Chapter 5
Tuneable Dynamic Behaviour in Beams with Phase-Changing Materials

T. de Ruiter, E. Habtour, and D. Di Maio

Abstract This research investigates the dynamic properties of phase change materials (PCMs), specifically their damping and eigenfrequency, which are directly related to stiffness. The goal of this study is to demonstrate that the composition of PCMs can be tailored to achieve desired material properties. In this work, the PCM composition was modified by combining hard paraffin wax with silicone rubber. The temperature was adjusted to exploit the high thermal expansion coefficient of the wax, thereby altering the material properties. The silicone rubber served as an encapsulating material to contain the wax when it melts. To test this hypothesis, two carbon fibre beams incorporating wax and silicone were manufactured and experimental modal analysis (EMA) was performed to determine their modal properties. The results indicate that adding wax to the system increases the eigenfrequency and locally enhances damping by up to 250%. Furthermore, the study identifies two competing mechanisms that determine the material's final damping and stiffness.

Keywords Adaptive materials · Phase changing materials · Paraffin wax · Silicone rubber · FRF · Loss factor

Introduction

In the aerospace and space industry, there is a continuous drive to develop innovative materials that are lighter, stronger and more cost-efficient. In the current design process, the evaluation of a structure's dynamic properties is typically conducted at the final stage. As a result, implementing design changes at that point often becomes impractical and costly.

Phase-change materials (PCMs) offer a potential solution. These materials can transition between phases, for example, from solid to liquid, when exposed to external stimuli such as temperature or pressure. This phase transition alters the material properties, which provides a unique advantage: instead of being restricted to one material with fixed characteristics, the properties can be adapted after manufacturing. This flexibility brings two major benefits. First, it increases design freedom, since properties can be tuned even after fabrication. Second, it facilitates optimisation by enabling the structure to be adjusted to specific load cases. Third, PCMs reduce the need for worst-case design by allowing properties to change dynamically during operation, thereby avoiding over-engineering and resulting in lighter, more cost-effective structures.

Phase Changing Materials (PCMs) can be divided into three categories: organic, inorganic and eutectic compounds, as shown in Figure 1 [1]. The scope of this study is limited to organic paraffin compounds. Paraffin compounds are the result of refined de-waxed petroleum and are divided into soft and hard wax. The difference is the length of the hydrocarbon chains $(C_n H_{2n+2})$, where n typically ranges from 20 (for soft wax) to 60 (for hard wax) carbon atoms. This results in a lower melting point for soft paraffins than for hard paraffins, at 45 °C and 68 °C, respectively [2]. Hard paraffin wax is a tasteless, odourless, white translucent material. They are safe to use, inexpensive, non-corrosive, chemically inert and have a great Coefficient of Thermal Expansion (CTE). The CTE is the greatest when the wax changes phase and can reach up to 1500 $\frac{ppm}{K}$ [3].

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However, using hard paraffin wax as PCM, poses some drawbacks. Firstly, hard paraffin waxes exhibit a relatively low thermal conductivity of approximately $0.2\ \frac{W}{mK}$ [4]. Consequently, when exploiting the thermal expansion characteristics, it is important that the material efficiently absorbs heat to raise its temperature. Secondly, waxes are used in flammable candles, meaning they should be handled with care [5]. Thirdly, the Young's modulus is in the order of 50 to 200 MPa [6], but drops when the material reaches its melting temperature, and it is also very brittle. Lastly, when the wax transitions from the solid to the liquid phase it becomes fluid; as a result, it will leak and lose its material properties. To prevent this, a second material is added, which acts as an encapsulation of the wax. This material is silicone rubber and has a higher melting point than wax.

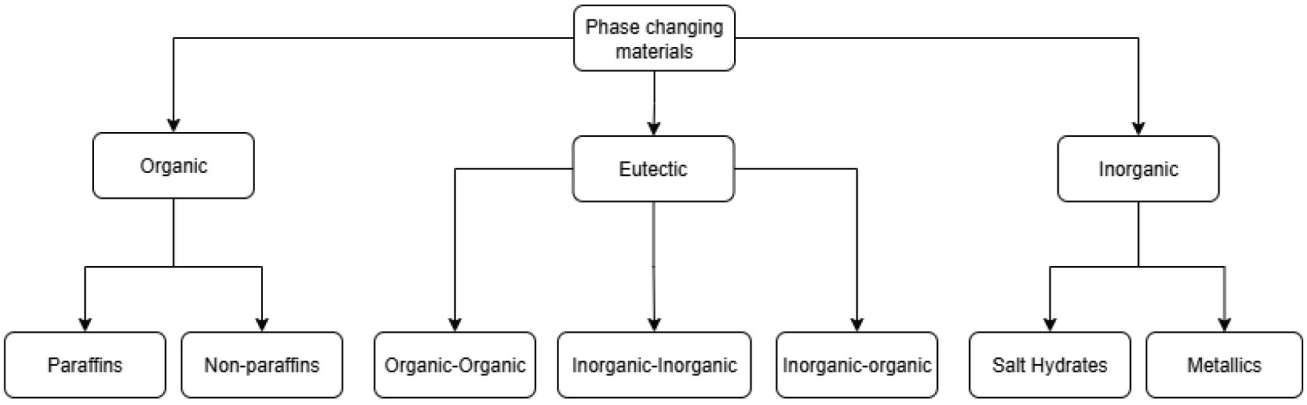


Fig. 1 Classification of Phase Changing materials

Silicone rubber is an elastomer consisting of multiple elements. It is a polymer composed of silicon and oxygen atoms in the backbone and side branches consisting of methyl groups; it is also referred to as polydimethylsiloxane. Silicone rubbers can be one- or two-part polymers. In the case of a two-part polymer, there is an A component, which is the base polymer and provides the silicone with its bulk properties, and there is a B component, which acts as the catalyst. When the A and B components are mixed, crosslinking is activated, and the material starts to cure. A special type is room-temperature-vulcanised (RTV) silicone, which cures at room temperature. This type comes in different curing times, ranging from 10 minutes to 24 hours. It also comes in different hardnesses, ranging from 10A (soft, comparable to a rubber band) to 100A (hard, comparable to shopping cart wheels). Silicone rubber can be used across a wide temperature range, from -50°C to 230 [7]. The CTE of silicone rubber ranges from 200-300 $\frac{ppm}{K}$, which slightly contributes to the total thermal expansion [8]. Additionally, the thermal conductivity of silicone rubber is similar to that of paraffin wax [9], which means that a sufficient dwell time is critical to achieve complete melting of the wax at elevated temperatures. Lastly, the Young's modulus of silicone is a factor of 10 lower than paraffin wax, ranging from 1 to 10 MPa [10]. However, the modulus remains relatively constant across the temperature service range, and it is also very ductile. All these properties make it an excellent encapsulating material.

Method

An implementation of PCMs was presented in the Master Thesis of Flint [11]. In his study, the goal was to demonstrate how the eigenfrequency and damping ratio of beams could be tuned as a function of temperature by embedding materials with differing thermal and mechanical properties. The present work builds upon and extends his findings.

To this end, two hollow carbon fibre beams with a symmetric layup of $[-45/45/0/45/-45]$ were manufactured. Both beams had identical geometry but were filled with different core materials. The beam dimensions and an example of the geometry are shown in Figures 2 and 3, respectively. The first beam served as a reference and was filled with silicone rubber, while the second beam was filled with a multiphase composition consisting of 85% silicone and 15% paraffin wax by volume. Both beams were equipped with Kapton foil heating elements to control the internal temperature, as well as thermocouples to monitor it. To prevent leakage of molten wax and maintain a closed system, the beams were sealed with plastic end caps. Additionally, the weight and theoretical eigenfrequencies were calculated, as summarised in Table 1.

The dynamic properties were characterised using Experimental Modal Analysis (EMA). In this procedure, the beam is excited using an electrodynamic shaker, while an accelerometer measures the response. The input is the force from the shaker, and the output is the acceleration of the beam. For spatial resolution, the beam was divided into 13 equal segments

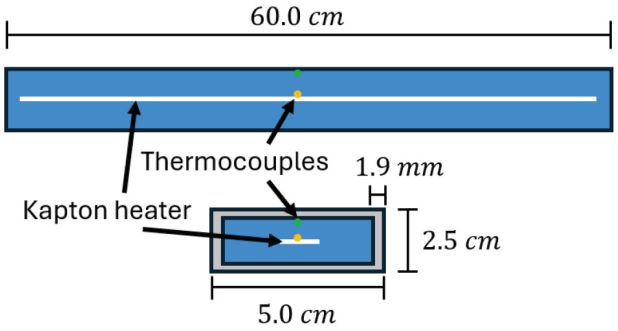


Fig. 2 Schematic representation of the beam dimensions and content

Table 1 Composition and weight of the beams and analytically calculated first eigenfrequency

Sample	Si/wax [%]	Weight [g]	ω_1 [Hz]
Beam 1	100/0	1024	370
Beam 2	85/15	978	379

with 14 nodes. A preliminary test was conducted to identify the most suitable excitation and response points. Node 12 was chosen as the excitation point, and node five was selected as the response point, as shown in Figure 4. This figure also shows that the beam is freely suspended at two points by a small string. It also displays the force sensor, which measures the input force from the shaker, and the thermocouple cables.

The excitation was applied as a frequency sweep, ranging from 50 to 500 Hz, with the force level kept constant. Since the first bending eigenfrequency of the beam was expected between 370 and 380 Hz. During post-processing in Matlab, the frequency response function (FRF) was computed by dividing the Fast Fourier transform of the output by that of the input. From the FRF, the first eigenfrequency and its corresponding damping ratio were extracted using the peak-picking method.

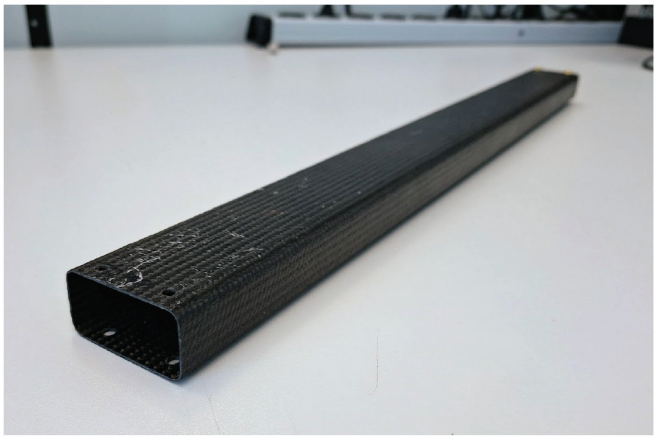


Fig. 3 Close up of the outside of the carbon fibre beam

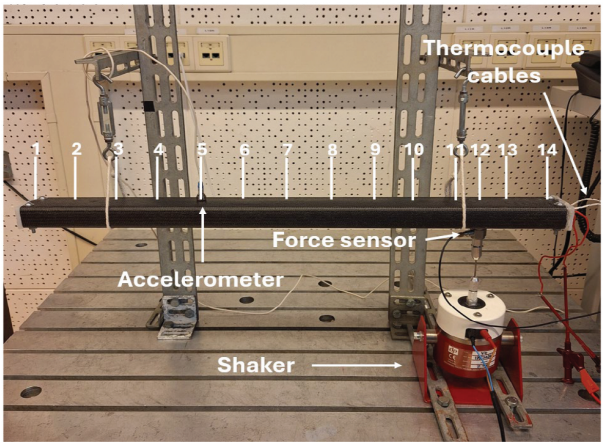


Fig. 4 Experimental test setup

The measurements were repeated at multiple temperatures to study the thermo-mechanical effect of the PCM. Starting from room temperature (20 °C), the temperature was increased stepwise up to 50 °C, which is slightly above the melting point of the paraffin wax used. The ramp rate is 0.2 °C/min. At each step, the heating elements were allowed to dwell for 5 min before the modal test was repeated.

Results

Figure 5 (eigenfrequency) and Figure 6 (loss factor) plot the modal response of the two beam compositions as a function of mean beam temperature (x-axis). The eigenfrequency and loss factor are shown normalised to their first measurement. For Beam 1 (100% silicone), the normalised first-mode frequency rises rapidly to a maximum near 32 °C ($\approx$ 108%, approximately +12 Hz in absolute terms), after which it declines approximately linearly with a slope of about -0.36 Hz/°C to roughly +3.9% at 50 °C. Beam 2 (85% silicone / 15% wax) exhibits the same trend, but with a lower peak near 29 °C

($\approx +105\%$, approximately 9 Hz) and a steeper post-peak decline of about -0.49 Hz/°C, which brings the frequency below its initial value at higher temperatures. These numerical trends are reproduced in the duplicate runs. Before the peak, minor deviations are observed between the data points; however, beyond the peak, the measurements converge and follow a single consistent trend.

The behaviour of the frequency response can be understood as the result of two competing thermo-mechanical effects. First, increasing temperature increases polymer chain mobility and reduces the stiffness of the matrix material, which is directly related to a reduction in the eigenfrequency. Second, near the wax melting range, the paraffin undergoes a large constrained volumetric expansion (up to 15%), which increases internal pressure and acts like a stiffening preload on the beam walls, thereby raising stiffness. This effect explains the sharp rise in frequency around the melting interval. Once the wax is fully molten, the expansion-driven stiffening vanishes and the temperature-dependent softening of the polymer dominates, causing the frequency to fall again.

The results also indicate that beam two consistently exhibits a higher eigenfrequency than beam one. Since a higher eigenfrequency is directly associated with increased stiffness, it can be argued that the addition of wax enhanced the stiffness of the system not only at the peak but across the entire temperature range. There are two likely explanations for this increase: first, the Young's modulus of wax is approximately an order of magnitude greater than that of silicone rubber, and second, the density decreased. Because eigenfrequency is inversely related to density, and wax possesses a lower density than silicone rubber, the eigenfrequency consequently increased.

The loss factor curves follow a distinct pattern. Beam 1 begins near 0.118 and increases with 8.6E-3 1/ °C, peaks around 29 °C ($\approx$ 165 %), then falls rapidly to 48 % at 39 °C before it stays constant. Beam 2 starts lower at 0.063, but reaches a larger relative peak at 25 °C (250 %) and then falls below the initial value, after which it remains constant. This behaviour indicates that the added wax shifts the peak loss factor by a few degrees. When paraffin wax is embedded into a silicone matrix, its phase transition introduces an additional dissipation mechanism that is absent in the single-phase system. Paraffin undergoes a solid-to-liquid transition over a narrow temperature range, during which it exists in both solid and liquid states. Under dynamic loading, these domains continuously rearrange, and the solid–liquid interface then creates internal friction. This internal friction results in higher hysteresis losses during each vibration cycle, thereby increasing the effective loss factor.

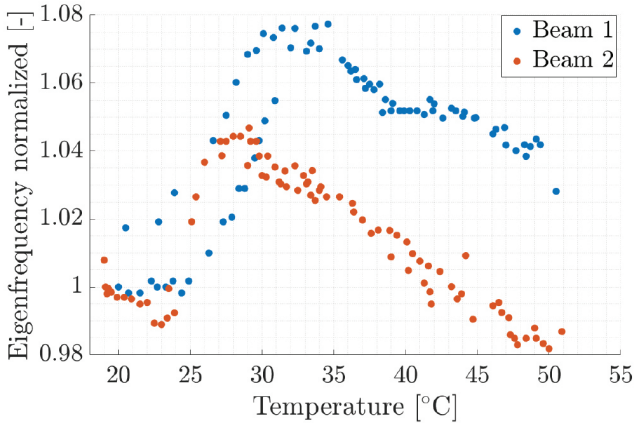


Fig. 5 The eigenfrequency results of the EMA for different temperatures

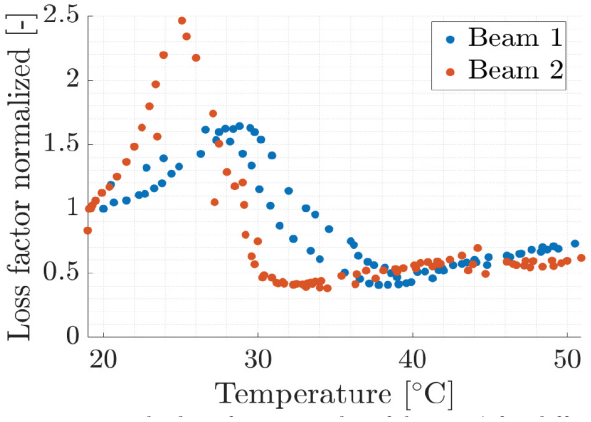


Fig. 6 The loss factor results of the EMA for different temperatures

Conclusions

This study demonstrated that combining silicone rubber with hard paraffin wax enables temperature-dependent tuning of dynamic properties in composite beams. Two competing mechanisms were identified: stiffness reduction due to increased polymer chain mobility and stiffness enhancement resulting from wax expansion during the phase transition. The results showed that eigenfrequency can be shifted and local damping improved by up to a factor of 2.5. These findings provide a proof of concept for integrating phase-change materials into structural components to achieve adaptive behaviour. While this work provides a proof of concept, future studies should address higher wax compositions and more in-depth research about the behaviour of PCMs.

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