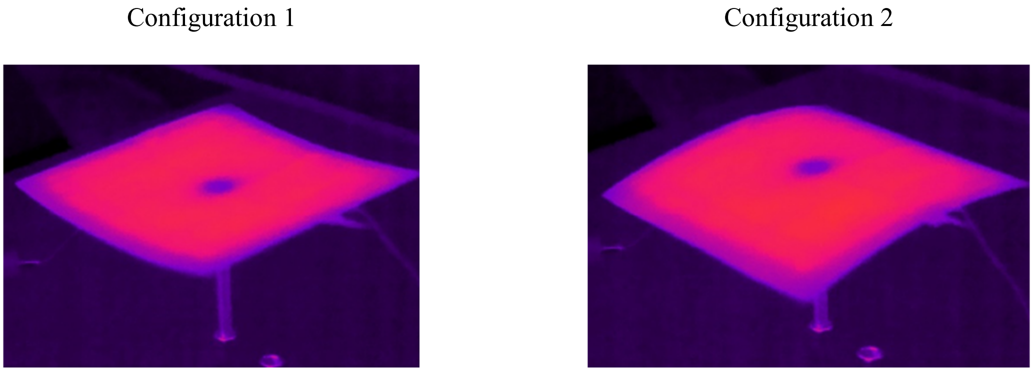


Fig. 8 - The two bistable configurations of the manufactured composite at room temeprature.

Here, the self-heating composite is tested by actively controlling the material temperature thanks to the previously described embedded heating system. The sample is fully constrained in the center point and free vibration tests are performed. In particular, vibrations, thus the oscillations, are induced by making the material snapping from one configuration to the other as shown in Figure 8. It is in fact well known that once the plate changes configuration it vibrates around the new stable configuration. This is usually an undesired phenomenon which can hardly be controlled with conventional approaches. Here these vibrations are monitored with the help of a scanning laser vibrometer pointed at the free corner of the plate.

The response is obtained in terms of velocity which allows to determine the actual oscillation frequency as well as the material damping, as shown in Figure 9. The laser was directly pointed onto the surface of the composite and no specific target was adopted, thus the acquired signal is affected by some noise. Despite this issue, it is clearly possible to identify the first vibration frequency, that, for the room temperature configuration, is around 50 Hz.

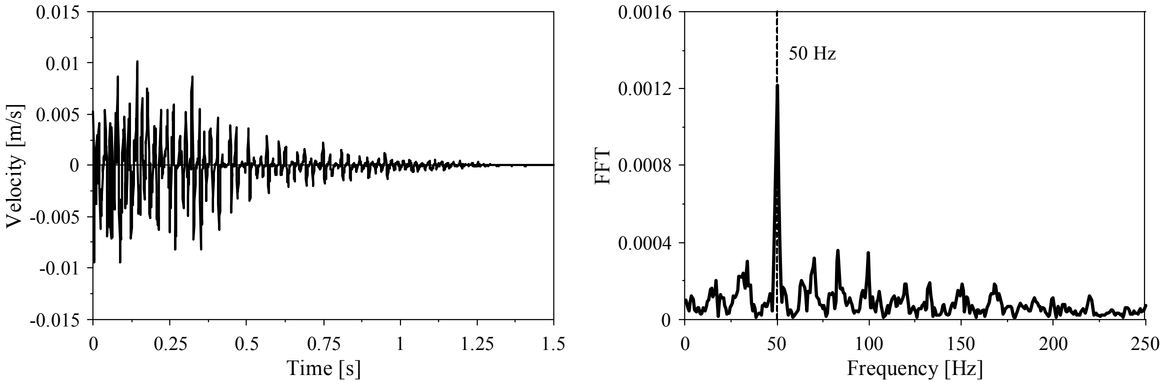


Fig. 9 - Snap-through induced oscillations in terms of velocity and corresponding frequency.

The time history signal allows also to evaluate the material damping that can be derived by fitting the absolute-value velocity time history and evaluating the logarithmic decrement that characterizes the decrease of the peaks.

The test is repeated at multiple input values of the current which lead to different temperature levels ranging from room temperature to 90°C. These results are resumed in Figure 10, in terms of frequency and identified damping as a function of temperature.

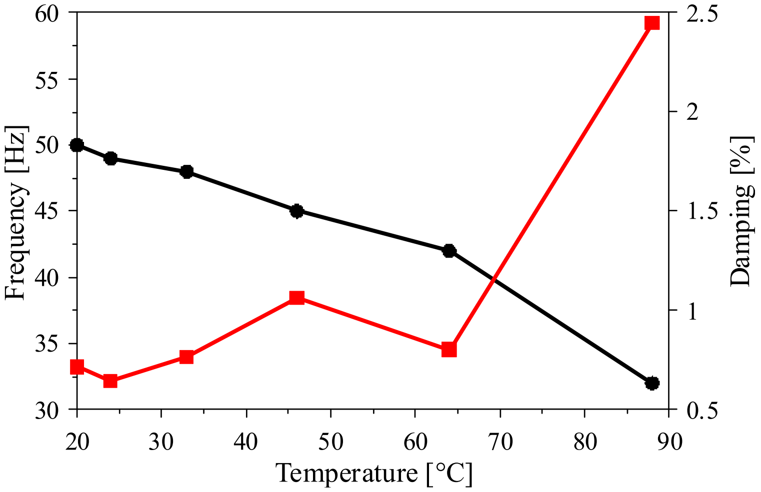


Fig. 10 - Identified frequency and damping at different temperatures.

The results show that the material properties experience a large variation: the frequency changes from 50 Hz to almost 30 Hz, with a maximum variation of 40%; on the other hand, the identified damping increases from less than 0.5% at room temperature to a maximum value of 2.5%.

This implies that by performing the shape change at higher temperatures it is possible to reduce the activation energy, but also that the oscillations arising from the snap-through are considerably reduced thanks to the higher damping.

CONCLUSIONS

In this study, an innovative approach to derive morphing materials based on carbon-fiber composites with load-bearing capability is proposed. The approach relies on an active control of the temperature within a carefully designed material. Typically, the shape change experienced by bistable composites is characterized by the snap-thorough which requires a considerable high activation energy (proportional to the load-bearing capability of the material) and, moreover, the unstable nature of the phenomenon causes unwanted oscillations.

The experimental campaign allowed to demonstrate that the proposed approach can actively and gradually govern shape changes of a composite material and, at the same time it allows to considerably mitigate the unwanted oscillations when this material goes from one configuration to a new stable configuration. Mitigation of vibrations is achieved by an increased damping capability of the material.

The active control of temperature via the application of current to the material reveals to be a reliable method to govern the shape of multistable composites in feasible temperature ranges (T<100°C). The results confirmed the capability of the proposed approach to govern and optimize the shape-changing process as well as to tune the material properties as desired.

ACKNOWLEDGMENTS

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