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**Wave dynamics of additive manufactured ABS/PLA
phononic structures at different temperatures**

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Abstract

Elastic metamaterials can control wave propagation through engineered periodic structures and may exhibit bandgaps in which waves cannot propagate. Introducing tunability into these bandgaps enables adaptive vibration control in changing environments. One promising approach is to exploit the temperature-dependent mechanical properties of polymers produced by additive manufacturing. This research investigates the wave dynamics of multimaterial additively manufactured metamaterial structures composed of PLA and ABS. The study explores how the reduction in the Young's modulus of PLA near its glass transition temperature can be used to achieve thermally tunable bandgaps. First, printing parameters for reliable multimaterial fabrication were optimized. Dispersion and transmission behaviour of several unit-cell configurations were then analyzed numerically using COMSOL. Finally, wave transmission experiments were conducted using a Macro Fiber Composite actuator and a laser Doppler vibrometer while the structures were heated on a controlled print bed. The analytical results predict a significant downward shift of bandgaps when PLA transitions from the glassy to the rubbery state. Experiments confirm the overall trend but show discrepancies at lower frequencies, mainly attributed to simplified numerical modelling and damping introduced by the experimental boundary conditions. The results demonstrate the potential of multimaterial additive manufacturing for realizing thermally tunable phononic structures.

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1 Introduction

Elastic metamaterials, also known as phononics, have gained significant research interest due to their ability to control wave propagation through engineered periodic architectures rather than intrinsic material composition. These architected materials can exhibit bandgaps, frequency ranges in which waves cannot propagate. Such bandgaps enable applications in vibration isolation, energy harvesting, waveguiding, and structural health monitoring, making metamaterials increasingly relevant in aerospace, automotive, and other mechanical engineering contexts [1].

Additive manufacturing (AM) has emerged as a key enabler for realizing metamaterials in practice. AM provides almost unlimited geometric freedom which allows complex lattice structures and multi-material designs to be produced with relative ease, enabling rapid prototyping of architected materials that would be difficult or impossible to manufacture conventionally. Polymers are often used in AM, due to their accessibility and low costs [2]. Polymers exhibit viscoelastic behaviour, meaning their mechanical response combines elastic energy storage and viscous energy dissipation. Under dynamic loading, this behaviour is described by a complex modulus consisting of storage modulus (E'), representing stiffness, and a loss modulus (E''), representing damping. Both stiffness and damping are strongly depending on temperature. As temperature increases, polymer chain mobility increases and near the glass transition temperature (T_g) the material undergoes a transition to a rubber state. This transition is characterized by a significant reduction in stiffness and peak in damping [3].

The ability to tune bandgaps is of growing interest because it enables adaptive control of wave propagation without requiring complete structural redesign. Tunable bandgaps allow metamaterial/ phononic structures to respond to changing operational conditions, such as variations in excitation frequency, environmental conditions, or loading, thereby expanding their applicability. Compared to fixed bandgap structures, tunable metamaterials offer increased flexibility and functionality, making them particularly attractive for engineering applications under varying operating conditions [1].

The temperature dependence of polymers can be exploited to achieve thermally tunable wave control, as the structural stiffness directly influences wave propagation characteristics. In elastic structures, the speed at which mechanical waves travel depends on the stiffness of the material. When the temperature increases, the stiffness of many polymers decreases, particularly near the glass transition temperature (T_g). As a result, waves propagate more slowly through the structure, which can shift the frequency ranges in which waves are allowed or blocked. Consequently, the viscoelastic softening of polymers near T_g provides a natural mechanism for tuning the bandgap behaviour of elastic metamaterials [1].

Among commonly used AM polymers, polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are particularly suitable for such application due to their difference in thermal-mechanical behaviour. PLA exhibits a relatively low T_g ($\approx 60^\circ\text{C}$) compared to ABS ($\approx 100^\circ\text{C}$), this difference provides a stiffness contrast for temperatures between T_g of PLA and ABS [4, 5]. PLA will act as a thermally responsive phase while ABS maintains stiffness. Such a combination could enable thermally tunable wave dynamics while preserving mechanical stability, an important consideration for real-world applications.

This research aims to investigate the wave dynamics of multi-material additively manufactured ABS/PLA metamaterial structures at elevated temperatures. By exploiting the temperature-dependent viscoelastic behaviour of PLA while maintaining contrast in stiffness through ABS, the study seeks to understand how multi-material polymer lattices can achieve thermally tunable bandgaps and adaptive vibration attenuation. The work combines AM, numerical modelling of dispersion and transmission behaviour, and experimental validation to bridge the gap between simulation-driven metamaterial design and practical realization.

2 Literature Review & Context

2.1 Wave Propagation and Bandgaps

Mechanical waves are disturbances that travel through a material due to the interaction between inertia and elastic restoring forces. In elastic solids, when a material point is displaced from its equilibrium position, internal stresses develop that attempt to restore it. These stresses are transferred to neighboring particles, causing the disturbance to propagate through the medium as a wave [6]. In homogeneous elastic solids, wave propagation is governed by the balance between inertia and elastic restoring forces, leading to the classical elastic wave equation [6]. The corresponding wave velocity is given by

$$c = \sqrt{\frac{E}{\rho}}, \quad (1)$$

indicating that wave speed is determined by the stiffness-to-mass ratio of the material. In such uniform structure, the wave velocity is constant and independent of frequency, resulting in non-dispersive propagation [7].

In contrast, structured or heterogeneous materials exhibit dispersive behaviour, meaning that the propagation velocity depends on frequency. Dispersion arises from spatial variations in mass and stiffness, which cause different frequency components to propagate at different phase velocities [1]. This frequency-dependent behaviour is fundamental to periodic structures and phononic crystals. A particularly important phenomenon in dispersive media is the formation of bandgaps. A bandgap is a frequency range in which propagating wave solutions do not exist. The ability to engineer and tune bandgaps enables selective vibration attenuation and wave control, forming the foundation of phononic crystals and elastic metamaterials.

While homogeneous media support uniform wave propagation, periodic structures introduce spatial variations in stiffness and mass. This spatial repetition fundamentally alters wave behaviour. When a structural pattern is repeated with a constant lattice spacing a , waves interact with this periodicity, leading to dispersion and the possible formation of bandgaps.

The mathematical framework used to describe wave propagation in periodic media is Bloch–Floquet theory. Because the geometry and material properties repeat in space, the wave field in the structure also follows a repeating pattern. Instead of modelling an infinitely long periodic structure, Bloch’s theorem states that the displacement field can be expressed as the product of a periodic function and a complex exponential term:

$$u(\mathbf{x}) = \tilde{u}(x)e^{ik \cdot x}, \quad (2)$$

where $\tilde{u}(x)$ is a function with the same periodicity as the unit cell and k is the wave vector [1]. The exponential term represents the phase shift that occurs between neighboring unit cells. Physically, this means that the deformation pattern inside each unit cell is identical, but shifted in phase as the wave propagates through the structure.

Bloch–Floquet theory therefore allows the analysis of an infinite periodic structure by studying only a single unit cell with phase-shifted boundary conditions. By varying the wave vector k , different propagation states of the wave can be obtained. The possible values of the wave vector are limited to the first Brillouin zone, which represents the smallest unique region in the reciprocal space of the periodic lattice. Due to symmetry, it is sufficient to evaluate the wave vector only along specific paths inside this zone. Figure 1 shows a schematic representation of the Brillouin zone for a two-dimensional periodic square lattice. The high-symmetry points Γ , X , and M correspond to specific phase relationships between neighboring unit cells. At Γ the wave vector is zero and all unit cells oscillate in phase. At X and M the phase shift between adjacent cells becomes larger, representing different propagation conditions in the periodic structure [8].

By sweeping the wave vector along the path Γ – X – M – Γ and solving the corresponding eigenvalue problem, the dispersion relation is obtained. The resulting dispersion curves describe the relationship between frequency and wave vector and reveal the presence of bandgaps, which appear as frequency regions without propagating wave solutions.

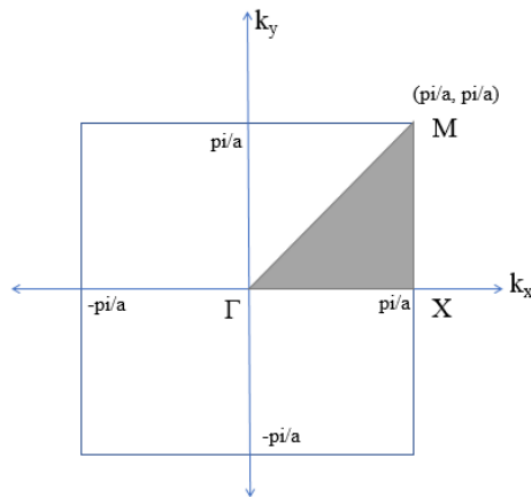


Figure 1: First Brillouin zone of a two-dimensional periodic lattice. The dispersion relation is typically evaluated along the high-symmetry path Γ – X – M – Γ [8].

2.2 Elastic Metamaterials

Metamaterials are artificially engineered structures whose effective properties are primarily determined by their geometry rather than their chemical composition. By arranging structural elements in a periodic pattern at length scales comparable to or smaller than the wavelength of interest, metamaterials can manipulate wave propagation in ways that are not typically observed in conventional materials [1].

Elastic metamaterials are designed to control the propagation of elastic waves such as vibrations in solids. Their behaviour arises from the interaction between the periodic structural architecture and the dynamic response of their internal elements. As a result, these materials can exhibit unusual wave phenomena, including negative effective mass or stiffness, wave localization, and the formation of bandgaps. By tailoring the geometry and material properties of the repeating unit cell, the position and width of bandgaps can be tuned to target specific frequency ranges. This ability enables elastic metamaterials to selectively filter, guide, or attenuate vibrations and waves [9].

The concept of wave manipulation through periodic structures gained significant attention with the introduction of phononic crystals and locally resonant materials. Liu et al. [10] demonstrated that internal resonators embedded within a periodic structure can generate bandgaps at frequencies much lower than those predicted by classical periodic scattering mechanisms. Subsequent studies have further investigated how the dynamic properties of internal resonators influence wave propagation. For example, Huang and Sun [11] analyzed the dispersion behaviour of lattice systems with multiple resonators modeled as masses connected by springs, showing that variations in resonator mass and coupling stiffness can shift the location of bandgaps. Bandgaps can arise from two primary mechanisms: Bragg scattering, which results from destructive interference when the wavelength becomes comparable to the lattice spacing, and local resonance, where internal resonant elements generate frequency regions of dynamic isolation [10, 11].

2.2.1 Bragg Scattering

One of the primary mechanisms responsible for bandgap formation in phononic crystals and periodic lattices is Bragg scattering. In periodic structures, waves are repeatedly reflected at the interfaces between neighboring unit cells. When the wavelength becomes comparable to the periodic spacing of the structure, these reflected waves interfere destructively, preventing the propagation of waves within a specific frequency range [1, 12]. For a one-dimensional periodic structure with unit cell size a , Bragg scattering occurs when the wavelength λ approximately satisfies the condition

$$\lambda \approx 2a. \quad (3)$$

At this condition, reflections from neighboring unit cells interfere destructively, resulting in a bandgap in the dispersion relation. The corresponding Bragg bandgap frequency can be approximated by

$$f_{\text{Bragg}} \approx \frac{c}{2a}, \quad (4)$$

where c denotes the wave velocity in the material [13].

An important implication of this relation is that the bandgap frequency is primarily determined by the size of the unit cell and the wave speed of the material. Consequently, Bragg bandgaps typically occur when the wavelength is on the same order as the unit cell size. Achieving low-frequency bandgaps using this mechanism therefore requires relatively large structural dimensions, which can limit the practical implementation of purely Bragg-based phononic crystals in vibration mitigation applications [1].

2.2.2 Local Resonance

Another mechanism for bandgap formation is local resonance, where internal resonating elements embedded within the unit cell interact dynamically with the propagating wave. In contrast to Bragg scattering, local resonance does not rely on interference caused by periodic spacing. Instead, bandgaps arise from the dynamic coupling between the host structure and internal resonators [14].

A simple representation of a locally resonant unit cell is a mass-spring system, where the resonator mass m is connected to the surrounding structure through an effective stiffness k . The resonance frequency of such a system is given by

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m}}. \quad (5)$$

Near this resonance frequency, the resonator oscillates strongly and interacts with the propagating wave in the host structure. This interaction can produce a frequency range in which wave propagation is strongly attenuated, resulting in a locally resonant bandgap. A key advantage of locally resonant systems is that the bandgap frequency depends mainly on the resonator mass and stiffness rather than the lattice spacing. Consequently, locally resonant bandgaps can occur at wavelengths much larger than the unit cell size, enabling subwavelength bandgaps. This property makes locally resonant metamaterials particularly attractive for low-frequency vibration attenuation and wave control [14, 1].

2.3 Viscoelasticity of Polymers

In AM, polymers are widely used due to their processability, low cost, and design flexibility. These materials typically exhibit viscoelastic behaviour, meaning their mechanical response combines both elastic energy storage and viscous energy dissipation. As a result, their stiffness depends on temperature, loading frequency, and time scale. Viscoelastic properties are commonly characterized using Dynamic Mechanical Analysis (DMA), in which a small oscillatory load is applied while temperature and frequency are precisely controlled. DMA enables accurate determination of the T_g , the dynamic modulus, and the damping factor ($\tan\delta$), which are important indicators for predicting stiffness, energy dissipation, impact behaviour, and practical service temperatures of polymer materials [15].

Under oscillatory loading, stress and strain are not perfectly in phase because of internal molecular friction. Consequently, the elastic modulus of viscoelastic polymers becomes complex and can be expressed as

$$E = E' + iE'', \quad (6)$$

where E' is the storage modulus, representing the elastic energy stored in the material, and E'' is the loss modulus, representing viscous energy dissipation [3]. The ratio of these quantities defines the damping factor:

$$\tan \delta = \frac{E''}{E'}. \quad (7)$$

A key feature of polymer viscoelasticity is the strong temperature dependence of its dynamic mechanical properties, particularly near the glass transition temperature. As temperature approaches T_g , increased molecular mobility leads to a significant decrease in storage modulus and an increase in viscous dissipation. For amorphous polymers such as PLA, the storage modulus typically decreases by three orders of magnitude across the glass transition region [4]. This transition is accompanied by a pronounced peak in the damping factor ($\tan \delta$), which reflects increased energy dissipation due to enhanced molecular motion. Figure 2 schematically illustrates the typical evolution of the storage modulus (E'), loss modulus (E''), and damping factor ($\tan \delta$) as a function of temperature during a DMA experiment. Because elastic wave speed c depends on the ratio of the polymer stiffness to density, formula 1, a reduction in storage modulus results in a lower wave propagation velocity. This decrease in wave speed directly affects dispersion characteristics in polymer materials.

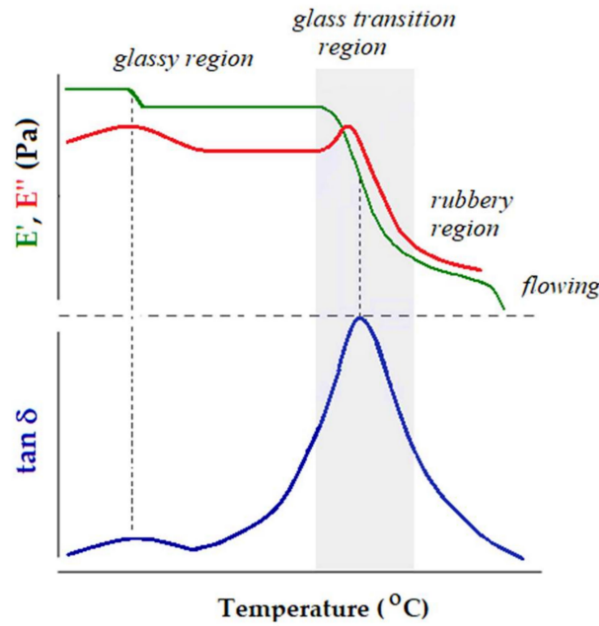


Figure 2: Schematics of storage modulus (E'), loss modulus (E''), and damping factor ($\tan \delta$) as a function of temperature during DMA [4].

In elastic metamaterials, this viscoelastic softening influences both primary bandgap formation mechanisms. For Bragg scattering, the bandgap frequency scales approximately with wave speed and lattice spacing, meaning that a reduction in modulus shifts Bragg bandgaps toward lower frequencies. Similarly, for local resonance bandgaps, the resonance frequency depends on the stiffness–mass ratio, where the effective stiffness k is directly related to the material’s Young’s modulus. Consequently, temperature-induced viscoelastic changes in polymers can significantly alter bandgap frequencies, width, and attenuation characteristics.

2.4 Temperature Dependent Metamaterials

While conventional metamaterials exhibit fixed responses determined by their geometry and materials, temperature-dependent metamaterials introduce dynamic tunability by exploiting temperature-responsive mechanisms to actively control their electromagnetic, optical, or acoustic properties. The ability to adjust to constantly changing external conditions of structural components cause variable vibration characteristics that need to be mitigated. Tunable metamaterials or phononic crystals have been explored in literature using mechanisms as deformations, applied loads, temperature-sensitive materials, topological transformation of structure, applied voltage to control the thickness and tension in elastomers, magneto-granular materials and magnetoelastic materials [16]. While prior research has shown the ability to open, close and generally tune bandgaps with a variety of mechanisms, this research focuses on a method to tune bandgaps given the ability to tune the modulus of the structure constituents by changing temperature. Polymers are especially attractive because they exhibit large modulus variations over relatively small temperature ranges compared with metals or ceramics. An example of thermal tuning

based on the temperature-dependent elastic modulus is demonstrated by Zhao et al. [17], who investigated temperature-dependent phononic crystal plates and show that modifying material properties with temperature changes the wave dispersion and thus bandgap locations. Similarly, Wang et al. [18] propose a one-dimensional mechanical lattice system with local resonators as an elastic metamaterial, which shows that the wave dispersion in the metamaterial is affected by temperature and thus shows great ability to manipulate wave propagation.

2.5 Experimental Methods for Wave Propagation Studies

Experimental investigation of wave propagation in elastic metamaterials requires controlled excitation of mechanical waves, accurate measurement of the structural response, and, for temperature-dependent studies, reliable thermal control of the structure. Various experimental approaches have been developed to study dispersion characteristics, bandgaps, and transmission behaviour in periodic structures.

Mechanical waves can be excited using several actuation mechanisms. Electrodynamic shakers are widely used in structural dynamics experiments because they provide controlled harmonic excitation over a broad frequency range and allow precise control of excitation amplitude and frequency [19]. Shakers are therefore commonly applied in vibration testing and modal analysis of mechanical structures. Another frequently used method is impact excitation using an instrumented hammer, which introduces broadband energy into the structure and allows identification of resonant frequencies through frequency response analysis [19]. Although impact testing is simple and effective for modal identification, it offers less control over the input signal compared to continuous harmonic excitation.

Piezoelectric actuators provide an alternative approach for generating mechanical waves in structures. These actuators convert electrical signals directly into mechanical strain through the piezoelectric effect and can therefore excite vibrations without requiring mechanical coupling to external equipment [20]. Because of their small size, low mass, and high actuation bandwidth, piezoelectric patches are widely used in structural health monitoring, vibration control, and wave propagation experiments.

Among the available piezoelectric actuators, Macro Fiber Composite (MFC) actuators have gained significant attention for vibration and wave control applications. MFC actuators consist of rectangular piezoceramic fibers embedded in a flexible polymer matrix and connected through interdigitated electrodes, enabling efficient in-plane actuation while maintaining mechanical flexibility [21]. This configuration allows the actuator to generate relatively large strains compared to conventional piezoelectric patches. Due to their lightweight construction and ability to conform to curved surfaces, MFC patches can be bonded directly to structural components,

making them particularly suitable for experimental studies involving lightweight or additively manufactured structures. Commercial MFC actuators are produced by Smart Material and are widely used for structural actuation, sensing, and vibration suppression.

The structural response in wave propagation experiments is typically measured using accelerometers, strain gauges, or laser Doppler vibrometers (LDV). Non-contact optical measurement techniques such as LDV are particularly advantageous because they provide high spatial and temporal resolution without adding mass to the structure, which could otherwise alter its dynamic response [22]. Consequently, LDV systems are commonly employed in experimental studies of phononic crystals and elastic metamaterials.

For temperature-dependent metamaterial studies, the experimental setup must also allow controlled heating of the specimen. Several approaches have been reported in the literature, including environmental chambers, resistive heating elements, and heated support plates [23, 24]. Environmental chambers enable uniform temperature control but may limit optical access for laser-based measurements. Alternatively, localized heating using heated plates or embedded resistive elements allows direct temperature control of the specimen while maintaining accessibility for excitation and measurement devices.

2.6 Additive Manufacturing

AM, is a rapid prototyping technology used to build objects in layers. There are many commercially available 3D printing technologies like fused deposition modeling (FDM), stereo lithography, inkjet 3D printing, selective laser sintering, digital light manufacturing, selective laser melting, electronic beam melting, and laminated object manufacturing [25]. FDM is widely used because it can produce complex geometries in a cost-effective and accessible manufacturing environment [26]. A CAD file is processed by software which mathematically slices and orients the model for the build process and in FDM a thermoplastic polymer is continuously supplied as filament. Through a heated nozzle the melted polymer is extruded, followed by subsequent cooling and solidification [27]. FDM allows for the creation of complex 3D models, prototypes, and products quickly and at low cost [26].

2.7 Multi-Material Additive Manufacturing

Most AM techniques are designed to fabricate structures using a single material. However, the increasing demand for higher functionality and structural complexity has driven the development of multi-material additive manufacturing (MMAM). By integrating different materials within a single build process, MMAM enables the fabrication of structures with spatially varying properties and functionalities, such as tailored mechanical stiffness, electrical conductivity, optical behaviour, or chemical resistance [27]. This capability significantly expands the design space

compared to conventional single-material AM.

In polymer-based AM, MMAM is commonly realized through systems equipped with multiple extrusion heads, allowing different filaments to be deposited sequentially or simultaneously within a single build. Each nozzle can be individually controlled in terms of temperature, printing speed, and deposition path, enabling the integration of materials with different physical or mechanical properties in a single structure. Espalin et al. [28] demonstrated such an approach by integrating two legacy FDM machines into a single manufacturing platform. Their system enabled the fabrication of components with discrete multi-material regions as well as process variations, highlighting the potential of MMAM for producing multifunctional structures.

Several commercial AM technologies currently support multi-material fabrication. Dual- or multi-extrusion FDM is among the most widely used approaches, where multiple thermoplastic filaments are deposited layer-by-layer using separate nozzles. This method enables combinations such as rigid and flexible polymers or the use of soluble support materials, and is implemented in many commercial desktop printers such as the Ultimaker and Prusa platforms [29]. In addition to extrusion-based systems, material jetting technologies such as Stratasys PolyJet can deposit multiple photopolymers as droplets that are subsequently cured using ultraviolet light, enabling parts with graded material properties and high printing resolution [30]. For metallic systems, multi-material fabrication has also been explored in processes such as binder jetting and directed energy deposition, where different powders can be selectively deposited and fused during the manufacturing process [30].

In addition to combining separate materials during the printing process, multi-material structures can also be achieved through the use of composite materials. In composite AM, a polymer matrix is reinforced with secondary phases such as short fibers, continuous fibers, or particles to enhance mechanical, thermal, or electrical properties. For example, thermoplastic matrices reinforced with carbon or glass fibers are commonly used to increase stiffness and strength while maintaining printability [31]. Another approach involves the use of pre-mixed multi-material filaments, where reinforcing particles or functional additives are already embedded in the filament prior to printing. These composite filaments enable the fabrication of materials with tailored properties without requiring multiple extrusion heads, although the material distribution is fixed within the filament itself [32]. Such material systems provide an alternative route for achieving multifunctional behaviour in additively manufactured structures.

2.8 PLA and ABS for Thermal Tunability

PLA and ABS are among the most widely used thermoplastic polymers in FDM. PLA is a biodegradable polyester derived from renewable resources, typically characterized by good stiffness, ease of printing, and limited warping. ABS, in contrast, is an engineering thermoplastic known for its higher thermal resistance, toughness, and ductility, but requires elevated processing temperatures and controlled environmental conditions during printing to prevent warping and poor interlayer adhesion [33].

A key difference between these materials lies in their glass transition temperature and the corresponding temperature-dependent mechanical behaviour. PLA generally exhibits a glass transition around 60 °C, above which its storage modulus decreases significantly and the material transitions toward a rubbery state. ABS has a substantially higher glass transition temperature, typically around 100 °C, allowing it to maintain structural stiffness over a broader temperature range [3]. This difference in viscoelastic response makes PLA particularly sensitive to temperature variations, while ABS preserves its stiffness under conditions where PLA has already softened.

These contrasting thermal-mechanical properties make PLA/ABS combinations attractive for MMAM metamaterials. In such architectures, PLA can act as a thermally responsive phase whose modulus decreases near its glass transition temperature, whereas ABS can provide a contrast in stiffness. The resulting temperature-dependent stiffness contrast offers a mechanism for tuning wave propagation characteristics without requiring external actuation.

From a manufacturing perspective, multimaterial FDM printing using PLA and ABS presents challenges, including differences in extrusion temperature, thermal contraction behaviour, and interfacial bonding strength. Poor adhesion between the two polymers may lead to interfacial defects or delamination, particularly under thermal cycling. Nevertheless, advances in dual-extrusion printing and interface design strategies, such as mechanical interlocking geometries or optimized processing parameters, increasingly enable reliable multimaterial polymer structures [28].

2.9 Research Gap

Although thermally tunable elastic metamaterials have been investigated through analytical modeling and numerical simulations, the translation of these concepts into experimentally validated structures remains limited. Many studies demonstrate temperature-induced bandgap shifts by incorporating temperature-dependent elastic properties into dispersion calculations or simplified material models, but experimental validation under controlled thermal conditions is comparatively scarce. A further limitation in the current state of the art is the relatively limited exploration of MMAM using widely available thermoplastics. Most thermally tunable metamaterial studies rely either on specialized responsive materials, such as shape-memory polymers or phase-change media, or on single-material architectures whose stiffness varies uniformly with temperature. In contrast, MMAM offers the possibility of combining materials with different glass transition temperatures to engineer spatially heterogeneous, temperature-dependent stiffness contrasts.

In particular, the combination of PLA and ABS presents a promising, yet insufficiently studied pathway toward thermally adaptive metamaterials. A multimaterial architecture that employs PLA as the thermally responsive phase and ABS as a structural backbone could enable temperature-dependent bandgap tuning while preserving structural integrity and geometric stability. However, systematic investigations that integrate MMAM, temperature-dependent material characterization, wave propagation modeling, and experimental validation are currently lacking.

Addressing this gap would contribute not only to the fundamental understanding of thermally tunable metamaterials but also to their practical implementation, enabling low-cost, additively manufactured structures capable of adaptive vibration filtering and wave control across varying thermal environments.

2.10 Research Objective

The objective of this research is to design, model, and experimentally validate a multimaterial ABS/PLA metamaterial structure with thermally tunable wave dynamics. The study aims to exploit the temperature-dependent viscoelastic behaviour of PLA, whose stiffness decreases significantly near its glass transition temperature, while ABS retains a relatively high stiffness. This stiffness contrast enables controllable bandgap behaviour in multi-material additively manufactured elastic metamaterials.

2.11 Research Questions

How can PLA and ABS be combined within a multi-material additive manufactured metamaterial structure to achieve thermally tunable wave dynamics while ensuring manufacturability and experimental feasibility?

2.11.1 Subquestions

- Which additive manufacturing parameters enable reliable multi-material 3D printing of ABS/PLA structures with sufficient interfacial bonding and mechanical integrity?
- How can the dispersion relations and transmission characteristics of the metamaterial be modeled at room temperature and increased temperatures, and how does the temperature-induced reduction in the PLA modulus influence the position and width of the bandgaps?
- Which unit-cell configurations allow the realization of thermally tunable bandgaps while remaining compatible with multimaterial additive manufacturing constraints?
- How should the experimental setup be designed to measure wave transmission and validate the numerically predicted bandgap behaviour under varying thermal conditions?

3 Multi-Material Additive Manufacturing for ABS and PLA

3.1 Optimisation of 3D Printing Parameters

In FDM, the mechanical performance of the printed components is governed not only by the intrinsic material properties, but also by process parameters that influence interlayer bonding, porosity, and thermal history. Key printing parameters include nozzle temperature, bed temperature, and cooling rate. As demonstrated by Yin et al. [34], interfacial bonding strength in MMAM is primarily related to inter-molecular diffusion across the filament interface. Their study shows that sufficient bonding requires both adequate wetting and sustained interface temperatures above the glass transition temperature to enable polymer chain interpenetration. The diffusion process at the filament interface can be understood as polymer chain interpenetration across the boundary between adjacent deposited roads. After extrusion, the molten filament comes into contact with a previously deposited layer that is at a lower temperature. If the interface temperature remains above T_g , polymer chains retain sufficient mobility to diffuse across the interface, forming molecular entanglements. This process is analogous to polymer welding and is essential for achieving strong interlayer bonding.

As illustrated in figure 3, the bonding mechanism generally involves three stages: initial contact between filaments, wetting of the interface, and subsequent inter-diffusion of polymer chains. The degree of diffusion depends strongly on the thermal history of the interface, which is governed by the printing parameters. Too low temperatures or rapid cooling reduces chain mobility and limits diffusion, resulting in weak interfaces, increased porosity, and reduced mechanical performance. When printing ABS and PLA together in one structure, diffusion becomes even more critical. ABS and PLA are printed within a single structure and the difference in T_g , viscosity, and thermal expansion behaviour can hinder interfacial diffusion. For example, PLA typically solidifies more rapidly than ABS, while ABS requires higher temperatures to maintain chain mobility. Careful control of printing parameters is therefore necessary to promote adequate diffusion and ensure reliable mechanical performance in MMAM. In MMAM, a compromise must be found to ensure sufficient bonding of both materials while maintaining dimensional accuracy and structural integrity. Therefore, a systematic optimisation of the printing parameters was required prior to fabricating multimaterial metamaterial samples.

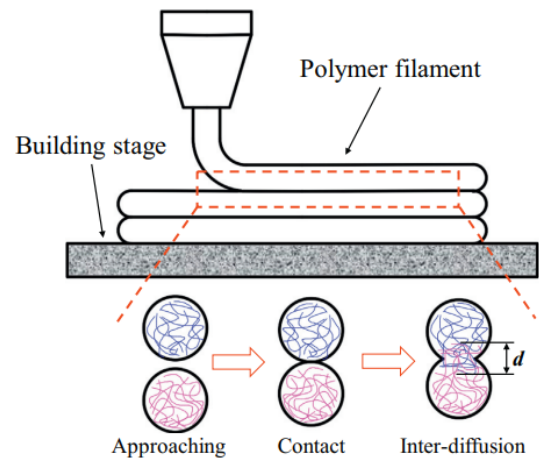


Figure 3: Schematic illustration of inter-molecular diffusion between polymer filaments during FDM printing. [34].

3.1.1 Printing Setup

All samples were manufactured using an Ultimaker 3 dual-extrusion FDM printer. The dual-nozzle system allows controlled deposition of PLA and ABS within a single build, enabling both layered configurations and adjacent multimaterial structures. The specifications of the Ultimaker 3 3D printer are listed in table 1 below.

	Specification
Maximum build volume	(w) 19.7 cm × (d) 21.5 cm × (h) 20.0 cm
Print layer height	0.06-0.20 mm
Nozzle diameter	0.40 mm
Build plate temperature	20–110 °C
Nozzle printing temperature	up to 280 °C
Cooling method	Dual cooling fans
Extrusion system	Dual extrusion (two print cores)

Table 1: Specifications of the Ultimaker 3 3D printer.

The specifications and recommended printing parameters for PLA and ABS according to Ultimaker are summarized in table 2.

	PLA	ABS
Colour	White	Black
Wire diameter	2.85 mm	2.85 mm
Density	1240 kg/m ³	1100 kg/m ³
Nozzle temperature	200–210 °C	225–260 °C
Bed temperature	60 °C	80–90 °C
Cooling fan speed	80%	5%

Table 2: Recommended printing parameters according to Ultimaker [35, 36].

3.1.2 Nozzle temperature

The nozzle temperature determines the thermal state and viscosity of the extruded filament. The filament is guided into a heated print core, where it is melted and forced through a nozzle with a defined diameter. The selected nozzle temperature must be sufficiently high to ensure proper melting and flow of the polymer. If the temperature is too low, incomplete melting and high viscosity may result in poor bonding and increased porosity. Conversely, excessively high temperatures can cause material degradation, stringing, or dimensional inaccuracies [37].

The Ultimaker 3 is equipped with a dual extrusion system consisting of two independent print cores. Each nozzle has its own heating element and temperature sensor, allowing the extrusion temperature to be set separately for both materials. During printing, the machine alternates between the two nozzles depending on the material being deposited. Switching between nozzles involves mechanical repositioning and thermal stabilization, which introduces a delay in the printing process. The nozzle temperature for PLA is kept constant at 200 C° and the nozzle temperature of ABS is tested for 235 C° and 240 C°.

3.1.3 Bed temperature

The build plate temperature plays an important role in controlling the cooling rate of deposited filaments and the adhesion of the printed part to the build surface. A heated bed reduces thermal gradients between the extruded filament and the surrounding environment, thereby limiting residual stresses, warping, and interlayer delamination. Maintaining an elevated bed temperature also helps to keep previously deposited layers above their glass transition temperature for a longer period, which promotes polymer diffusion and improves interlayer bonding. In multimaterial printing with the Ultimaker 3, both PLA and ABS are deposited onto the same build plate, meaning that a single bed temperature must be selected for both materials. Since ABS generally requires higher bed temperatures than PLA, a compromise temperature is necessary. The chosen bed temperature should be sufficiently high to ensure adequate adhesion and dimensional stability for ABS, while remaining low enough to avoid excessive softening or deformation of PLA. Therefore, PLA is tested for a bed temperature of 50, 60, 70, and 80 C° and ABS is tested for 80, 90, and 100 C°.

3.1.4 Cooling fan speed

To improve the adhesion between the ABS and PLA, the cooling fan speed is altered. The cooling fan is a small fan close to the nozzle which allows the layers to cool faster and improve the physical accuracy of the design. The hypothesis behind changing the fan speed is that when lowering the cooling fan speed, the interlayer adhesion will improve and as a result increase strength. Ferreira Neto, Luiz Felipe, et al. [38] underpin this in their research about the effect of cooling on the strength and visual aspect of PLA additive manufactured parts. They find that the average rupture strength increases significantly when decreasing the level of cooling. The cooling fan speed of ABS is kept constant at 5%, since ABS does not need cooling to improve physical accuracy. The cooling fan speed of PLA is tested for 20% and 80%.

3.1.5 Interlocking

Printing PLA and ABS adjacent to each other, rather than in a layered configuration, presents a significant challenge due to the limited chemical adhesion between the two materials. When deposited side-by-side, small gaps can form at the interface, resulting in insufficient bonding and reduced mechanical integrity of the printed structure. To address this issue, Kuipers et al. [39] developed an interlocking interface design implemented within the Ultimaker CURA slicing software. This approach introduces a repeating geometric pattern, consisting of small triangular features, at the boundary between the two materials. These features create a mechanical interlock that enhances load transfer across the interface, independent of chemical adhesion, see figure 4. The interlocking mechanism allows PLA and ABS to be printed adjacently while maintaining structural integrity. By relying on geometric constraints rather than solely on polymer diffusion, this strategy enables reliable fabrication of multi-material components in which the materials are positioned side-by-side instead of in layered configurations.

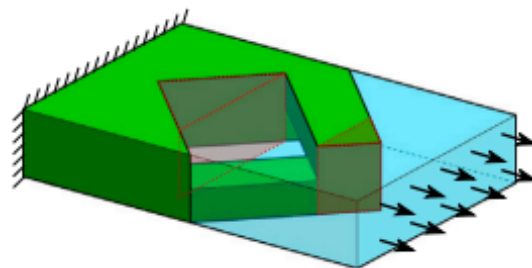


Figure 4: Triangular interlocking mechanism to enhance load transfer at the interface [39].

The nozzle temperature, build plate temperature, and cooling fan speed were varied to determine suitable printing parameters for fabricating multimaterial ABS/PLA structures. Table 3 summarizes the investigated parameter values. The parameters were varied individually in an iterative manner in order to evaluate their influence on print quality. Comments about the iterative process of varying the printing parameters are summarized in table 4 in the Appendix.

Parameters	1	2	3	4
Nozzle temperature ABS (°C)	235	240		
Build plate temperature ABS (°C)	80	90	100	
Build plate temperature PLA (°C)	50	60	70	80
Cooling fan speed PLA (%)	20	80		

Table 3: The variation of nozzle temperature, build plate temperature of ABS and PLA, and cooling fan

Based on this parameter exploration, several printing configurations were produced to assess the mechanical performance of different material arrangements. In total, seven types of samples were manufactured: pure PLA, pure ABS, ABS/PLA printed adjacently with an interlocking interface, and layered configurations consisting of two layers (ABS/PLA) and four layers (ABS/PLA/ABS/PLA).

To quantify the mechanical properties of these configurations, tensile tests were performed to determine the Young's modulus of each sample type. The tensile specimens were manufactured according to the ISO 527-2 international standard [40]. Figure 5 shows the geometry of the dog-bone specimen used in the tests, while figure 7 illustrates the different sample configurations. The white material represents PLA and the black material represents ABS.

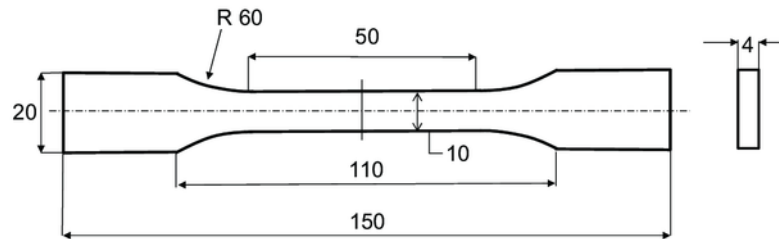


Figure 5: ISO 527-2 type 1B geometry for the tensile test specimen. All dimensions are in mm [40].



Figure 6: PLA, ABS, interlocking and layered dog bone structures, white representing PLA and black representing ABS material.

3.2 Tensile testing

The mechanical performance of the printed specimens was evaluated by uniaxial tensile testing using an INSTRON 3400 universal testing machine. All tests were conducted at a constant displacement rate of 1 mm/min. Each specimen is tested three times within the linear regime, to ensure repeatability and obtain representative mechanical properties.

During tensile testing, the applied force and corresponding elongation of the specimen are recorded to obtain stress–strain curves. The Young’s modulus is determined from the initial linear portion of the stress–strain curve, where the material behaviour is predominantly elastic. The Young’s modulus describes the stiffness of the material and indicates its resistance to elastic deformation under load. Determining the Young’s modulus is particularly relevant for additively manufactured polymers because the stiffness of FDM parts is strongly influenced by printing parameters. Insufficient bonding or increased porosity typically reduce stiffness, whereas improved interlayer diffusion results in higher effective modulus values. The Young’s modulus of pure PLA and ABS is necessary to know for later simulations.

In multi-material structures the measured Young’s modulus reflects both the intrinsic properties of the individual polymers and the quality of the interface between them. Therefore, tensile testing provides a quantitative method to evaluate the effectiveness of the selected printing parameters and to assess the mechanical integrity of the printed multi-material components. The obtained Young’s modulus values are summarized in figure 7.

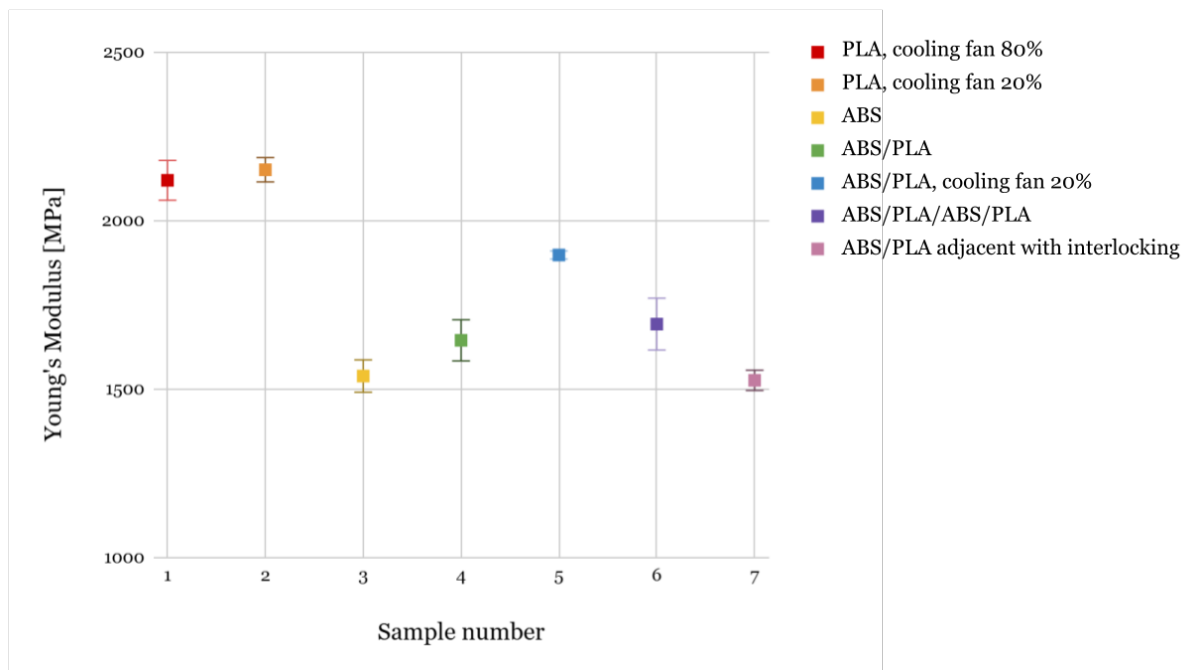


Figure 7: Tensile test results with standard deviation of three tests.

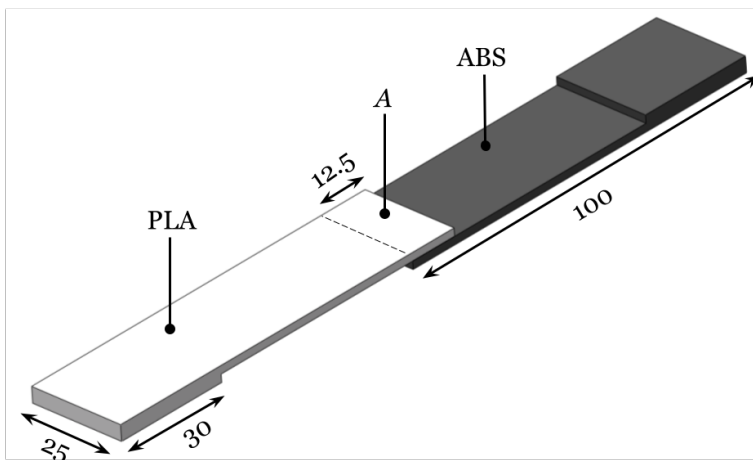
The tensile test results show that PLA has a Young's modulus of 2150 MPa and ABS of 1550 MPa. The layered ABS/PLA of two layers has a slightly higher Young's Modulus than ABS, when decreasing to cooling from the standard 80% to 20%, the Young's modulus of the layered structure increases significantly. The structure where ABS and PLA are adjacent has almost the same Young's modulus as ABS, since not the interlocking mechanism failed but the ABS broke at the interface, see figure 25 in the Appendix.

3.3 Lap Shear Test

To investigate the influence of cooling on the adhesion between ABS and PLA, a lap shear test is conducted. Lap shear strength (LSS) is a measure of the ability to resist in-plane shear forces in a bonded joint, calculated as the maximum force divided by the bonded area:

$$LSS = \frac{F_{max}}{A} \quad (8)$$

To ensure pure shear loading, a gripping area is added on both ends so the sample can be placed perfectly vertical. Both sheets have a length of 100 mm and width of 25 mm, the bonded area (A) is the area where PLA is printed on ABS. The LSS strength is tested for two cooling rates, 20% and 80%. The tests are performed on the INSTRON 3400 universal testing machine with a constant displacement rate of 1 mm/min. Figure 8 shows the lap shear test sample dimensions and setup.



(a) Dimensions of lap shear test sample, all in mm.



(b) Lap shear test setup

Figure 8

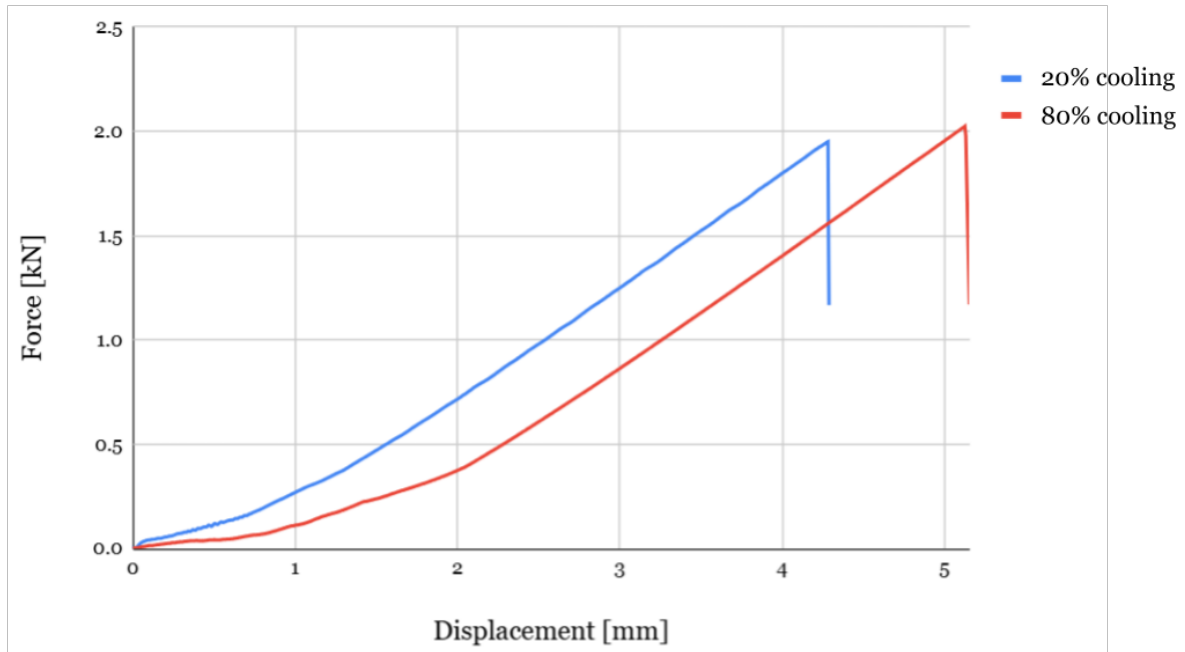


Figure 9: Lap shear test results showing the applied force as a function of displacement for two cooling fan speeds (20% and 80%).

The maximum force measured for 80% cooling is 2.025 kN and for 20% cooling 1.951 kN.

The LSS can then be calculated for both samples:

$$LSS_{80\%} = \frac{2.025 \cdot 1000}{0.025 \cdot 0.0125} = 6.48 \text{ MPa} \quad (9)$$

$$LSS_{20\%} = \frac{1.951 \cdot 1000}{0.025 \cdot 0.0125} = 6.24 \text{ MPa} \quad (10)$$

The results indicate that cooling has no significant influence on the adhesion between PLA and ABS, the higher cooling rate of 80% even resulted in a higher LSS.

3.4 Main findings

The main findings regarding the printing parameters are summarized as follows:

- A nozzle temperature of at least 240 °C is required for printing ABS. At lower temperatures the material viscosity remains too high, causing insufficient flow through the nozzle and resulting in nozzle clogging and print failure.
- A build plate temperature of 90 °C or higher is necessary to ensure proper adhesion of ABS to the print bed. At lower bed temperatures, insufficient bed adhesion was observed, leading to detachment of the printed part during fabrication.
- For PLA, reducing the build plate temperature to 50 °C reduces warping and improves dimensional stability of the printed samples.
- Printing multiple multimaterial samples simultaneously is not recommended. When several parts are printed at the same time, the deposited ABS layer cools excessively before the PLA layer is printed on top, resulting in poor interfacial bonding between the two materials.
- Within the investigated parameter range, variations in cooling fan speed did not show a significant influence on the adhesion strength between ABS and PLA.
- Printing ABS and PLA directly adjacent to each other without additional interface design leads to poor bonding. A mechanical interlocking geometry is therefore required to ensure sufficient attachment between the two materials.

4 Numerical Modeling

The studied metamaterial is a quasi-1D periodic structure consisting of circular disks connected by ligaments, figure 10. The disks act as concentrated mass, while the narrow ligaments introduce connections of a lower stiffness. This high mass-to-stiffness ratio promotes local resonance effects, which can lead to bandgap formation. Periodicity is assumed along one axis, so the structure is treated as one-dimensionally periodic.

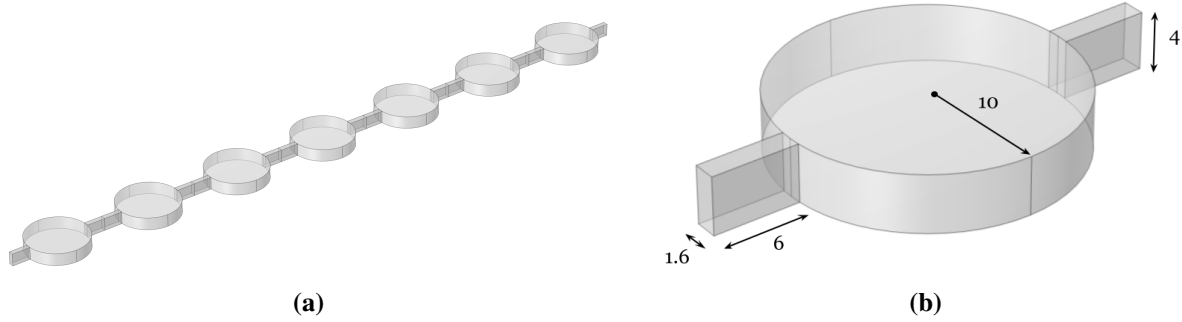


Figure 10: Quasi-1D periodic phononic structure formed by seven unit cells placed along one axis (a) and dimensions of the unit cell in mm (b).

DMA measurements reported by Cristea et al. [4] show that the Young's modulus of PLA decreases by three orders of magnitude across the glass transition region. To represent this temperature-dependent behaviour in the numerical model, the Young's modulus of PLA is reduced to approximate the transition from room temperature conditions to the rubbery state above the glass transition temperature T_g . The Young's modulus at room temperature is obtained from tensile testing, while the rubbery state is modeled by reducing the modulus by three orders of magnitude. The dispersion and transmission behaviour of the metamaterial structure are then evaluated for both material states, allowing investigation of how the temperature-induced reduction in stiffness influences the position and width of the bandgaps.

4.1 Dispersion Analysis

Dispersion relations are computed in COMSOL Multiphysics using an eigenfrequency study combined with Bloch–Floquet periodic boundary conditions. To model wave propagation in an infinite periodic medium, Floquet periodicity is imposed on the unit cell boundaries. Since the structure is periodic only in one spatial direction, the dispersion relation is evaluated along the irreducible Brillouin zone path from Γ to X . This corresponds to the wavenumber range

$$k \in [0, \pi/a], \quad (11)$$

where a denotes the size of the unit cell in the periodic (x -)direction.

Eigenfrequencies are computed for discrete values of k along this path to obtain the dispersion curves. Frequency intervals in which no eigenfrequencies appear for any k are identified as bandgaps. Only out-of-plane (z-direction) wave modes are taken into account, since those can be measured by our experimental setup. Whether waves are in or out of plane is determined by the polarization factor

$$p = \frac{\int_V |w|^2 dV}{\int_V (|u|^2 + |v|^2 + |w|^2) dV}, \quad (12)$$

where u, v, w are displacement components in x, y and z directions and V is the unit cell volume. A threshold value of $p > 0.75$ is imposed to classify modes as predominantly out-of-plane. Only these modes are retained in the dispersion analysis and bandgap identification.

4.2 Transmission Analysis

Following the dispersion analysis, transmission simulations are performed on finite structures consisting of seven unit cells. A prescribed displacement is applied at one end of the rod, while the transmitted out-of-plane displacement amplitude is measured at the opposite end. A rectangular block is added; on this block the piezoelectric actuator can be placed.

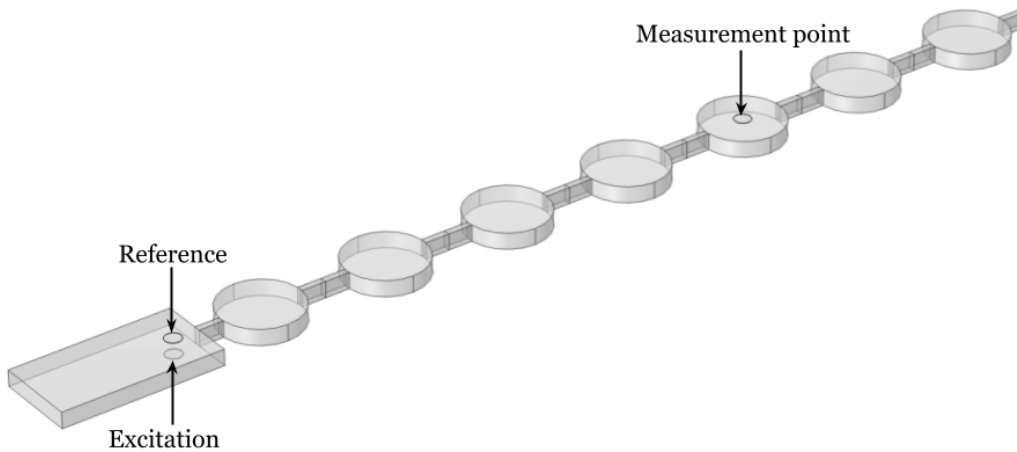


Figure 11: Finite structure consisting of seven unit cells and additional block for actuation, the excitation, reference and measurement point are visualized.

The wave transmission through the structure is evaluated by comparing the displacement amplitudes at the reference and measurement boundaries. The transmission coefficient is defined as

$$T(f) = \frac{|w_{\text{out}}|}{|w_{\text{in}}|}, \quad (13)$$

where w_{in} and w_{out} denote the out-of-plane displacement amplitudes at the reference and the measurement point, respectively. In the numerical model, these quantities are obtained from boundary probes. To express the transmission on a logarithmic scale, the displacement ratio is converted to decibels using

$$T_{\text{dB}}(f) = 20 \log_{10} \left(\frac{|w_{\text{out}}|}{|w_{\text{in}}|} \right). \quad (14)$$

Low transmission values indicate strong attenuation of the wave as it propagates through the structure. Frequency ranges where the transmission drops significantly correspond to bandgaps.

The following configurations are investigated:

- (a) Pure PLA structure
- (b) ABS disks connected by PLA ligaments
- (c) ABS disks and rotated PLA ligaments, allowing a mechanical interlocking mechanism

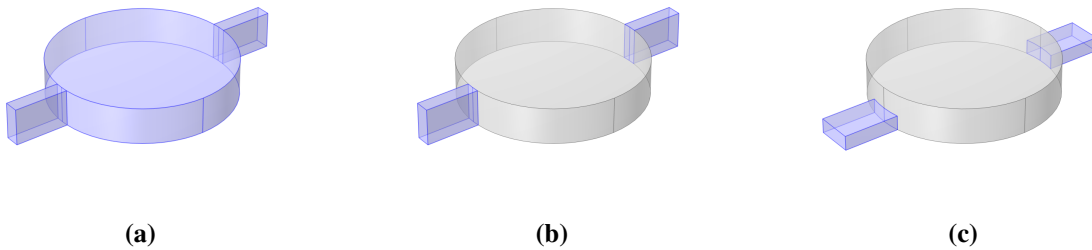


Figure 12: Three investigated configurations.

For each configuration, both dispersion and transmission analyses are conducted. The correspondence between predicted bandgaps and observed transmission dips is evaluated for validation.

5 Experimental Studies

Wave transmission in the metamaterial structures was measured using a pitch–catch configuration. In this method, one transducer acts as the wave source (pitch), while the response is measured at another location along the structure (catch). By comparing the excitation and received signals, the frequency-dependent transmission characteristics of the structure can be determined.

The excitation signal was generated using an arbitrary waveform generator (AWG, NETBOX DN2.653-16, Spectrum) controlled via the software SBench6. The signal was amplified using a power amplifier (HBK, Type 2718) before being applied to the actuator to ensure sufficient vibration amplitude. The vibrational response of the structure was measured using a LDV. The laser beam was directed onto reflective tape placed on the sample surface to improve signal quality. The LDV controller (Polytec OFV-5000) converts the Doppler shift of the reflected laser into the out-of-plane velocity of the vibrating surface. Both excitation and response signals were recorded through the DAQ system and transferred to a computer via a local area network (LAN) for data acquisition and post-processing.

An overview of the experimental setup is shown in Figure 13.

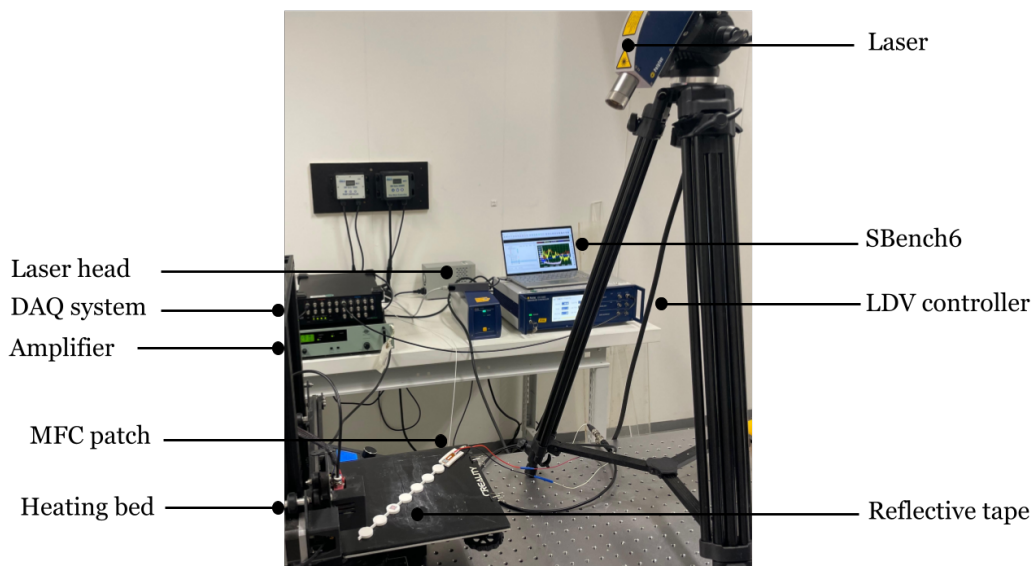


Figure 13: Experimental setup used to measure vibrational response and wave transmission.

The excitation signal was generated with a sampling rate of $F_s = 128$ kHz. A sine sweep was applied to excite the structure over a frequency range from $F_{\text{start}} = 0.5$ kHz to $F_{\text{end}} = 10$ kHz. The excitation signal was defined as

$$s(x) = \sin\left(\pi\left(2\frac{x}{F_s/F_{\text{start}}} + \left(\frac{1}{F_s/F_{\text{end}}} - \frac{1}{F_s/F_{\text{start}}}\right)\frac{x^2}{L}\right)\right), \quad (15)$$

where x is the sample index, F_s is the sampling frequency, and L is the signal length.

Mechanical waves in structures can be excited using several actuation methods, such as electrodynamic shakers, impact excitation, or piezoelectric actuators. In the present experiments, the metamaterial samples were placed on a heated print bed to control the temperature of the structure. This configuration made it impractical to mount an electrodynamic shaker beneath the specimen. To enable wave excitation under these conditions, a MFC actuator from Smart Materials was selected (M2814-P3). MFC patches are lightweight piezoelectric actuators that can be directly attached to the surface of a structure and driven electrically, allowing controlled excitation without requiring mechanical coupling to external equipment. Their small size and low mass make them particularly suitable for experiments where the specimen must remain on a heated support while still allowing reliable excitation of mechanical waves [41]. The MFC patch is bonded to the structure with double-sided tape to allow reuse of the patch on multiple structures.

To investigate the temperature-dependent behaviour of the metamaterial structures, the specimens were heated using the build plate of a 3D printer. This approach allows the temperature of the support surface to be accurately controlled and maintained during the experiments. Heating the structure from the build plate ensures that the entire specimen gradually reaches a uniform temperature, which is important when studying thermally induced changes in material stiffness. In addition, the flat and accessible surface of the print bed provides convenient optical access for the LDV, enabling reliable non-contact measurements of the vibrational response during heating. To ensure that the print bed and the specimen reached the desired temperature, the surface temperature was monitored using an infrared thermometer (Fluke 62 MAX). This allowed the temperature distribution across the structure to be checked during the experiment and verified that the specimen was heated uniformly before and during the measurements.

6 Results

6.1 Analytical Results

The three configurations, pure PLA, PLA rods with ABS disks and rotated PLA rods with ABS disks, are analyzed in COMSOL for their dispersion and transmission behaviour.

6.1.1 Dispersion Analysis

The dispersion relations of the three investigated metamaterial configurations were computed along the Γ -X direction of the Brillouin zone. The horizontal axis represents the normalized wave vector, while the vertical axis shows the normalized frequency. The frequencies were normalized to allow for direct comparison between the different configurations and temperature scenarios. Grey shaded regions indicate frequency ranges where no propagating modes exist, corresponding to bandgaps. The dispersion results show that the position of the first bandgap strongly depends on the stiffness of PLA. When the Young's modulus of PLA is reduced to represent the rubbery state above its glass transition temperature, the bandgaps consistently shift toward lower frequencies.

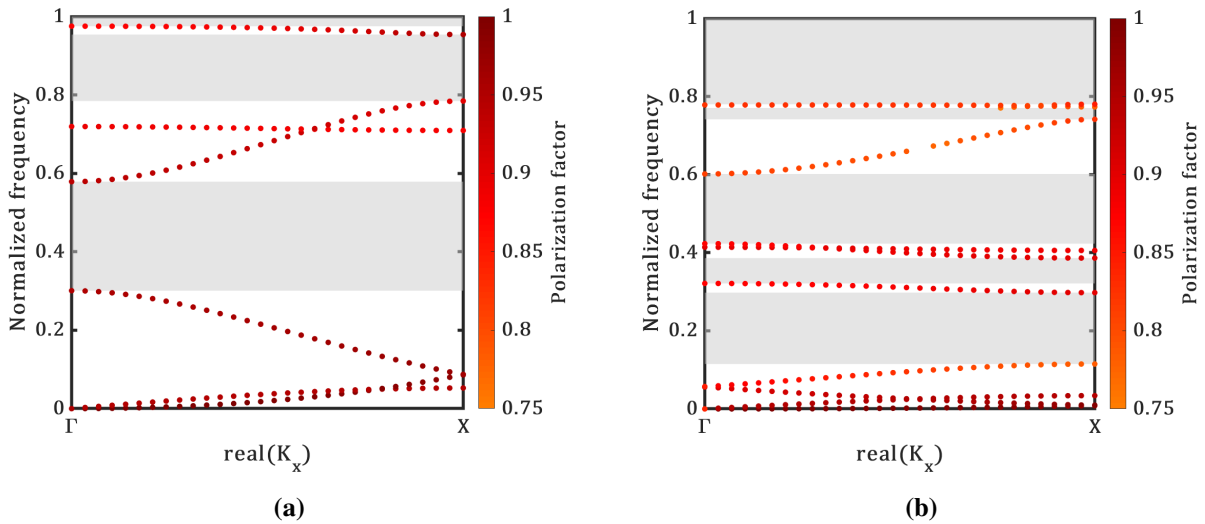


Figure 14: Dispersion graph of pure PLA for T_{room} (a) and T_g (b), grey shaded areas indicate bandgaps and the colourbar indicates the value for polarization.

For the pure PLA configuration, the first bandgap at room temperature occurs between approximately 6.7 kHz and 12.9 kHz. When the Young's modulus of PLA is reduced to represent temperatures above T_g , the bandgap shifts to a lower frequency range between approximately 2.6 kHz and 6.6 kHz. This large shift reflects the strong temperature dependence of the mechanical properties of PLA.

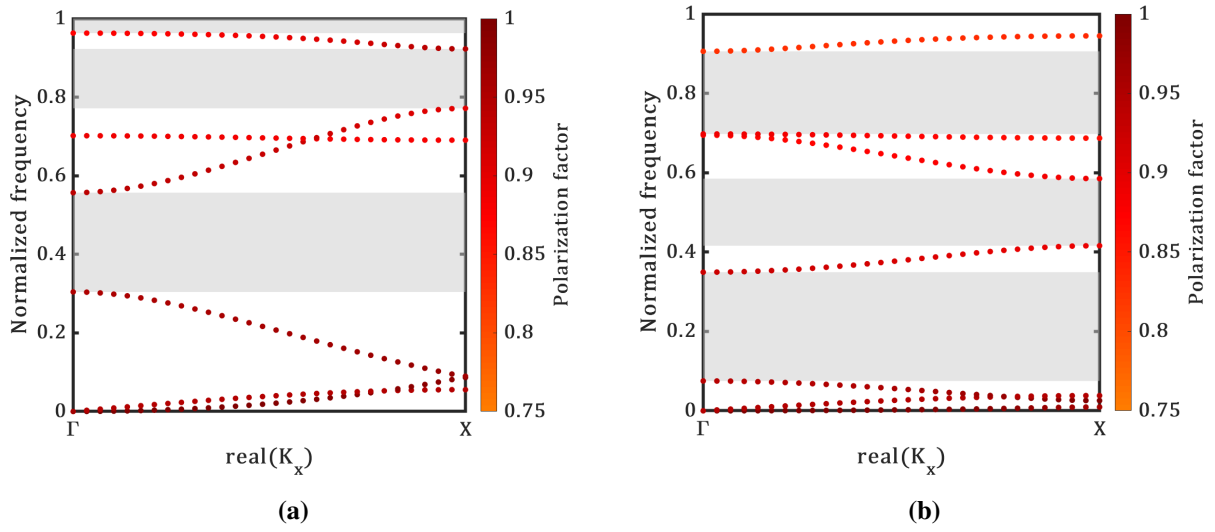


Figure 15: Dispersion graph of ABS disks and PLA rods for T_{room} (a) and T_g (b), grey shaded areas indicate bandgaps and the colourbar indicates the value for polarization.

For the configuration consisting of ABS disks connected by PLA rods, the first bandgap at room temperature is located between approximately 6.8 kHz and 12.4 kHz. After reducing the Young's modulus of PLA, the bandgap shifts to approximately 1.7 kHz to 7.8 kHz. The presence of stiffer ABS disks modifies the effective mass–stiffness distribution of the unit cell, which influences the width and position of the bandgap.

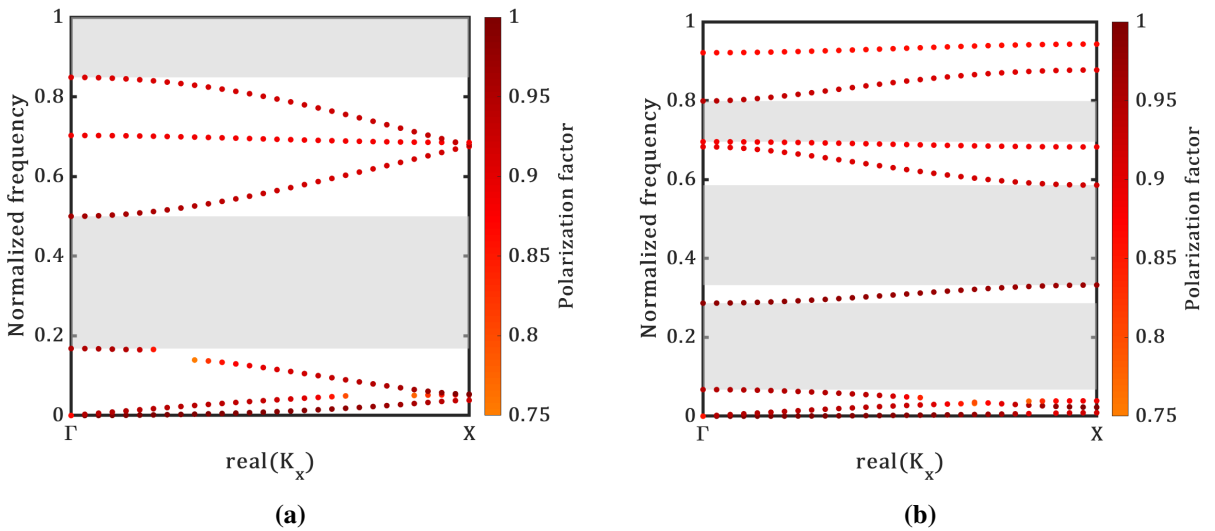


Figure 16: Dispersion graph of ABS disks and rotated PLA rods for T_{room} (a) and T_g (b), grey shaded areas indicate bandgaps and the colourbar indicates the value for polarization.

For the configuration with rotated PLA rods and ABS disks, the first bandgap at room temperature is observed between approximately 3.8 kHz and 11.2 kHz. When the Young's modulus of PLA is reduced, the bandgap shifts to approximately 1.5 kHz to 6.4 kHz.

Overall, the dispersion analysis demonstrates that temperature-induced softening of PLA leads to a consistent downward shift of the bandgaps across all configurations. The bandgap frequency ranges for all three configurations for room temperature and for rubbery state are listed in table 5 in the Appendix.

6.1.2 Transmission

The analytical transmission results are shown in figures 17-19. In these figures, the grey shaded regions represent the frequency range of the first bandgap predicted by the dispersion analysis. This allows direct comparison between the bandgaps of the infinite periodic structure and the transmission response of the finite structure. For most configurations the main transmission dips occur in the same frequency range as the bandgaps predicted from the dispersion analysis.

For the pure PLA structure in the rubbery state, the transmission curve does not show a clearly defined attenuation region within the frequency range predicted by the dispersion analysis. Instead, several local transmission minima appear throughout this region. One possible explanation for this behaviour is that, above the glass transition temperature, the stiffness of the entire PLA structure decreases significantly. As a result, the stiffness contrast within the unit cell is reduced, which weakens the bandgap formation mechanism. Consequently, the structure no longer exhibits a clear transmission gap. In contrast, the configurations containing ABS disks still show a clearer attenuation region in the predicted bandgap range.

Overall, the transmission analysis confirms the trends predicted by the dispersion relations. For all configurations, there is a clear shift of the bandgap frequency range to lower frequencies. These analytical results demonstrate that temperature-dependent changes in PLA stiffness can be used to tune the transmission behaviour.

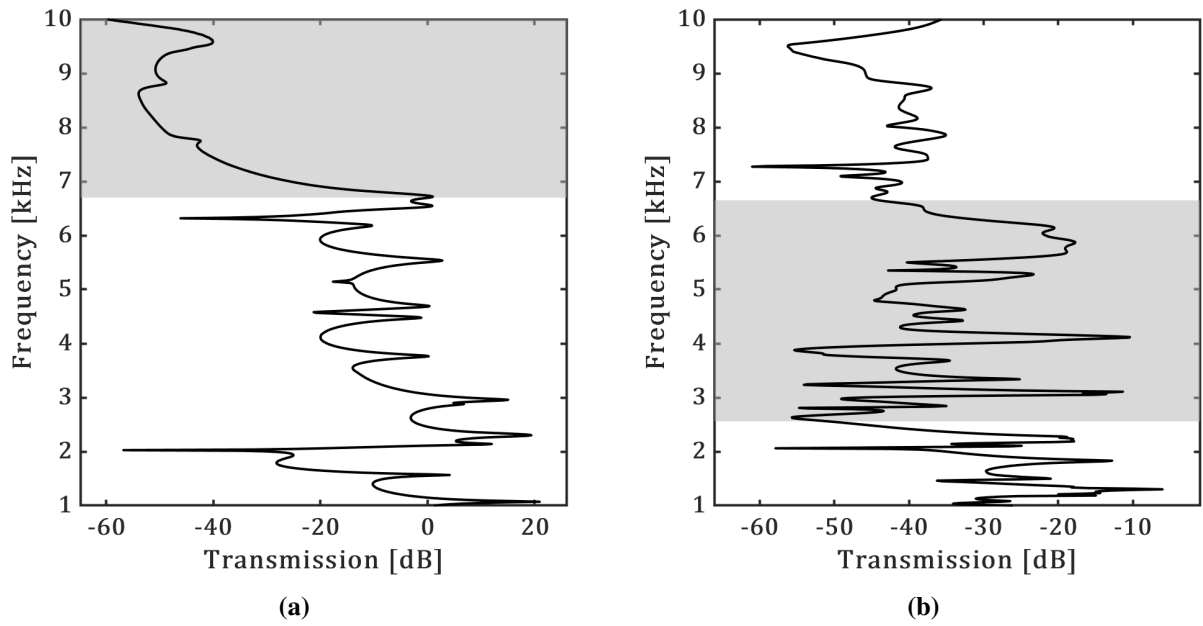


Figure 17: Transmission curves for the configuration of pure PLA at (a) room temperature and (b) in a rubbery state. The grey shaded region indicates the first bandgap predicted by the dispersion analysis.

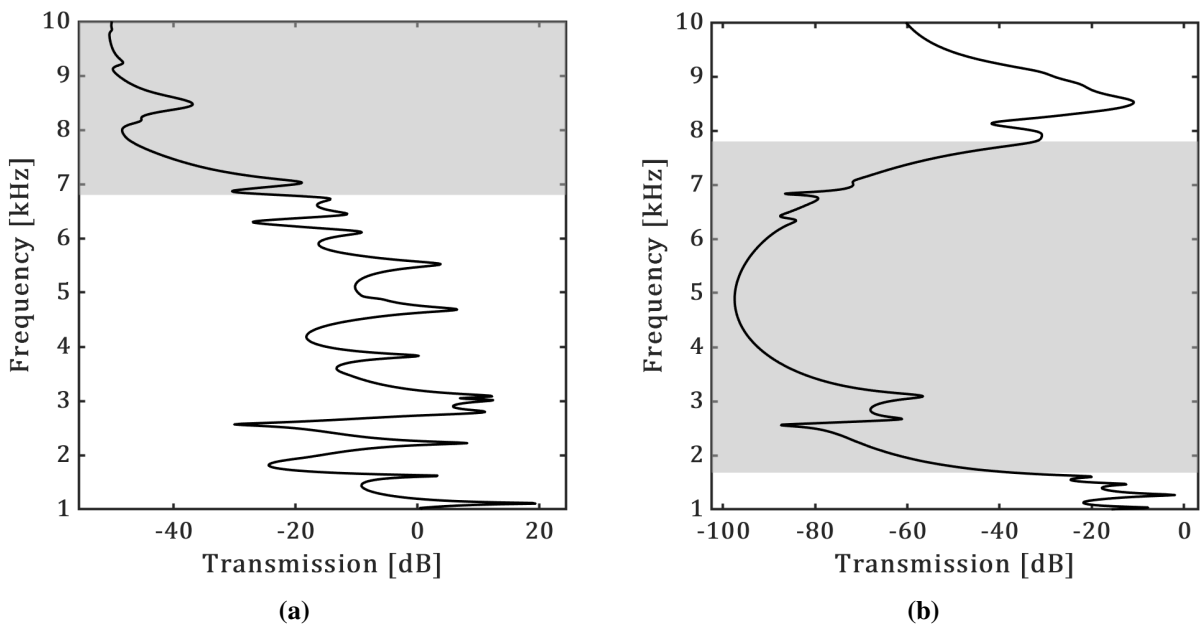


Figure 18: Transmission curves for the configuration with PLA rods and ABS disks at (a) room temperature and (b) in a rubbery state. The grey shaded region indicates the first bandgap predicted by the dispersion analysis.

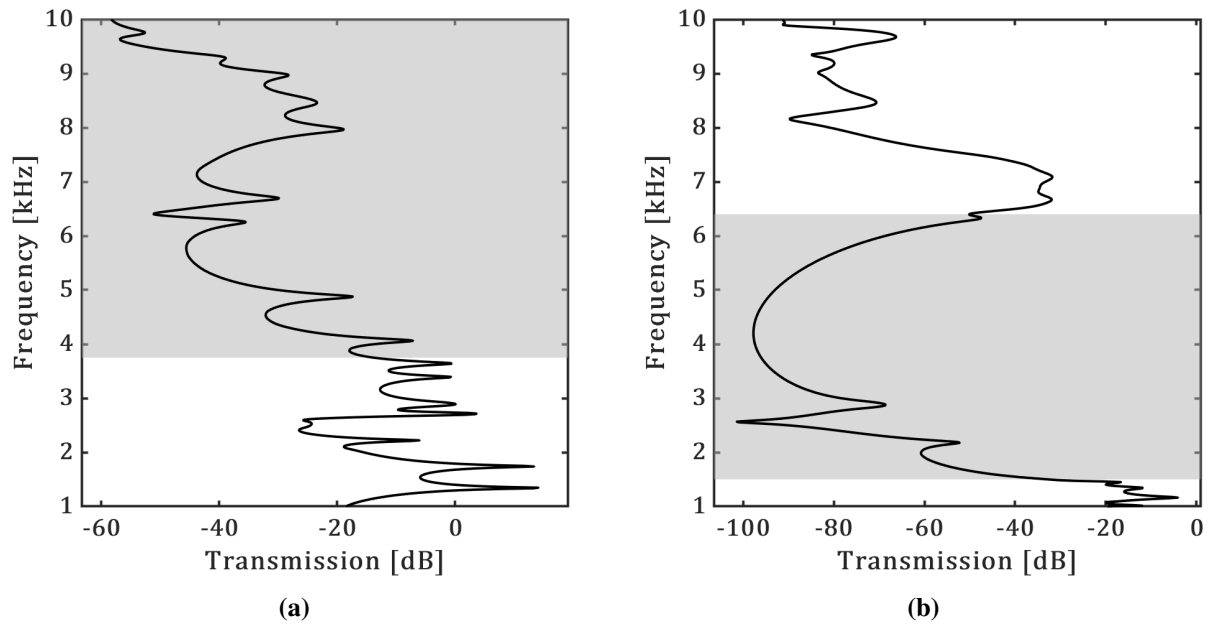


Figure 19: Transmission curves for the configuration with rotated PLA rods and ABS disks at (a) room temperature and (b) in a rubbery state. The grey shaded region indicates the first bandgap predicted by the dispersion analysis.

6.2 Experimental Results

6.2.1 Comparison of shaker and MFC patch

To evaluate the suitability of the excitation method used in the experiments, the transmission response obtained using a MFC actuator was compared with results obtained using shaker excitation (Philip Harris vibration generator, B8H30701) and with the analytical transmission results from COMSOL. This comparison was performed to verify whether the MFC actuator is capable of generating a reliable excitation signal for wave propagation measurements. The results shown in figure 20 indicate that the transmission response obtained with the MFC actuator corresponds well with the analytical transmission predictions and, in fact, shows an even closer agreement than the shaker-based measurements. This indicates that the MFC patch provides a suitable excitation method for the subsequent experiments and can reliably be used to investigate the transmission behaviour of the metamaterial structures.

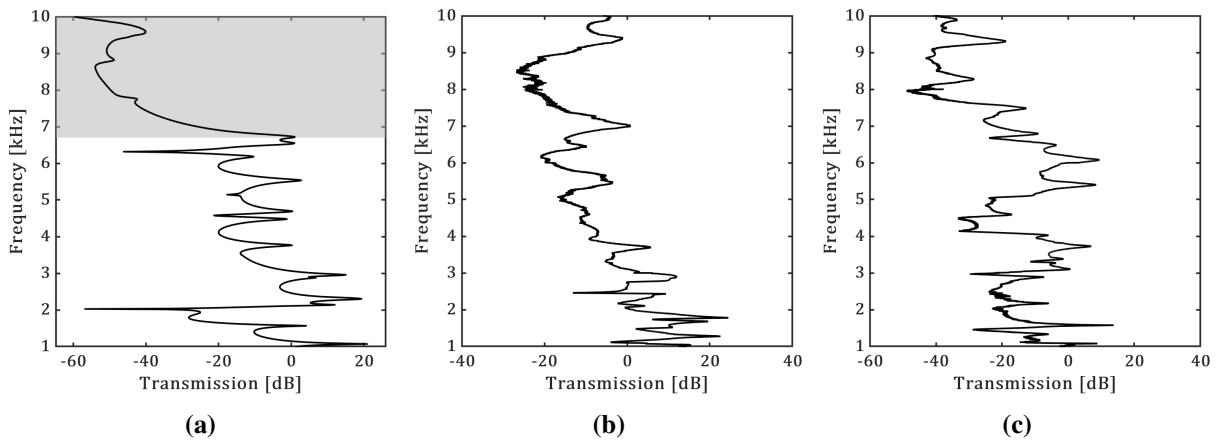


Figure 20: Transmission behaviour of pure PLA structure at room temperature modeled in COMSOL (a), experimentally tested with MFC patch as actuator (b) and experimentally tested with shaker as actuator (c).

6.2.2 Wave dynamics of pure PLA

Figure 21 compares the analytical transmission results obtained from COMSOL with the experimentally measured transmission for the pure PLA structure in a rubbery state. In the frequency range between approximately 7 and 10 kHz, the experimental transmission curve shows good agreement with the analytical results. At lower frequencies, however, the experimentally measured transmission is significantly lower than predicted by the COMSOL model. A likely explanation is the difference in boundary conditions between the analytical model and the experimental setup. In the COMSOL model, the structure is treated with idealized boundary conditions and does not interact with a supporting surface. In the experiments, however, the specimen is placed directly on the heated print bed in order to control the temperature during the measurements. The contact between the structure and the print bed introduces additional

damping and energy dissipation mechanisms that are not included in the simplified numerical model. Part of the vibrational energy can therefore be transferred from the specimen into the supporting surface, which reduces the transmitted amplitude measured along the structure. These additional losses may explain the lower transmission levels observed in the experimental results, particularly at lower frequencies.

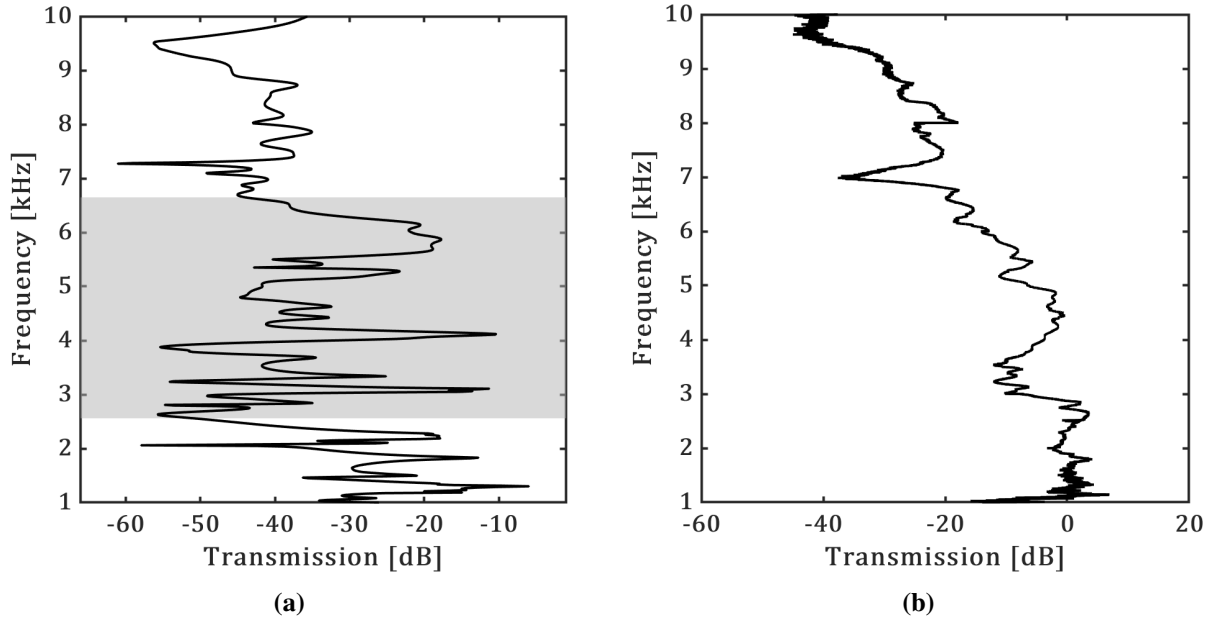


Figure 21: Transmission curves for the configuration consisting of pure PLA in a rubbery state: (a) analytical transmission obtained from the COMSOL model and (b) experimentally measured transmission.

6.2.3 Wave dynamics of ABS disks and rotated PLA rods

Figure 22 compares the analytical and experimental transmission results for the configuration consisting of rotated PLA rods and ABS disks at room temperature including an interlocking mechanism. In contrast to the pure PLA configuration, the correspondence between the analytical and experimental transmission curves is less clear. The overall transmission behaviour differs from the analytical prediction. In particular, the agreement between the analytical and experimental results is again weaker at lower frequencies.

Figure 23 shows the experimentally measured transmission at room temperature and at elevated temperature above the glass transition temperature of PLA. As discussed above, the transmission behaviour at room temperature already shows limited agreement with the analytical predictions, particularly at lower frequencies. Nevertheless, a shift of the transmission features towards lower frequencies can be observed when the structure is heated to the rubbery state. This shift indicates that the reduction in stiffness of PLA still influences the wave propagation behaviour of the structure. However, the observed shift is about 1 kHz and is smaller than

predicted by the analytical model. This difference may be attributed to the simplified assumptions of the numerical model and additional damping mechanisms present in the experimental setup.

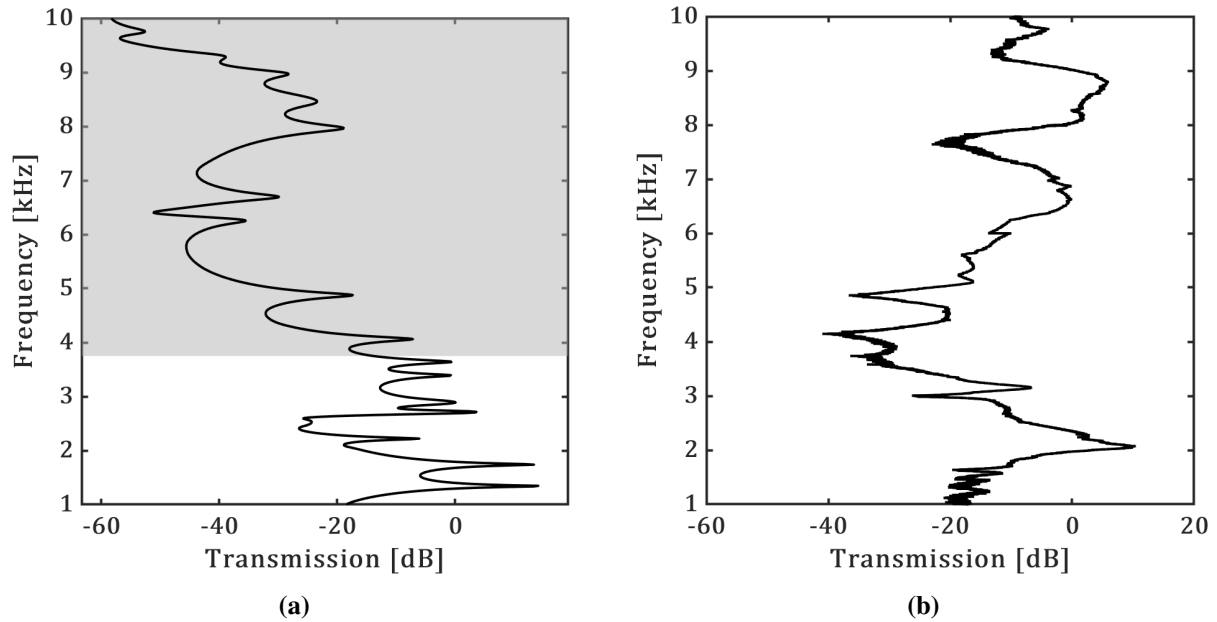


Figure 22: Transmission curves for the configuration consisting of rotated PLA rods and ABS disks at room temperature: (a) analytical transmission obtained from the COMSOL model and (b) experimentally measured transmission.

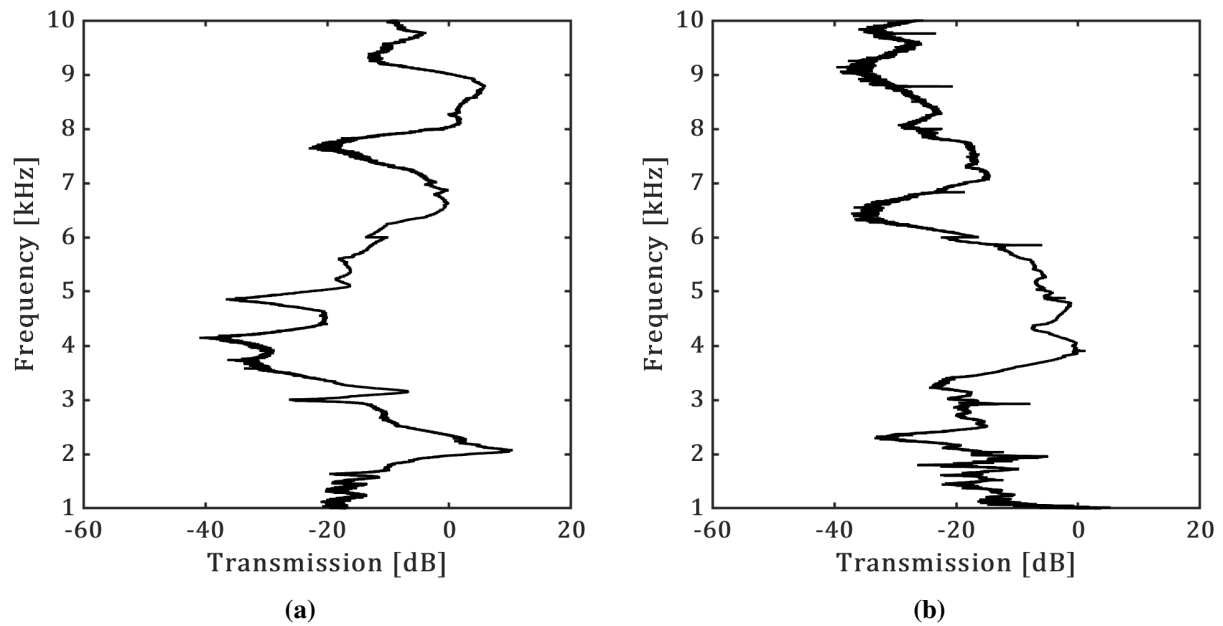


Figure 23: Experimentally measured transmission for the configuration consisting of rotated PLA rods and ABS disks: (a) room temperature and (b) elevated temperature above the glass transition temperature of PLA.

To investigate whether the reduced transmission observed at lower frequencies is caused by damping introduced by the heated print bed, an additional experiment was performed in which the structure was placed on a foam support. The foam was used to approximate free boundary conditions. Figure 24a shows the measured transmission when the structure is supported on foam, while figure 24b shows the corresponding setup. Compared to the measurements performed on the print bed, the transmission at lower frequencies is noticeably higher when the structure is placed on foam. This indicates that the supporting surface of the print bed introduces additional damping that affects the measured transmission, particularly in the low-frequency range. The transmission curve obtained with the foam support (figure 24a) shows a closer qualitative agreement with the analytical transmission results at room temperature presented in figure 22a.

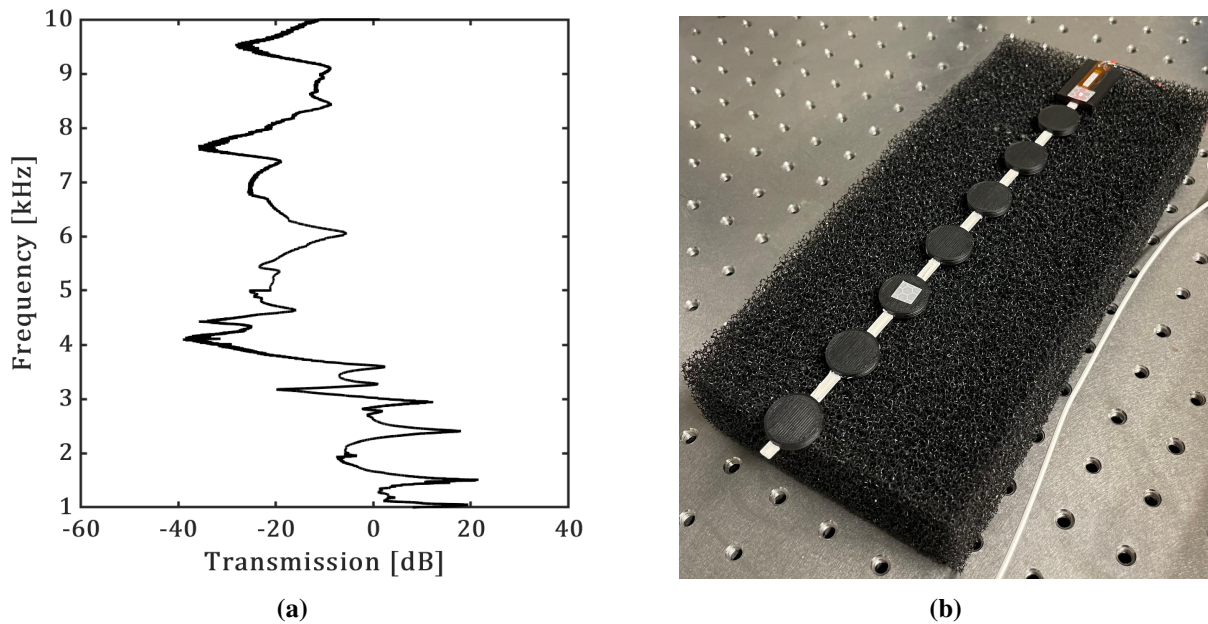


Figure 24: Verification experiment to investigate the influence of the supporting surface. (a) Transmission measurement of the metamaterial structure when supported on foam. (b) Experimental setup with the specimen placed on foam to approximate free boundary conditions.

7 Discussion

The objective of this research was to investigate whether multimaterial additively manufactured metamaterial structures composed of PLA and ABS can exhibit thermally tunable wave propagation behaviour. The numerical and experimental results provide insight into how temperature-dependent material properties influence the dynamic response of these structures.

The numerical dispersion and transmission analyses show that reducing the Young's modulus of PLA results in a downward shift of the predicted bandgap frequencies. This behaviour is consistent with the relationship between wave propagation and material stiffness, where a reduction in stiffness leads to lower wave velocities and consequently lower bandgap frequencies. From a modeling perspective, this confirms that temperature-induced stiffness changes in polymers can theoretically enable thermally tunable wave control.

The experimental measurements partially confirm this behaviour. For the pure PLA configuration, the experimental transmission curves show qualitative agreement with the analytical predictions in the higher frequency range. However, the experiments reveal significantly lower transmission levels at lower frequencies compared to the numerical model. This discrepancy can be attributed to differences between the simplified boundary conditions used in the simulations and the experimental setup. In the experiments, the specimens were placed directly on a heated print bed to control the temperature, which introduced additional damping through mechanical coupling with the supporting surface. An additional verification experiment supports this interpretation. When the structure was supported on foam to approximate free boundary conditions, the measured transmission at lower frequencies increased and showed improved qualitative agreement with the analytical predictions. This indicates that the supporting surface significantly influences the measured transmission behaviour and highlights the importance of boundary conditions in experimental studies of wave propagation in periodic structures.

These findings highlight several limitations of the present study. The numerical model uses simplified representations of temperature-dependent material properties and does not account for viscoelastic damping or experimental boundary conditions. Despite these limitations, the results demonstrate that temperature-dependent stiffness changes in polymer-based metamaterials can influence wave transmission behaviour. The experimental observations therefore support the general concept of thermally tunable wave propagation in multi-material additively manufactured structures, although the magnitude of the effect is reduced compared to the analytical predictions.

8 Conclusion

This research investigated the potential of multimaterial additively manufactured PLA/ABS metamaterial structures for thermally tunable wave control. By combining numerical modeling, additive manufacturing, and experimental transmission measurements, the influence of temperature-dependent material properties on wave propagation behaviour was evaluated.

The numerical analyses demonstrated that a reduction in the Young's modulus of PLA leads to a downward shift of bandgap frequencies in periodic metamaterial structures. This indicates that temperature-induced stiffness changes can be used as a mechanism to tune the dynamic response of polymer-based phononic structures. Experimental transmission measurements confirmed that heating the structures above the glass transition temperature of PLA influences the wave propagation behaviour. For the pure PLA configuration, the experimental results showed qualitative agreement with the numerical predictions in the higher frequency range. Additional verification experiments revealed that the supporting surface of the heated print bed significantly affects the measured transmission at lower frequencies, highlighting the importance of experimental boundary conditions. For the multimaterial configuration consisting of ABS disks and rotated PLA rods, the experiments showed a shift of transmission features toward lower frequencies when the structure was heated. Although the magnitude of this shift was smaller than predicted by the numerical model, the results demonstrate that combining materials with different thermal-mechanical properties can introduce temperature-dependent behaviour in additively manufactured metamaterial structures.

Overall, this study demonstrates that MMAM provides a promising approach for creating metamaterials with thermally tunable wave propagation behaviour. By exploiting the temperature-dependent stiffness of polymers such as PLA while maintaining a stiffness contrast through materials such as ABS, it is possible to design structures with adaptive dynamic responses. Future research could further improve the agreement between analytical and experimental results by incorporating more realistic material models in the numerical simulations. In particular, implementing viscoelastic material models based on DMA data would allow the temperature- and frequency-dependent stiffness and damping behaviour of PLA to be represented more accurately. In addition, experimental setups that better approximate free boundary conditions would reduce the influence of the supporting surface and enable more direct comparison with numerical models. This could be achieved, for example, by using heated environmental chambers or by integrating electrical heating elements directly into the structure, allowing temperature control without mechanically constraining the specimen. Finally, further studies could investigate alternative unit-cell configurations or material combinations to enhance the tunability and robustness of thermally adaptive phononic structures produced through MMAM.

References

- [1] Mahmoud I Hussein, Michael J Leamy, and Massimo Ruzzene. “Dynamics of phononic materials and structures: Historical origins, recent progress, and future outlook”. In: *Applied Mechanics Reviews* 66.4 (2014), p. 040802.
- [2] Maisyn Picard, Amar K Mohanty, and Manjusri Misra. “Recent advances in additive manufacturing of engineering thermoplastics: challenges and opportunities”. In: *RSC advances* 10.59 (2020), pp. 36058–36089.
- [3] Kevin P. Menard and Noah R. Menard. *Dynamic Mechanical Analysis: A Practical Introduction*. CRC Press, 2020.
- [4] Mariana Cristea, Daniela Ionita, and Manuela Maria Iftime. “Dynamic mechanical analysis investigations of PLA-based renewable materials: how are they useful?”. In: *Materials* 13.22 (2020), p. 5302.
- [5] Sifa Gul Demiryurek. “Evaluation of dynamic properties in ABS and PLA thermoplastics across frequency ranges”. In: *Scientific Reports* 15.1 (2025), p. 42629.
- [6] Jan Achenbach. *Wave propagation in elastic solids*. Elsevier, 2012.
- [7] Karl F Graff. *Wave motion in elastic solids*. Courier Corporation, 2012.
- [8] Abhishek Singh and Arpan Gupta. “Directional bandgap analysis in phononic crystal with rectangular super cell structure”. In: *International Journal of Mathematical, Engineering and Management Sciences* 7.3 (2022), p. 341.
- [9] R Augello and E Carrera. “Nonlinear dynamics and band gap evolution of thin-walled metamaterial-like structures”. In: *Journal of Sound and Vibration* 578 (2024), p. 118329.
- [10] Ping Sheng et al. “Locally resonant sonic materials”. In: *Physica B: Condensed Matter* 338.1-4 (2003), pp. 201–205.
- [11] GL Huang and CT Sun. “Band gaps in a multiresonator acoustic metamaterial”. In: *Journal of Vibration and Acoustics* (2010).
- [12] Charles Croënne et al. “Band gaps in phononic crystals: Generation mechanisms and interaction effects”. In: *AIP Advances* 1.4 (2011).
- [13] Elena Alonso-Redondo et al. “A new class of tunable hypersonic phononic crystals based on polymer-tethered colloids”. In: *Nature communications* 6.1 (2015), p. 8309.
- [14] Zhengyou Liu et al. “Locally resonant sonic materials”. In: *science* 289.5485 (2000), pp. 1734–1736.
- [15] *Introduction to Dynamic Mechanical Analysis and its Application to Testing of Polymer Solids*. Revised by A. Franck. TA Instruments. URL: <https://www.tainstruments.com/pdf/literature/TA441.pdf> (visited on 10/02/2025).

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- [16] Shuang Chen et al. “A review of tunable acoustic metamaterials”. In: *Applied Sciences* 8.9 (2018), p. 1480.
- [17] Zhao Zhao et al. “Thermal tuning of vibration band gaps in homogenous metamaterial plate”. In: *International Journal of Mechanical Sciences* 225 (2022), p. 107374.
- [18] Zhenyu Wang et al. “A new tunable elastic metamaterial structure for manipulating band gaps/wave propagation”. In: *Applied Mathematics and Mechanics* 42.11 (2021), pp. 1543–1554.
- [19] David J Ewins. *Modal testing: theory, practice and application*. John Wiley & Sons, 2009.
- [20] Jayesh Minase et al. “A review, supported by experimental results, of voltage, charge and capacitor insertion method for driving piezoelectric actuators”. In: *Precision Engineering* 34.4 (2010), pp. 692–700.
- [21] William K Wilkie et al. “Recent developments in nasa piezocomposite actuator technology”. In: *9th International conference on new actuators*. 2004.
- [22] Paolo Castellini, Milena Martarelli, and Enrico Primo Tomasini. “Laser Doppler Vibrometry: Development of advanced solutions answering to technology’s needs”. In: *Mechanical systems and signal processing* 20.6 (2006), pp. 1265–1285.
- [23] Lavina Backman et al. “Analysis of test specimen temperature gradients incurred in resistive heating system oxidation studies of ultra-high temperature ceramics”. In: *High Temperature Corrosion of Materials* 101.Suppl 1 (2024), pp. 85–105.
- [24] Yingying Wang et al. “Experimental study on the influence of temperature and humidity on the thermal conductivity of building insulation materials”. In: *Energy and Built Environment* 4.4 (2023), pp. 386–398.
- [25] Osama Abdulhameed et al. “Additive manufacturing: Challenges, trends, and applications”. In: *Advances in Mechanical Engineering* 11.2 (2019), p. 1687814018822880.
- [26] I John Solomon, P Sevel, and JJMTP Gunasekaran. “A review on the various processing parameters in FDM”. In: *Materials Today: Proceedings* 37 (2021), pp. 509–514.
- [27] Daehoon Han and Howon Lee. “Recent advances in multi-material additive manufacturing: methods and applications”. In: *Current Opinion in Chemical Engineering* 28 (2020), pp. 158–166.
- [28] David Espalin et al. “Multi-material, multi-technology FDM: exploring build process variations”. In: *Rapid Prototyping Journal* 20.3 (2014), pp. 236–244.
- [29] Ian Gibson Ian Gibson. *Additive manufacturing technologies 3D printing, rapid prototyping, and direct digital manufacturing*. 2015.

- [30] Tuan D Ngo et al. “Additive manufacturing (3D printing): A review of materials, methods, applications and challenges”. In: *Composites Part B: Engineering* 143 (2018), pp. 172–196.
- [31] Pedram Parandoush and Dong Lin. “A review on additive manufacturing of polymer-fiber composites”. In: *Composite Structures* 182 (2017), pp. 36–53.
- [32] Shukantu Dev Nath and Sabrina Nilufar. “An overview of additive manufacturing of polymers and associated composites”. In: *Polymers* 12.11 (2020), p. 2719.
- [33] Makara Lay et al. “Comparison of physical and mechanical properties of PLA, ABS and nylon 6 fabricated using fused deposition modeling and injection molding”. In: *Composites Part B: Engineering* 176 (2019), p. 107341.
- [34] Jun Yin et al. “Interfacial bonding during multi-material fused deposition modeling (FDM) process due to inter-molecular diffusion”. In: *Materials & Design* 150 (2018), pp. 104–112.
- [35] MakerBot Industries. *How to Print with UltiMaker ABS*. Accessed: 2026-03-07. 2025. URL: <https://support.makerbot.com/s/article/1667337602935>.
- [36] MakerBot Industries. *How to Print with UltiMaker PLA*. Online; accessed 7 March 2026. 2025. URL: <https://support.makerbot.com/s/article/1667337611872>.
- [37] Ming-Hsien Hsueh et al. “Effects of printing temperature and filling percentage on the mechanical behavior of fused deposition molding technology components for 3D printing”. In: *Polymers* 13.17 (2021), p. 2910.
- [38] Luiz Felipe Ferreira Neto et al. “The influence of active cooling on the strength and visual aspect of PLA FDM-printed parts, focused on reducing the need for support structures”. In: *Progress in Additive Manufacturing* (2025), pp. 1–17.
- [39] Tim Kuipers et al. “ITIL: Interlaced Topologically Interlocking Lattice for continuous dual-material extrusion”. In: *Additive Manufacturing* 50 (2022), p. 102495.
- [40] *Plastics — Determination of tensile properties — Part 2: Test conditions for moulding and extrusion plastics*. Second edition, 2012-02-15. International Organization for Standardization, 2012. URL: <https://www.iso.org/standard/56046.html>.
- [41] Smart Material Corporation. *Macro Fiber Composite (MFC) Datasheet V2.4*. Accessed: 2026-02-24. 2019. URL: https://smart-material.com/wp-content/uploads/2025/02/MFC_V2.4-datasheet-web.pdf.

Appendix

Sample	Nozzle PLA (°C)	Nozzle ABS (°C)	Bed (°C)	Comments
0. PLA/ABS	200	235	80	Good
1. PLA	200	–	80	Not perfect, some warping
2. ABS	–	235	80	Fail, ABS got stuck
3. ABS	–	240	100	Good
4. 3x PLA/ABS	200	235	90	Fail, PLA did not adhere to ABS. The reason might be printing 3 samples at the same time.
5. PLA/ABS	200	240	90	Good
6. PLA	200	–	60	Good, still a bit of warping but much better
7. ABS/PLA/ABS/-PLA	200	240	90	Good
8. PLA/ABS adjacent	200	240	90	Not perfect; they were attached but broke when applying some force
9. PLA/ABS adjacent (interlocking)	200	240	90	Good

Table 4: Overview of tested printing parameters for PLA and ABS combinations.



Figure 25: Interlocking sample after tensile test.

Configuration	Bandgap	Room temperature [kHz]	Rubbery state [kHz]
Pure PLA	1st	6.72 - 12.93	2.57 - 6.65
	2nd	17.53 - 21.32	7.18 - 8.63
	3rd	21.79 - 24.90	9.45 - 13.44
	4th	30.93 - 32.16	17.43 - 24.50
PLA rods	1st	6.80 - 12.44	1.68 - 7.80
	2nd	17.24 - 20.62	9.29 - 13.07
	3rd	21.52 - 24.73	15.59 - 20.24
Rotated rods	1st	3.76 - 11.17	1.51 - 6.40
	2nd	18.97 - 23.04	7.43 - 13.09
	3rd	25.31 - 27.62	15.55 - 17.85

Table 5: Frequency ranges of the bandgaps obtained from the dispersion analysis for the investigated configurations at room temperature and in the rubbery state.