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A THERMALLY DRIVEN SMART SANDWICH STRUCTURE WITH A SHAPE MEMORY POLYMER CORE FOR SEMI-PASSIVE VIBRATION CONTROL

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Abstract. *Constrained layer damping (CLD) treatment is a passive technique used to reduce vibration levels by incorporating viscoelastic materials into multilayered structures to increase structural damping. As a passive vibration control technique, it does not require external energy input to operate. In particular, the damping layer contributes to vibration reduction when the structure is subjected to high-frequency excitations. However, the efficient design of such a solution often requires an appropriate strategy for allocating the viscoelastic layer, since the strain energy distribution varies with load frequency and boundary conditions. Moreover, improving the robustness of traditional CLD solutions leads to an increase in structural mass, and the resulting multilayered structures still lack adaptability once fabricated. The development of advanced materials such as shape memory polymers (SMPs) enables the design of structures with enhanced adaptability. By controlling the temperature-dependent mechanical properties – storage modulus and loss factor – of these viscoelastic materials, a multilayered structure can exhibit various dynamic behaviors. In this work, a thermally driven sandwich structure is developed by integrating embedded thermocouples and in-core heaters to achieve active thermal control. The structure is divided into independently controllable patches, allowing it to be programmed with distinct thermal configurations. This capability enables local adjustments of stiffness and damping through temperature control at each patch, thereby enhancing the overall adaptability of the structure. An equivalent modeling approach for the sandwich structure is adopted to construct a Pareto front that evaluates the damping and static stiffness levels of various thermal configurations. Based on different damping–stiffness trade-offs, the dynamic responses of selected configurations are experimentally characterized. The results demonstrate that the proposed structure exhibits improved adaptability and achieves significant vibration reduction under different imposed thermal configurations.*

Keywords: smart sandwich structure, shape memory polymer, in-core thermal control, damping optimization, vibration control

1. INTRODUCTION

Vibration reduction in lightweight structures is an important issue in many engineering applications. Among passive control techniques, constrained layer damping (CLD) treatments are widely used and extensively studied from a modeling perspective (Kosmatka and Liguore, 1993). They consist of incorporating viscoelastic materials into multilayered structures in order to increase damping through energy dissipation within the viscoelastic layer. Such solutions are particularly effective for attenuating vibrations in the medium- and high-frequency ranges.

However, the performance of classical CLD treatments depends on design parameters, such as the thickness of the viscoelastic layer, as well as on operating conditions, such as the excitation frequency and the boundary conditions. The strain energy distribution in the structure is subject to uncertainties since these conditions may vary during operation. As a result, the optimal design of multilayered damping structures remains challenging (Gröhlich *et al.*, 2021), and their ability to adapt to changing operating conditions is still limited.

Advanced viscoelastic materials such as shape memory polymers offer new possibilities for adaptive vibration control. Their mechanical properties are strongly temperature-dependent. Through thermal actuation, it becomes possible to tune the damping and stiffness properties of a shape memory polymer core and, by heating selected regions, to modify the dynamic response while seeking a compromise between damping and stiffness (Butaud *et al.*, 2020). This gives the structure a higher level of adaptability.

In this work, a thermally driven smart sandwich structure with a shape memory polymer core and instrumented skins is proposed for semi-passive vibration control. The structure is divided into thermally driven patches and, to identify relevant thermal configurations with reduced computational cost, an equivalent plate modeling approach is adopted to compute damping and stiffness indicators (da S. Raqueti *et al.*, 2025) and to construct a Pareto front. This approach makes it possible to select two representative thermal configurations, which are then imposed experimentally on the structure and evaluated through vibration tests.

This manuscript is organized as follows. Section 2 presents the thermally driven smart sandwich structure with a shape memory polymer core. Section 3 adopts an equivalent plate modeling approach to construct a Pareto front of thermal configurations exhibiting different damping-stiffness trade-offs. Section 4 presents the experimental results obtained for the smart sandwich structure under imposed thermal configurations. Finally, Section 5 summarizes the main conclusions and outlines perspectives for future work.

2. A THERMALLY DRIVEN SMART SANDWICH STRUCTURE FOR VIBRATION CONTROL

The main subject of this work is the development of a thermally driven smart sandwich structure for vibration control. The structure is composed of a shape memory polymer core made of tert-butyl acrylate/poly(ethylene glycol) dimethacrylate (tBA/PEGDMA) and two instrumented skins made of flame retardant grade 4 printed circuit board (FR-4 PCB), as shown in Fig. 1. This section first presents the principle by which the mechanical properties of the sandwich structure can be tuned through temperature. It then briefly describes the embedded heating and temperature regulation systems used to impose different thermal configurations on the structure.

2.1 Thermal tuning of the storage modulus and loss factor of the tBA/PEGDMA core

The mechanical properties of tBA/PEGDMA were characterized in (Butaud *et al.*, 2018), in which the complex modulus E^* was described using the rheological model given in Eq. (1):

$$E^* = E_0 + \frac{E_\infty - E_0}{1 + \gamma (j\omega\tau)^{-k} + (j\omega\tau)^{-h} + (j\omega\beta\tau)^{-1}}. \quad (1)$$

The temperature dependence of the complex modulus is introduced through the characteristic time $\tau = a_T\tau_0$, where a_T is defined by the Williams–Landel–Ferry (WLF) law given in Eq. (2):

$$\log(a_T) = \frac{-C_1^0(T - T_0)}{-C_2^0 + T - T_0}. \quad (2)$$

The parameter values adopted in this work for the definition of the complex modulus are listed in Tab. 1.

Table 1: Complex modulus model parameters of the tBA/PEGDMA material (Butaud *et al.*, 2016).

E_0 (MPa)	E_∞ (MPa)	γ (-)	β (-)	k (-)	h (-)	C_1^0 (-)	C_2^0 (K)	T_0 (K)	τ_0 (s)
0.67	2,221	1.68	38,000	0.16	0.79	10.87	32.57	313.15	0.61



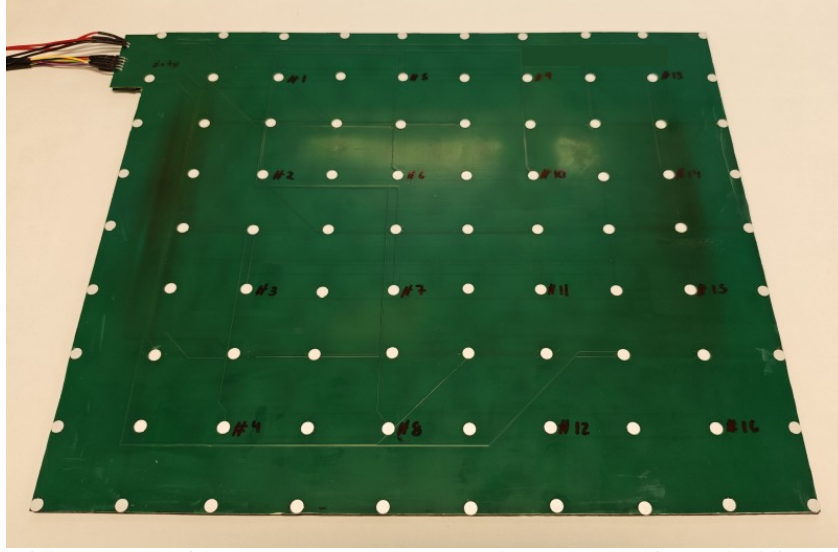


Figure 1: Smart sandwich structure with a tBA/PEGDMA core and FR-4 PCB skins embedding heaters and thermocouples.

Equation (3) defines the storage modulus E' and the loss factor $\tan(\delta)$ from the complex modulus:

$$E' = \Re(E^*), \quad \text{and} \quad \tan(\delta) = \frac{\Im(E^*)}{\Re(E^*)}. \quad (3)$$

Figure 2 shows the evolution of the storage modulus E' and the loss factor $\tan(\delta)$ of tBA/PEGDMA over the temperature range from 20 °C to 120 °C, for frequencies ranging from 10 Hz to 1024 Hz.

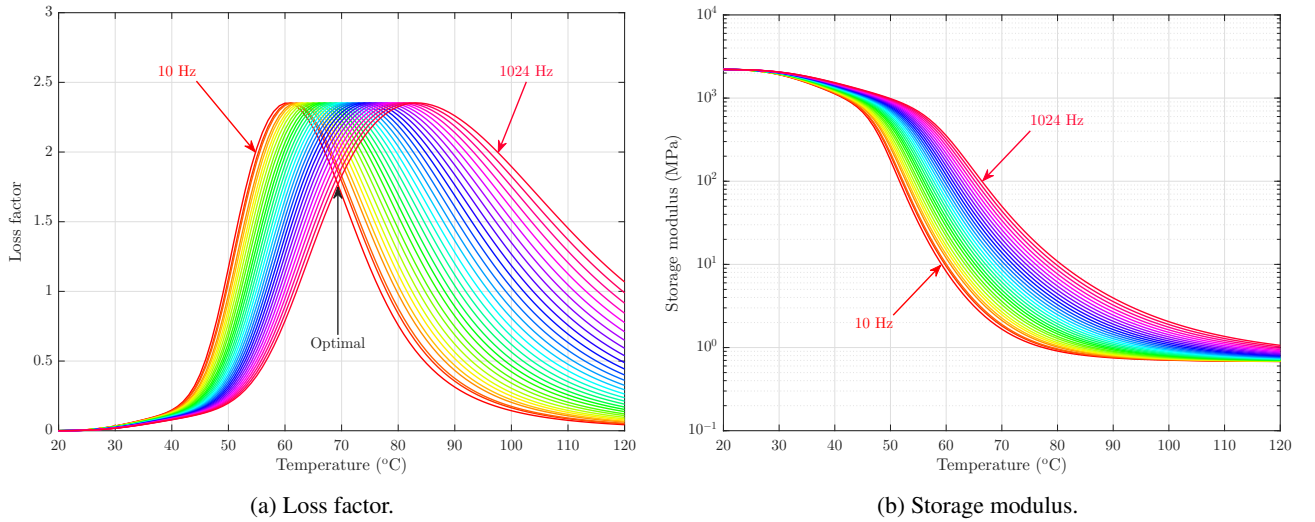


Figure 2: Mechanical properties of the tBA/PEGDMA (Butaud *et al.*, 2016).

Figure 2a shows that tBA/PEGDMA exhibits high damping levels around its glass transition temperature. At 69 °C, the loss factor $\tan(\delta)$ remains higher than 1.74 over the considered frequency range, which is favorable for vibration reduction applications.

However, as observed in Fig. 2b, this temperature increase is accompanied by a reduction in the storage modulus. Although higher temperatures improve damping levels, they also reduce stiffness and may therefore deteriorate the structural performance of the sandwich structure. A compromise between damping and stiffness must therefore be sought.

For this purpose, a patch-based strategy, as described in (Butaud *et al.*, 2020), is considered. By prescribing high temperatures locally rather than over the entire structure, it becomes possible to enhance damping in selected regions while preserving overall stiffness level. The combination of the temperature-dependent behavior of tBA/PEGDMA, its high damping capability, and the patch arrangement strategy thus provides the structure with enhanced adaptability. In addition, it makes it possible to explore thermal configurations exhibiting different damping-stiffness trade-offs.

2.2 Instrumented sandwich structure

The smart sandwich structure shown in Fig. 1 consists of a tBA/PEGDMA shape memory polymer core and two FR-4 PCB skins. The nominal thickness of the core is $h_2 = 2.20$ mm, while the nominal thicknesses of the top and bottom skins are $h_1 = 0.72$ mm and $h_3 = 0.66$ mm, respectively. The overall dimensions of the sandwich structure are 380 mm in length and 320 mm in width.

Both skins incorporate 16 printed copper circuits on their inner surfaces, *i.e.*, at the interfaces with the tBA/PEGDMA core. These circuits form rectangular patches of $73.75 \text{ mm} \times 77.50 \text{ mm}$ distributed over the structure, each with an electrical resistance of 22Ω . These printed circuits define the heated areas of the tBA/PEGDMA core and, consequently, the 16 patches of the smart sandwich structure.

One of the skins is instrumented with DS1822Z thermocouples, enabling *in situ* temperature measurements. For each patch, the temperature is measured at one central point within the heated area. These measurements are used by an Arduino-based proportional-integral-derivative (PID) control system to regulate the temperature of each patch. In this work, a thermal configuration is defined as the set of reference temperatures assigned to the 16 patches. The next step is therefore to identify thermal configurations exhibiting different damping-stiffness trade-offs.

3. IDENTIFICATION OF THERMAL CONFIGURATIONS FOR DAMPING-STIFFNESS TRADE-OFFS

In order to identify thermal configurations exhibiting different damping-stiffness trade-offs, suitable estimators must first be defined to assess the damping and stiffness of the sandwich structure. These estimators are obtained from a numerical model of the structure. In previous studies, sandwich structures with a tBA/PEGDMA core were modeled using three-dimensional solid finite element models based on continuum mechanics (Butaud *et al.*, 2016, 2020). Although such models provide a detailed description of the structure, they remain computationally demanding and limit the exploration of a large number of thermal configurations.

As an alternative, equivalent modeling approaches can be adopted to determine relevant indicators in vibroacoustic applications (Ross *et al.*, 1959; Guyader and Cacciolati, 2007; Arasan *et al.*, 2021; Tuozzo and Atalla, 2025; da S. Raqueti *et al.*, 2025). Accordingly, this section adopts an equivalent plate modeling approach to compute the estimators of the sandwich structure and to construct a Pareto front of thermal configurations.

3.1 Equivalent plate modeling approach

In a recent work, homogenization techniques were investigated in (Tuozzo and Atalla, 2025) to assess vibroacoustic indicators of multilayered structures with high damping capability. These techniques are based on the conservation of the three main waves propagating in the structure (bending, shear and quasi-longitudinal waves), whose wavenumbers are used to determine the effective properties of an equivalent plate. The equivalent plate is then used to estimate vibroacoustic indicators such as total energy and diffuse-field transmission loss.

Concerning damping, a multi-wave-based approach was proposed in (Cui *et al.*, 2024) to estimate the structural damping loss factor. This approach accounts for the contribution of several wave types in the computation of energy indicators and has proven suitable for estimating the damping of highly damped structures.

By combining these developments, an equivalent plate approach was proposed in da S. Raqueti *et al.* (2025). In that work, the bending, shear and quasi-longitudinal wavenumbers of the structure are used to compute the effective properties of an equivalent plate (Tuozzo and Atalla, 2025), which are then introduced into a finite element implementation. Damping is incorporated in a second step through a structural damping loss factor (Cui *et al.*, 2024). This finite element implementation can account for boundary conditions as well as patchwise distribution of material properties. The results showed that this approach provides an adequate estimation of the damping of highly damped sandwich structures with patch arrangement at a reduced computational cost.

The same approach detailed in (da S. Raqueti *et al.*, 2025) is adopted in the present work. The smart sandwich structure is modeled as an equivalent plate composed of 16 patches, as shown in Fig. 3. Each patch is assigned a set of effective properties that depend on both frequency and temperature. The governing equation of motion is written as

$$\left([\tilde{K}^*(\omega, T)] - \omega^2 [\tilde{M}(\omega, T)] \right) \{U\} = \{F\}, \quad (4)$$

where $[\tilde{M}(\omega, T)]$ and $[\tilde{K}^*(\omega, T)]$ denote, respectively, the equivalent mass matrix and the complex stiffness matrix of the equivalent plate, while $\{U\}$ and $\{F\}$ are the displacement and force vectors. The complex stiffness matrix incorporates the structural damping loss factor η associated with each patch.

The effective properties assigned to each patch are computed from the wavenumbers k_B , k_T and k_L . The explicit formulas are given in (da S. Raqueti *et al.*, 2025). These wavenumbers are obtained using the General Laminate Model (GLM) (Ghinat and Atalla, 2011), which is a semi-analytical discrete model for multilayered plates accounting for bending, in-plane and transverse shear effects, rotational inertia and interlayer forces. The wavenumbers are selected according to the procedure described in (da S. Raqueti *et al.*, 2025), and only their real parts are retained.

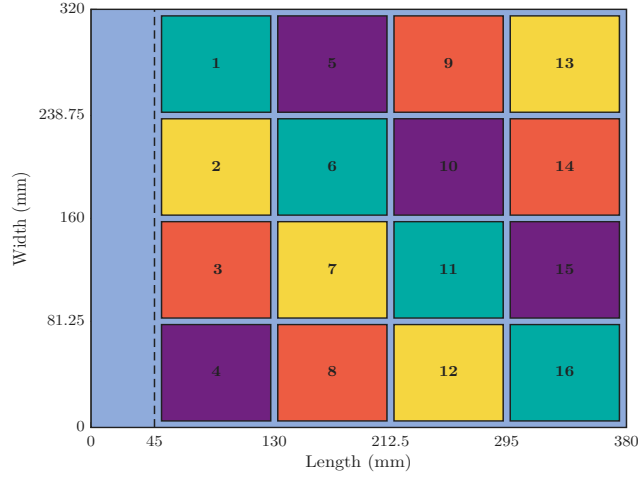


Figure 3: Equivalent plate representation with 16 independently thermally programmable patches.

The layer thickness h_i and the material properties density ρ , Poisson's ratio ν , Young's modulus E and loss factor η used in the wavenumber computations are listed in Tab. 2. For the tBA/PEGDMA core, the Young's modulus and loss factor are temperature-dependent and are taken from Fig. 2b and Fig. 2a, respectively.

Table 2: Layer properties of the sandwich structure used to compute the equivalent plate properties.

Layer	h_i (mm)	ρ (kg/m ³)	ν (-)	E (GPa)	η (-)
Top skin (FR-4 PCB)	0.72	1,900	0.15	22	0.001
Core (tBA/PEGDMA)	2.20	990	0.37	T -dependent	T -dependent
Bottom skin (FR-4 PCB)	0.66	1,900	0.15	22	0.001

The finite element implementation of the equivalent plate is used to compute the estimators describing the damping and stiffness of the sandwich structure.

3.2 Construction of a Pareto front

Two indicators are introduced to characterize the dynamic and static behavior of the structure. First, the damping level is assessed through the structural damping loss factor, estimated from energy indicators as

$$\eta = \frac{\Pi_d}{\omega E_{tot}}, \quad (5)$$

where Π_d is the dissipated power and E_{tot} is the total energy over one load cycle. A dynamic indicator is defined as

$$\mathcal{J} = \frac{1}{\eta}. \quad (6)$$

From Eq. (6), lower values of $\mathcal{J}$ correspond to higher damping levels.

Second, the stiffness level is assessed from the static transverse displacement under a point load. In the static limit, the displacement vector is obtained as

$$\{U_0\} = [\tilde{K}^*(\omega \rightarrow 0, T)]^{-1} \{F\}, \quad (7)$$

where $\{U_0\}$ is the static displacement vector. The static indicator $\mathcal{C}_0$ is defined as the transverse displacement component obtained at the same degree of freedom where the transverse point load is applied.

Temperatures are assigned to each patch and the indicators corresponding to the thermal configuration are computed using the equivalent plate model. A total of 1026 thermal configurations are sampled and its distribution in the $(\mathcal{C}_0, \mathcal{J})$ plane is shown in Fig. 4. In addition, two "homogeneous" thermal configurations are indicated: a uniform configuration at 20 °C, associated with the smallest static displacement; and a uniform configuration at 80 °C, associated with the highest damping level.

From this Pareto front, two thermal configurations representative of a damping–stiffness trade-off are selected. The experimental response of the smart sandwich structure is then characterized under these imposed thermal configurations.

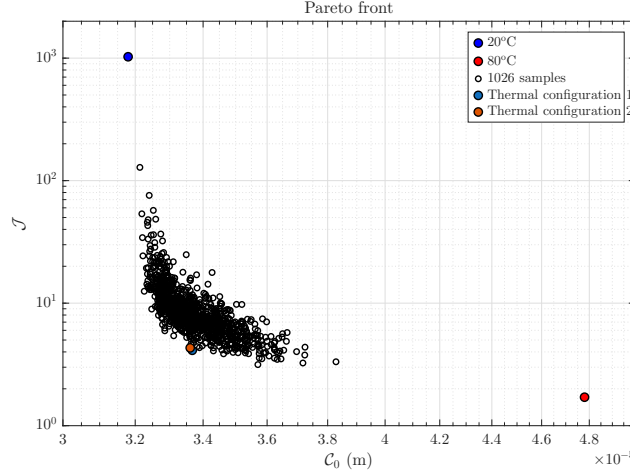


Figure 4: Pareto front of 1026 thermal configurations in terms of the static and dynamic indicators (C_0 , J). Two representative configurations showing a damping-stiffness trade-off are selected.

4. RESULTS AND DISCUSSION

Figure 5 shows the experimental setup used for vibration testing. The smart sandwich structure is suspended by nylon lines to approximate free boundary conditions. A shaker is positioned to apply a transverse excitation and a white-noise signal in the frequency range from 10 Hz to 1024 Hz is imposed on the structure. The vibration velocity is measured at different points on the structure surface using a PSV-500 Xtra 1D laser vibrometer. The measured data are then processed using Modan©, an in-house developed program for modal analysis.

Vibration tests are performed only after the temperatures of the patches have reached steady-state conditions. As shown in Fig. 5b, an Optris PI 450 thermal camera is also included in the experimental setup. During the experimental campaign, this camera is used as an auxiliary measurement tool to monitor the spatial temperature distribution over the structure surface. Figure 6 illustrates the temperature field obtained when a homogeneous thermal configuration at 50 °C is imposed. Thermal regulation is achieved by a PID control strategy using temperature measurements provided by the embedded thermocouples. In the following subsection, these measurements are used to present the imposed thermal configurations and the corresponding temperature levels reached in the different patches.

4.1 In-core thermal control

Figure 6 shows that the smart sandwich structure is able to heat its patches and maintain stable temperature levels, thereby heating the tBA/PEGDMA core. In this case, all patches are prescribed at 50 °C. The boundaries of the patches are clearly visible in Fig. 6, with lower temperatures observed at the interfaces between patches. The difference between the prescribed temperatures and the temperatures observed on the surface is mainly due to thermal diffusion through the FR-4 PCB skin.

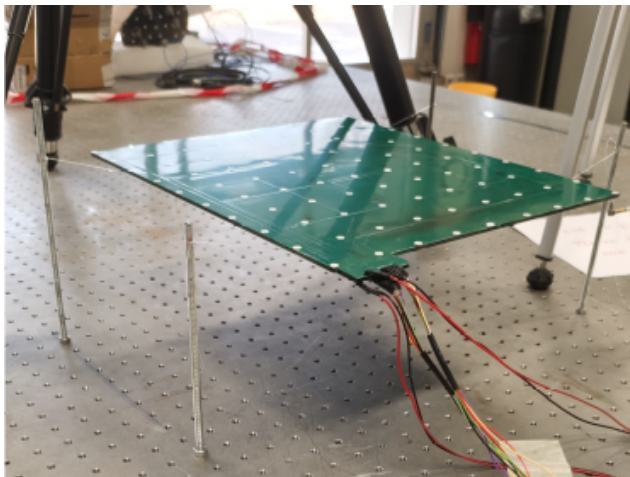
The two thermal configurations selected from Fig. 4 are then imposed on the sandwich structure. Figure 7a shows the prescribed temperatures of Thermal Configuration 1, while the differences between the prescribed and measured temperatures from the embedded thermocouples are presented in Fig. 7b. The largest temperature errors are observed in the patches prescribed at lower temperatures. This behavior is mainly attributed to thermal diffusion from neighboring patches set at higher temperatures. Overall, the temperature levels remain below the glass transition region, which is consistent with preserving the stiffness of the sandwich structure while still providing additional damping.

Figure 8 presents the same type of results for Thermal Configuration 2. In both configurations, Patch 3 exhibits the largest negative deviation from the prescribed temperature, indicating lower heating performance than the other patches. In all cases, vibration tests are conducted only after the patch temperatures have reached steady-state conditions.

4.2 Vibration tests under imposed thermal configurations

A first vibration test is conducted on the sandwich structure at room temperature, without thermal actuation. This test provides a reference for the dynamic behavior of the structure in its unactuated state. Figure 9 shows the measured mean square velocity (MSV) spectrum of the smart sandwich structure. The experimental responses obtained at room temperature and under imposed Thermal Configurations 1 and 2 are compared in Fig. 9.

Figure 9 shows that the two imposed thermal configurations reduce the MSV level of the smart sandwich structure compared with the room temperature case. This reduction is observed over a wide frequency range, with vibration modes at medium and high frequencies being more strongly attenuated. Noticeable peak reductions are also observed for some



(a) Smart sandwich structure under free boundary condition.



(b) Instrumentation: PSV-500 Xtra 1D laser vibrometer and Optris PI 450 thermal camera.

Figure 5: Experimental setup for vibration testing.

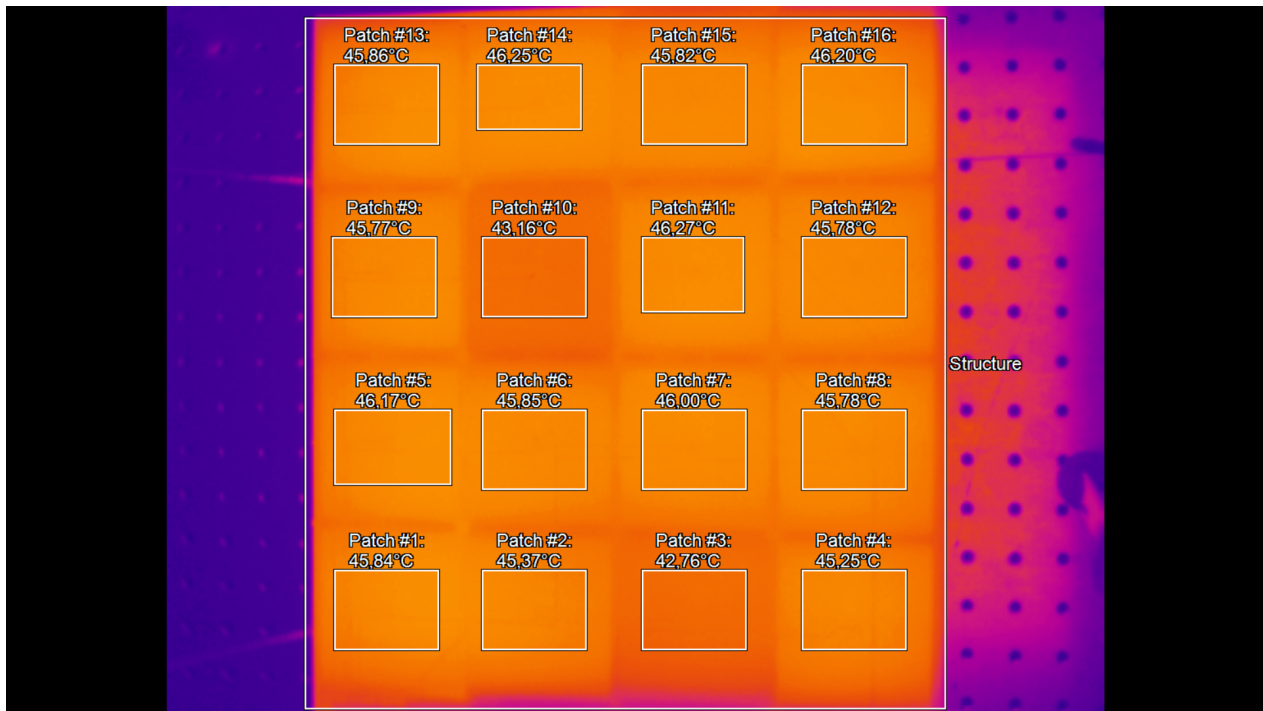


Figure 6: Smart sandwich structure under a homogeneous thermal configuration (all patches set to 50 °C).

lower frequency modes, *e.g.*, around 260 – 300 Hz). This suggests that certain thermal configurations may be better suited to mitigate specific modes, which may be related to the corresponding mode shapes and the distribution of strain energy relative to the heated patches. In addition, slight shifts in some resonance frequencies can be observed, reflecting changes

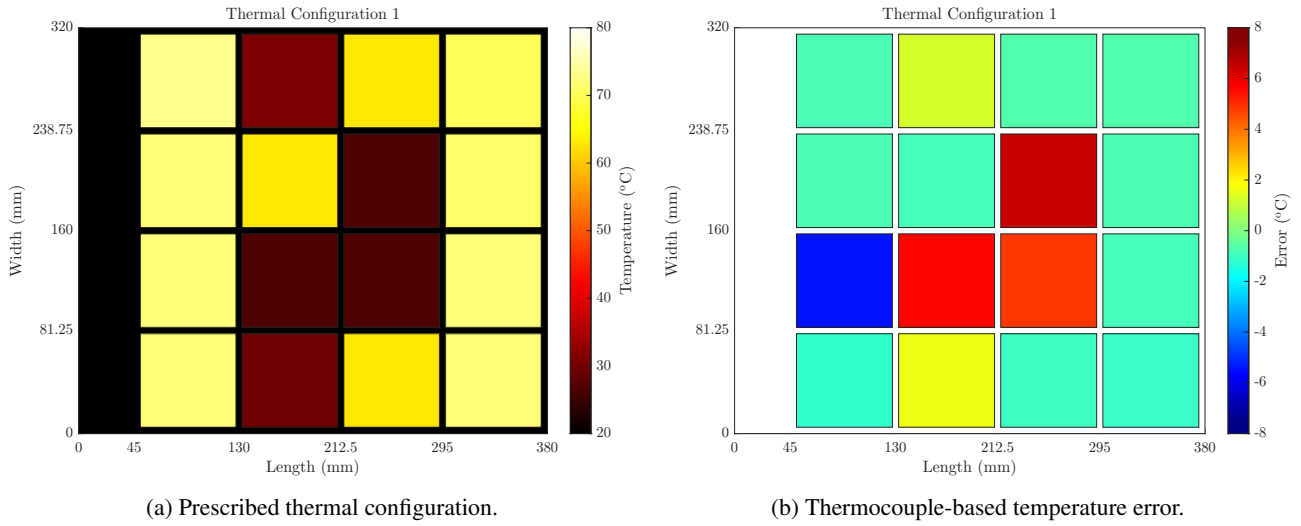


Figure 7: Thermal Configuration 1: prescribed patch temperatures and the corresponding thermocouple-based temperature error after stabilization.

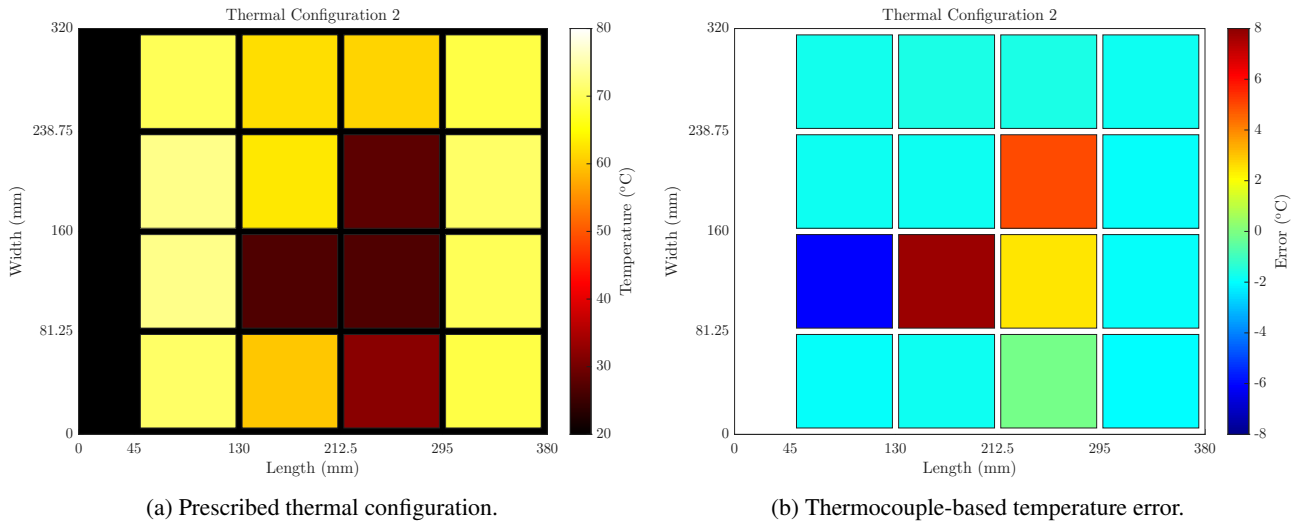


Figure 8: Thermal Configuration 2: prescribed patch temperatures and the corresponding thermocouple-based temperature error after stabilization.

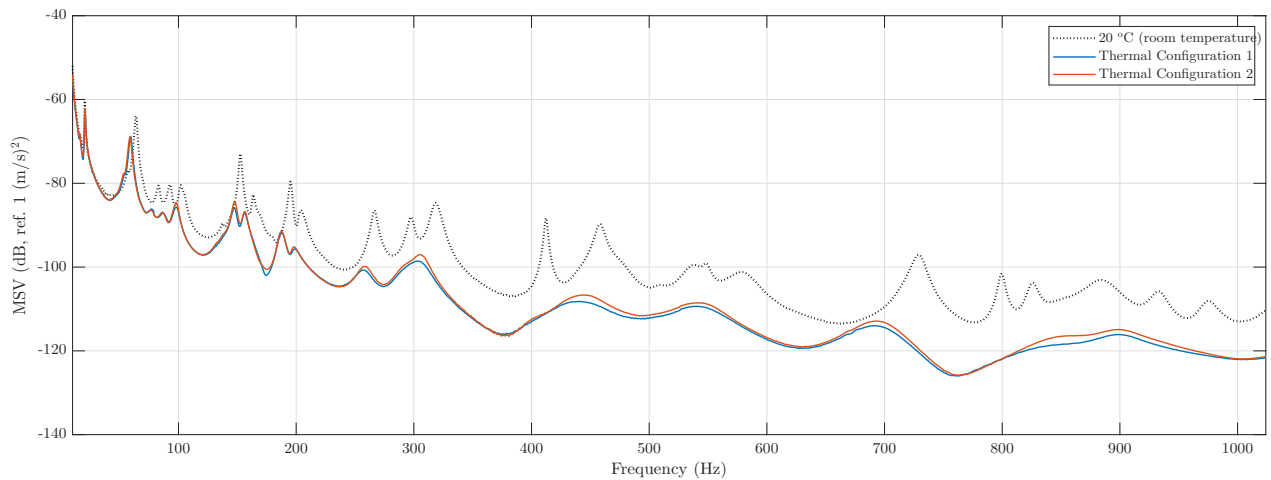


Figure 9: Experimental mean square velocity (MSV) spectrum of the smart sandwich structure at room temperature and under imposed Thermal Configurations 1 and 2.

in structural stiffness induced by the temperature-dependent behavior of the tBA/PEGDMA core.

Although Thermal Configurations 1 and 2 exhibit similar global trends, small differences in attenuation level can be observed in certain frequency bands, *e.g.*, between 400 Hz and 500 Hz. This highlights the programmable character of the proposed smart sandwich structure, in which different thermal configurations can lead to adapted responses. At lower frequencies, the responses remain close to the room temperature case, which is consistent with a limited reduction in stiffness.

5. CONCLUSIONS

This work presented a thermally driven smart sandwich structure with a tBA/PEGDMA shape memory polymer core for semi-passive vibration control. By imposing different thermal configurations on independently heated patches, the structure can modify its dynamic response through local temperature-driven changes in viscoelastic properties. An equivalent plate modeling approach with reduced computational cost was used to identify thermal configurations corresponding to damping–stiffness trade-offs. These configurations were then imposed experimentally, and the vibration tests confirmed broadband attenuation compared with the room temperature case. In addition, the experimental results showed that the dynamic response changes with the imposed thermal configuration, demonstrating the programmable and reconfigurable character of the proposed structure. Such a capability opens the way to self-adaptive sandwich structures able to respond to changing environmental and operating conditions.

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