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Maura Healey
Governor

Kim Driscoll
Lieutenant Governor

Phillip Eng
Acting MassDOT Secretary & CEO

3D-Printed Lattice-Based Structures for Next Generation Bridge Bearings and Bridge Isolation Bearings

Principal Investigator (s)

Simos Gerasimidis Ph.D.

John Hart Ph.D.

Wen Chen Ph.D.

Haden Quinlan

Thomas Vitalis

University of Massachusetts Amherst

**Research and Technology Transfer Section
MassDOT Office of Transportation Planning**



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16. Abstract This study evaluated the laboratory feasibility of elastomeric bearing prototypes reinforced with additively manufactured pentamode lattices. Stainless steel lattice configurations were embedded within a cast polyurethane elastomer and evaluated through material characterization and axial and cyclic shear testing. Within the tested range, lattice geometry influenced axial stiffness while producing comparatively smaller changes in shear stiffness. The study was limited to small scale prototypes, a limited number of specimens, shear testing without simultaneous vertical compression, and a prototype elastomer that differs from conventional bridge bearing materials. The results establish proof of concept but do not demonstrate suitability for implementation on MassDOT bridge structures. Additional full scale combined loading, fatigue, durability, environmental, modeling, and economic studies are required.			
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3D-Printed Lattice-Based Structures for Next Generation Bridge Bearings and Bridge Isolation Bearings

Final Report

Prepared By:

Thomas Vitalis
Graduate Researcher

Haden Quinlan
Co-Principal Investigator

Wen Chen Ph.D.
Co-Principal Investigator

John Hart Ph.D.
Co-Principal Investigator

Simos Gerasimidis Ph.D.
Principal Investigator

University of Massachusetts Amherst

Prepared For:

Massachusetts Department of Transportation Office of Transportation Planning
Ten Park Plaza, Suite 4150 Boston, MA 02116

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Executive Summary

This project, 3D-Printed Lattice-Based Structures for Next Generation Bridge Bearings and Bridge Isolation Bearings (Phase III), was conducted as part of the Massachusetts Department of Transportation (MassDOT) Research Program, funded through the Federal Highway Administration (FHWA) State Planning and Research (SPR) program. The objective was to investigate the feasibility of using architected lattice materials and additive manufacturing to develop bridge bearing systems with independently tunable mechanical properties.

Bridge bearings play a critical role in transferring vertical loads while accommodating rotations and horizontal movements caused by thermal expansion, creep, shrinkage, traffic loading, and seismic demands. Conventional steel-reinforced elastomeric bearings rely on the geometry of laminated steel plates and the mechanical properties of the elastomer to achieve these functions, limiting the degree to which vertical and horizontal stiffness can be independently tailored for specific applications.

This research investigated an alternative bearing concept consisting of stainless steel pentamode lattice structures embedded within a polyurethane elastomeric matrix. The study included experimental characterization of the bulk elastomer, followed by fabrication and testing of composite bearing prototypes manufactured using laser powder bed fusion and elastomer casting. Mechanical testing included material characterization, small-strain stiffness measurements, and large-displacement cyclic shear loading.

Within the tested range, lattice geometry influenced the measured axial stiffness of the composite prototypes, while the measured shear stiffness varied within a comparatively narrower range. These findings provide initial evidence that architected lattice reinforcement may offer a means of influencing the mechanical response of elastomeric composite systems through geometric design. The cyclic tests also indicated that lattice geometry and interface behavior affected the measured hysteretic response and stiffness evolution. However, the limited testing program does not establish performance advantages over conventional bridge bearings.

Overall, the study demonstrates the laboratory feasibility of manufacturing and testing lattice reinforced composite bearing prototypes and provides initial experimental evidence that their mechanical response can be influenced through geometric design. The investigation should be considered a proof of concept rather than validation of a bridge ready bearing system. The cyclic shear tests were performed without simultaneous vertical compression, and the program was limited to small scale specimens, a limited number of configurations, and a prototype polyurethane matrix. Full scale testing under combined compression and shear, dynamic and fatigue testing, environmental exposure, durability assessment, and calibrated numerical modeling are required before the concept can be evaluated for implementation on MassDOT structures.

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List of Acronyms

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1.0 Introduction

This study was conducted as part of the Massachusetts Department of Transportation (MassDOT) Research Program, funded through the Federal Highway Administration (FHWA) State Planning and Research (SPR) program. The objective of this research is to investigate the feasibility of using architected lattice materials and additive manufacturing to develop bridge bearings with mechanically tunable properties for future transportation infrastructure.

Bridge bearings are structural components installed between the bridge superstructure and substructure to transfer vertical and horizontal loads while accommodating rotations and translational movements caused by thermal expansion, creep, shrinkage, traffic loading, and seismic actions [1,2]. Their proper performance is essential for maintaining the intended structural behavior of bridges throughout their service life. Corrosion, bearing deterioration, or debris accumulation can restrict the intended movement of bridge bearings and introduce unintended forces into the structure, potentially resulting in cracked decks, distressed expansion joints, girder distortion, and deterioration of supporting elements. [3–7].

Historically, bridges relied on mechanical steel bearings, including rockers, rollers, pins, and sliding plates. Although effective, these systems required regular maintenance and were susceptible to corrosion and mechanical seizure. Beginning in the mid-twentieth century, elastomeric bearings gradually replaced many of these systems because they provide a simpler, more durable solution with no moving mechanical parts [4,5]. Modern elastomeric bearings accommodate rotations and horizontal movements through deformation of the elastomer while embedded steel laminates restrain lateral bulging, thereby providing high vertical stiffness together with relatively low shear stiffness [3,5,8].

Despite their widespread success, conventional steel-reinforced elastomeric bearings have several inherent limitations. Their mechanical response is largely governed by the geometry of the laminated construction and the properties of the elastomer, limiting the degree to which vertical and horizontal stiffness can be independently tailored. In addition, embedded steel laminates remain susceptible to long-term corrosion if exposed, while some seismic isolation systems rely on lead cores or other specialized components to achieve enhanced energy dissipation [5,7].

Recent advances in architected materials and additive manufacturing offer new opportunities to address some of these limitations. Architected lattice materials derive their effective mechanical behavior primarily from their geometry rather than solely from their constituent materials, enabling a wider range of mechanical responses than conventional solid materials. Among these, pentamode lattice architectures are of particular interest because they can be designed to provide high resistance to compression while maintaining relatively low shear stiffness. Embedding such lattices within an elastomeric matrix offers the potential to develop composite bridge bearings with tunable mechanical properties while reducing reliance on conventional laminated reinforcement.

This report presents the development and experimental evaluation of prototype composite bridge bearings consisting of additively manufactured stainless steel pentamode lattices embedded within a polyurethane elastomer. The work includes numerical design, material characterization, fabrication, and experimental testing to assess the feasibility of this concept and to establish a foundation for future development of architected bridge bearing systems.

1.1 Conventional Bridge Bearings

Conventional bridge bearings are predominantly elastomeric systems, including plain elastomeric pads, steel-reinforced elastomeric bearings, cotton-duck reinforced pads, and fiberglass-reinforced pads [9]. Among these, steel-reinforced elastomeric bearings have become the standard solution for highway bridges because they provide high vertical stiffness while accommodating horizontal movements and rotations through shear deformation of the elastomer. This behavior is achieved by alternating layers of elastomer and vulcanized steel shims, which restrain lateral bulging under compression while maintaining flexibility in shear [3,5,9].

The design of elastomeric bearings in the United States is governed by the AASHTO LRFD Bridge Design Specifications, which provide two design procedures: Method A and Method B [9]. Method A is based primarily on elastomer hardness and conservative stress limits, whereas Method B relies on the measured shear modulus of the elastomer and permits more refined designs through additional material characterization. MassDOT adopts Method B for most steel-reinforced elastomeric bearings and specifies a standard elastomer shear modulus of 0.160 ksi [11].

Although AASHTO provides the overall design framework, state transportation agencies adopt different design practices to address local construction methods and environmental conditions. For example, MassDOT, TxDOT, WisDOT, and MoDOT differ in their preferred design methods, allowable bearing geometries, installation requirements, and treatment of skewed or curved bridges [10–12]. Despite these regional differences, all conventional elastomeric bearings rely on the same fundamental design concept: the mechanical response is governed by the interaction between the elastomer and embedded steel reinforcement.

This reliance on laminated steel reinforcement inherently limits the degree to which vertical and horizontal stiffness can be independently tailored and motivates the exploration of alternative bearing architectures capable of achieving greater mechanical tunability.

1.2 Problem Statement

Despite the widespread use of conventional elastomeric and seismic isolation bearings, these systems have inherent limitations. Conventional elastomeric bearings rely on embedded steel laminates (Figure 1.1a,b) to restrain lateral expansion of the elastomer and provide the required vertical stiffness. Over time, these steel components may become susceptible to corrosion if exposed to moisture, potentially leading to deterioration of the bearing system and increased maintenance requirements. In addition, many seismic isolation bearings rely on lead cores or other specialized components to achieve enhanced energy dissipation during earthquake loading [13]. The mechanical response of these systems is also largely governed by the properties of the elastomer and the embedded reinforcement, limiting the degree to which vertical and horizontal stiffness can be independently tailored for specific applications.

Pentamode architected materials offer an alternative approach for designing mechanically

tunable bearing systems. Pentamode lattices are a class of mechanical metamaterials that exhibit a high bulk modulus combined with a comparatively low shear modulus through their geometric architecture rather than solely through their constituent materials [15,16]. This behavior is achieved by carefully designing the dimensions and arrangement of the internal struts and nodal connections (Figure 1.1c), allowing the effective mechanical properties of the structure to be adjusted through geometric design.

This geometric tunability provides the potential to tailor the compressive and shear stiffness of bridge bearings more independently than is possible with conventional laminated elastomeric systems. By replacing continuous steel laminates with an architected lattice embedded within an elastomeric matrix, it may also be possible to reduce the amount of steel required while maintaining the desired structural performance. The extent to which these potential advantages can be realized, however, depends on the mechanical interaction between the lattice architecture and the surrounding elastomer.

Although previous studies have investigated the behavior of pentamode lattices and their application in mechanical metamaterials and seismic isolation systems, limited information is available regarding their performance as composite structures embedded within an elastomeric matrix. The objective of this research is to investigate the feasibility of such composite bridge bearings through numerical design, additive manufacturing, material characterization, and experimental testing. Particular emphasis is placed on evaluating the influence of lattice geometry on the compressive and shear response of the composite system and assessing whether architected lattice reinforcement can provide a practical alternative for future bridge bearing applications.

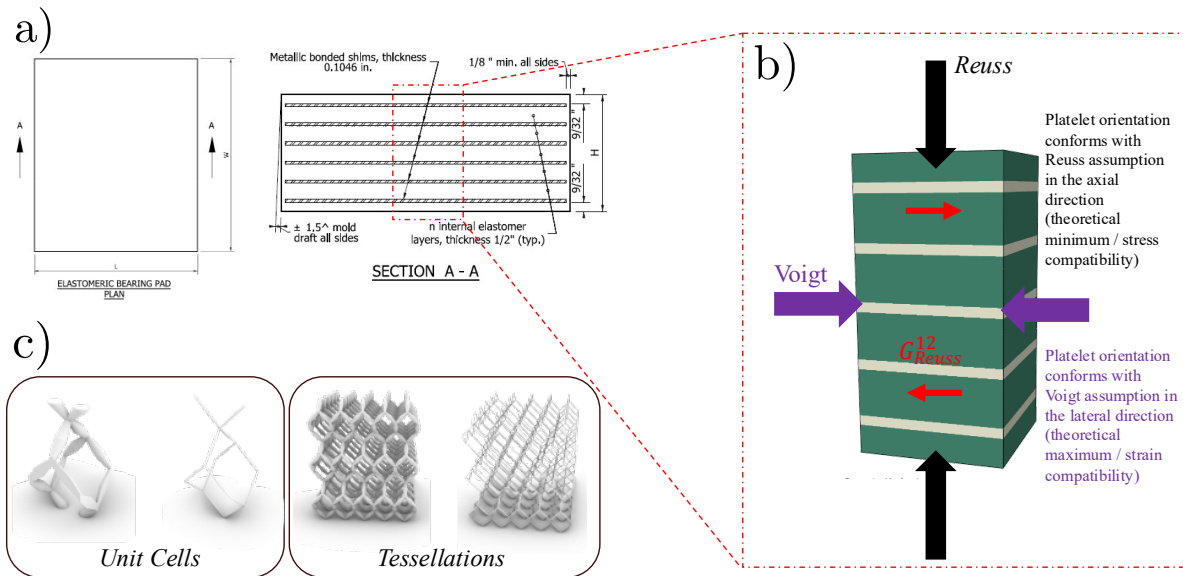


Figure 1.1: a) Plan view and section cut of a conventional bridge bearing, illustrating the steel bearing reinforcing plates embedded throughout the thickness of the elastomer. b) Mechanics of a slice of the conventional bridge bearing, showing the governing stiffness

homogenization assumptions for the principal directions of the bearing. c) Periodic unit cells and spatial tessellations of the pentamode architected material geometry, that exhibits minimal shear stiffness.

2.0 Research Methodology

2.1 Initial Design Space Exploration

The theoretical foundation of pentamode architected materials is rooted in the spectral analysis of the fourth-order elasticity tensor, C_{ijkl} , which mathematically governs the linear relationship between stress and strain in a three-dimensional continuum. For a thermodynamically stable solid, the elasticity tensor must be positive definite, meaning its six eigenvalues must be non-negative [15]. A pentamode metamaterial is defined as a highly specialized extremal solid wherein five of these six eigenvalues approach zero [21]. Physically, this indicates that the bare lattice is exceptionally compliant in five independent modes of shear deformation and resists only one specific mode of stress, which is typically hydrostatic compression [16].

This extreme mechanical decoupling results in a structure with a finite, highly programmable bulk modulus (K) and a vanishingly small shear modulus (G), allowing the solid lattice to mimic the macroscopic behavior of an ideal fluid [22, 23]. The fundamental architecture enabling this behavior is the diamond-type lattice, conceptualized by Milton and Cherkaev, which relies on four interconnected struts meeting at point-like vertices [15]. By replacing theoretical infinite point-hinges with double-cone struts characterized by a small junction diameter (d) and a large mid-span diameter (D), the kinematics of the lattice are driven into a pure stretching-dominated regime where bending rigidity is negligible. Consequently, the macroscopic properties of the pentamode truss—including its extreme K/G ratio—are dictated strictly by the rational geometric design of its microarchitecture rather than the bulk properties and chemical composition of the base material [16].

In contrast to pentamode lattices, conventional steel-reinforced elastomeric bearings operate on a different scale of extremal behavior. A standard elastomeric bearing is a macroscopic composite of alternating soft rubber and rigid steel laminates. Within a two-dimensional analytical framework, such a laminate functionally operates as a bimode extremal material. Its localized two-dimensional elasticity tensor possesses two small eigenvalues and one large eigenvalue, making it highly compliant against two modes of deformation (transverse shear and rotation) while remaining highly rigid against one mode (axial compression) [19]. When this laminated architecture is evaluated as a full three-dimensional continuum, it behaves as a trimode extremal material, meaning that three eigenvalues of its elasticity tensor are small while the other three are large.

While both conventional bearings (effectively bimode in 2D, or trimode in 3D) and pentamode lattices (pentamode in 3D) utilize extremal mechanics to isolate specific structural loads, their theoretical limits are vastly different. The decoupling of shear and compressive stiffness in a conventional trimode laminate is strictly bounded by the shape factor of the pads and the inherent bulk limits of the continuous elastomeric phase, restricting the degree of achievable mechanical independence. Conversely, because a pentamode lattice provides five soft modes of deformation, it serves as a universal mechanical building block [16, 17, 18]. By superimposing and varying the microstructural geometries of pentamode trusses, the design engineers can theoretically synthesize a material with completely arbitrary, customized

elasticity tensors. This profound level of mathematical and geometric tunability allows pentamode bare trusses to be programmed for highly specific anisotropic responses and operational constraints that remain physically impossible to achieve with conventional monolithic laminates.

The Voigt and Reuss composite theories represent the foundational micromechanical bounds for estimating the effective elastic properties of multiphase materials [20]. Formulated under distinct kinematic and static assumptions, these classical models are frequently utilized to approximate the macroscopic behavior of conventional steel-reinforced elastomeric bridge bearings, which are fundamentally two-phase laminated structures. The Voigt model assumes an iso-strain condition, positing that all constituent phases experience an identical, uniform macroscopic strain under an applied load. This perfectly bonded, parallel configuration yields the theoretical upper bound for the composite's effective stiffness, calculated as the volume-weighted arithmetic mean of the individual phase stiffnesses. Conversely, the Reuss model operates on an iso-stress assumption, establishing a series configuration where the internal stress field is uniform across all phases. This yields the theoretical lower bound for stiffness, computed as the volume-weighted harmonic mean of the phase properties.

In the context of a conventional elastomeric bridge bearing, these theories reflect the directional dependencies of the layered laminate. When the bearing is subjected to loads parallel to its laminations (e.g., horizontal shear displacement), the phases deform in parallel, approaching the Voigt bound. When subjected to loads perpendicular to the laminations (e.g., vertical compressive gravity loads), the layers carry the load in series, approaching the Reuss bound (Figure 1.1b). However, the analytical application of classical Voigt and Reuss rules of mixtures to these bearings exhibits notable inaccuracies because they treat elastic parameters independently and neglect complex triaxial interactions. Specifically, the basic models fail to account for the Poisson effect, which induces secondary lateral stresses and strains due to the mutual kinematic constraints at the bonded interfaces between the stiff steel shims and the highly compliant elastomer.

While modified Voigt and Reuss formulations can partially address simple planar laminates, these analytical theories are fundamentally incapable of predicting the effective properties of three-dimensional pentamode architected materials. The macroscopic mechanical response of a pentamode metamaterial—characterized by an extremal bulk modulus and a near-zero shear modulus—is governed exclusively by its rationally designed microarchitecture, such as the spatial arrangement of double-cone struts and the specific diameter ratios of the mid-spans to the point-like nodal junctions. Because the Voigt and Reuss approaches rely solely on the volume fractions and bulk properties of the constituents and are completely agnostic to complex geometrical topologies and spatial microstructures, they cannot analytically resolve the complex extremal mechanics of 3D pentamode truss lattices.

To accurately characterize the behavior of such intricate microarchitectures, particularly when embedded within a secondary liquid-cast elastomeric matrix phase, Periodic Boundary Condition (PBC) homogenization serves as the mathematically rigorous and appropriate computational framework. PBC homogenization bridges the micro-scale architecture to the macro-scale continuum by formulating a boundary value problem on a Representative Volume Element (RVE) or Unit Cell (UC) [21]. The effectiveness of PBCs stems from their ability to enforce kinematic continuity across the UC boundaries, mimicking the constraints of an infinite periodic lattice and eliminating the artificial boundary stiffening or compliance effects that

plague standard Dirichlet (uniform displacement) or Neumann (uniform traction) boundary conditions.

Mathematically, PBC homogenization assumes that the microscopic displacement field at any point within the unit cell can be decomposed into a linear component representing the macroscopic deformation and a periodic fluctuation field that accounts for the micro-scale inhomogeneities of the complex truss-matrix geometry. To extract the effective fourth-order elasticity tensor of the pentamode composite, the finite element model of the UC is subjected to six fundamental, independent macroscopic load cases (three normal strains and three shear strains). By solving the periodic boundary value problem for each specified macroscopic strain state and calculating the resulting volume-averaged stress over the unit cell, the full, anisotropic homogenized stiffness tensor of the composite can be determined. This advanced computational method provides the precise insights necessary to predict and tailor the tunable vertical and horizontal stiffnesses of next-generation pentamode bridge bearings.

In this work, the PBC homogenization method is used with pentamode UC embedded in elastomeric matrices, to explore the relationship between their geometrical features and their elastic properties and identify potential candidate architectures for the fabrication of novel bearing experimental specimens using additive manufacturing methods. Specifically, a custom Python script was developed inside the Rhino 7 computer aided engineering (CAD) software to automate the generation of architectures that were later imported into the ABAQUS finite element analysis suite. For the initial explorative finite element analysis the elastomeric matrix properties were assumed to be $E_{100}=4.4$ MPa and $\nu=0.49$ (nearly incompressible), after a review of the mechanical properties of several elastomeric bearing matrices. Based on these values and by using Mooney-Rivlin hyperelastic model the effective analysis properties were back calculated as $C1=1.2$ and $C2=0.115$ (equivalent to approximately $E=8$ MPa at small strains). The steel properties of additively fabricated stainless steel considered anisotropy effects using $E=75$ GPa, $\nu=0.3$ for the near 45° angles present in the lattice, based on previous experimental testing [22].

The feature size of this study for the geometrical size of the tapered internal beams within the pentamode architecture varied between 0.5mm to 2mm. This range of features represents a feasible and economical printing range, in which four 5x5x5 specimens can be fabricated within a single base plate, with an adequate number of unit cells within each tessellation so that edge effects are minimized with respect to the mechanical properties.

The results of this explorative numerical study are presented in Figures 2.1 and 2.2. At a first glance, the coupling between elastic moduli and shear moduli remains weak even inside the composite structure. It also appears that low relative density composites can provide tunable properties within a great range of shear and elastic moduli, achieving tunable compliant structures with less steel. Combined with the composite interpenetrating phase composite (IPC) geometry, pentamode architectures can be beneficial for the dimensional stability of the matrix, limiting debonding with less steel (which in turn yields lighter components) compared to traditional shim plates.

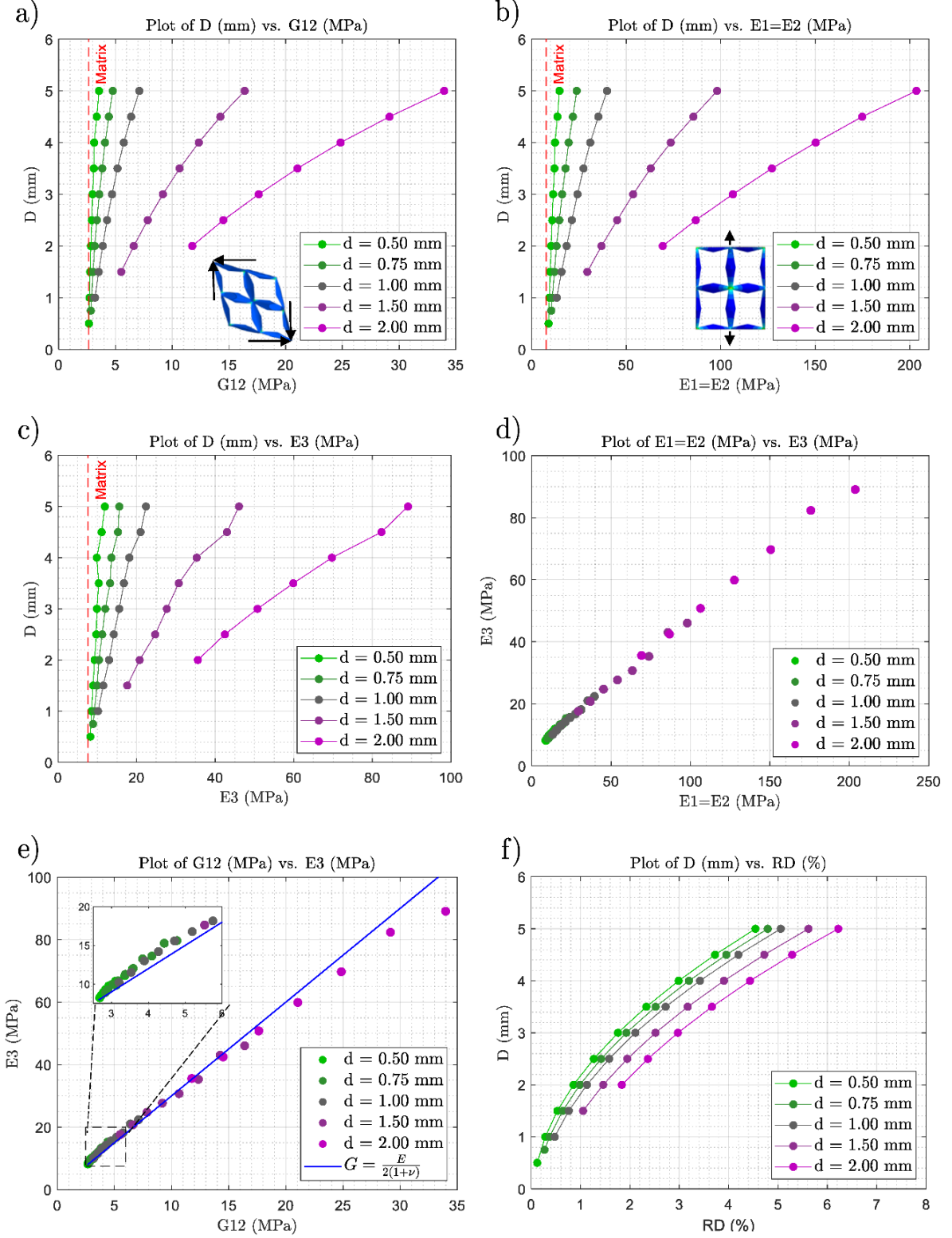


Figure 2.1: Periodic pentamode unit cell representative volume elements (RVE) finite element investigation, for the preliminary exploration of the effects of varying geometric

properties to the elastic properties of an elastomeric composite. Here D denotes the larger beam diameter and d denotes the smaller beam diameter of the tapered strut. The elastic modulus of the matrix phase provides a lower boundary for the shear compliance of the composite structure.

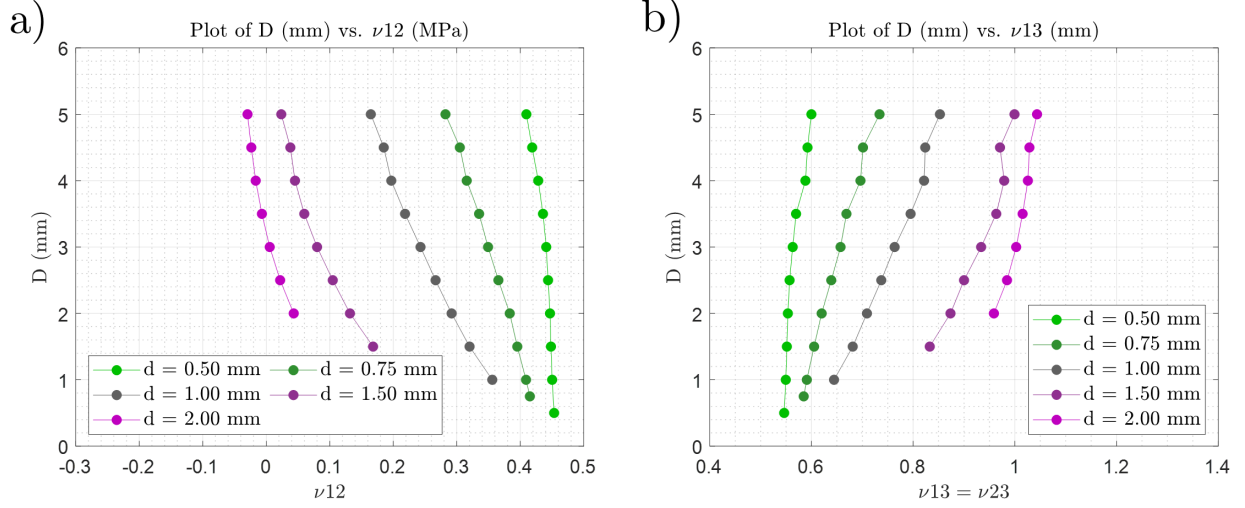


Figure 2.2: Poisson's ratios for varying geometric properties of composite pentamode RVEs.

Based on this initial explorative analysis, the geometrical property combinations of D1-d1, D3-d1, and D1.5-d1.5 (naming is designated by specific strut and unit cell dimensional parameters) were selected as candidate architectures that represented composite configurations within a viable fabrication range, possessing distinct mechanical properties in the small strain regime.

2.2 Materials & Methods

The fabrication of the next-generation interpenetrating phase composite (IPC) bridge bearings relies on the precise integration of a rigid, geometrically programmable microarchitecture with a highly durable, hyperelastic matrix. This composite material leverages the manufacturing capabilities of laser powder bed fusion (LPBF) for the steel truss lattices and the liquid-casting characteristics of an industrial-grade polyurethane elastomer.

Additively Fabricated Steel Lattices (PH1 15-5)

The reinforcement phase of the composite bearing consists of pentamode truss lattices fabricated using the LPBF additive manufacturing method, specifically utilizing an EOS M290 Direct Metal Laser Sintering (DMLS) system. The base material selected for the architected lattices is EOS PH1, a pre-alloyed precipitation-hardening 15-5 stainless steel powder. This

specific alloy was selected for its exceptional mechanical strength, hardness, and corrosion resistance, rendering it highly suitable for the demanding environmental and stress conditions inherent in civil bridge infrastructure. The chemical composition of the alloy consists of approximately 15% chromium and 5% nickel, yielding a fully dense part density of approximately 7.7 g/cm³. To ensure high-resolution fabrication of the micro-struts, the powder particle size distribution is tightly controlled, with only 0.5% of the grains exceeding 63 μ m.

The mechanical properties of the as-built 15-5 PH stainless steel exhibit the directional anisotropy that is characteristic of the LPBF process. Tensile testing of the manufactured alloy demonstrates that horizontally printed elements (XY plane) achieve an ultimate tensile strength (UTS) of 1200 $\pm$ 50 MPa, a yield stress of 1025 $\pm$ 85 MPa, and an elongation at fracture of 17 $\pm$ 4%. Conversely, vertically printed elements (Z plane) maintain an identical UTS of 1200 $\pm$ 50 MPa but exhibit a slightly reduced yield stress of 930 $\pm$ 75 MPa and an elongation at fracture of 14 $\pm$ 4% [22].

The manufacturing protocol for the intricate pentamode geometries utilizes a highly optimized exposure profile to prevent keyhole porosity and lack-of-fusion defects in the thin strut features. The optimal processing parameters include a laser power of 320 W and a scanning speed of 1300 mm/s for the internal infill, which delivers a volumetric energy density (VED) of 68.38 J/mm³. This is achieved using a layer recoating thickness of 40 μ m and a hatch distance of 0.09 mm. A critical mechanical advantage derived from this specific LPBF process is the inherent surface roughness of the as-built struts. Rather than acting strictly as a defect, this microscopic surface roughness significantly enhances the interfacial bonding and mechanical interlocking between the steel lattice and the surrounding elastomeric matrix.

Elastomeric Matrix (PMC-790)

To form the continuous second phase of the composite bearing, the additively manufactured steel pentamode lattices are embedded within a liquid two-part polyurethane elastomeric matrix, commercially designated as Smooth-On PMC-790 [23]. The PMC-790 urethane rubber compound was purposefully selected because of its initial low-viscosity liquid state (3,000 cps when mixed), which enables it to flow seamlessly through the narrow, complex void spaces of the pentamode microarchitecture without entrapping excessive air.

Table 2.1: Physical and Mechanical Properties of PMC-790 Elastomeric Matrix as provided by the vendor's specification sheet.

Property	Value	ASTM Standard
Shore A Hardness	90	ASTM D-2240
Tensile Strength	2,000 psi (13.8 MPa)	ASTM D-412
100% Modulus	640 psi (4.4 MPa)	ASTM D-412
Elongation @ Break	550%	ASTM D-412
Die C Tear Strength	300 pli	ASTM D-624

Specific Gravity	1.07 g/cc	ASTM D-1475
Specific Volume	25.9 cu. in./lb.	N/A
Mixed Viscosity	3,000 cps	ASTM D-2393
Shrinkage	< 0.001 in./in.	ASTM D-2566

The PMC-790 system requires mixing at a ratio of 2A:1B by weight and offers a working pot life of 20 minutes at 73°F (23°C). The liquid elastomer is poured at the lowest point of the containment mold, allowing it to seek its own level and properly encapsulate the metallic skeleton. The molds used for this process were custom made using an FDM (fused deposition modelling) process with PLA (polylactic acid) as the base material and an approximate wall thickness of 1.30mm to ensure spatial accuracy, snug fit of the trusses and unmolding ease. The compound undergoes a room-temperature cure over 48 hours with a negligible volumetric shrinkage of less than 0.001 in./in., which is essential for maintaining the strict geometric tolerances required for bridge isolation bearings. Once fully cured, PMC 790 has a Shore A hardness of 90 and provides the physical stability needed for handling and laboratory testing of the composite prototypes. Its low viscosity, room temperature curing process, and compatibility with the complex lattice geometry were the principal reasons for its selection. These characteristics made PMC 790 suitable for evaluating the manufacturability and basic mechanical response of the proposed composite concept, but they do not establish its suitability as a bridge bearing elastomer. The vendor reported physical and mechanical properties of PMC 790 are summarized in Table 2.1.

The materials used in this study were selected primarily to support prototype fabrication and laboratory feasibility testing. The selection considered the ability to cast the elastomer around the complex lattice geometry, commercial availability, and cost at the prototype scale. The materials were not selected to reproduce the physical or mechanical properties of a conventional MassDOT bridge bearing. In conventional practice, steel reinforced elastomeric bearings typically use vulcanized natural rubber or neoprene compounds with nominal Shore A hardness values of approximately 50 to 60 and specified shear moduli generally ranging from 0.080 to 0.175 ksi. These elastomers provide the flexibility needed to accommodate transverse and longitudinal bridge movements, while the internal steel reinforcing plates provide vertical restraint.

In contrast, this study used PMC 790, a commercially available two part polyurethane elastomer with a Shore A hardness of 90. PMC 790 was selected primarily because its low viscosity permits room temperature casting around the narrow and geometrically complex voids of the additively manufactured lattice. This casting capability was important for prototype manufacturability and avoided the need to develop a specialized vulcanization process during the feasibility study. The greater hardness of PMC 790 means that its mechanical response differs from that of the softer elastomers commonly used in conventional bridge bearings. Accordingly, the measured stiffness and cyclic response of the prototypes should not be interpreted as demonstrating equivalence to conventional MassDOT bridge bearing elastomers. Future development should investigate lattice reinforced composites manufactured with

elastomers that satisfy applicable bridge bearing material requirements.

Regarding the rigid phase, the internal reinforcement in conventional elastomeric bearings consists of solid, flat rolled mild steel sheets, typically specified as ASTM A36, A570, or A1011 Grade 36 or 50 [30]. These standard carbon steel shims possess a yield strength of 36 to 50 ksi and are highly susceptible to environmental corrosion, necessitating thick protective elastomer edge cover to prevent degradation and delamination.

Conversely, the reinforcing phase in the current composite bearing is the additively manufactured pentamode truss lattice fabricated from EOS PH1 15-5 precipitation-hardening stainless steel powder. The choice of 15-5 stainless steel offers superior inherent corrosion resistance compared to conventional mild steel. Furthermore, the 15-5 PH steel provides significantly enhanced mechanical properties, demonstrating a yield stress of approximately 135 to 148 ksi (930 to 1025 MPa) and an ultimate tensile strength of 174 ksi (1200 MPa) [22]. The ductility of the additively manufactured steel (14% to 17% elongation at fracture) is slightly lower than that of mild rolled steel. Advanced additive manufacturing techniques, specifically laser powder bed fusion (LPBF), are fundamentally required for this study; the complex, rationally designed extremal microarchitecture of the pentamode lattice possesses internal voids and specific nodal geometries that cannot be fabricated using conventional sheet-rolling or subtractive machining techniques. The LPBF procedure can feasibly produce larger specimens than the ones shown in this study, for production purposes, while smaller specimens such as the ones presented here are beneficial for rapid prototyping.

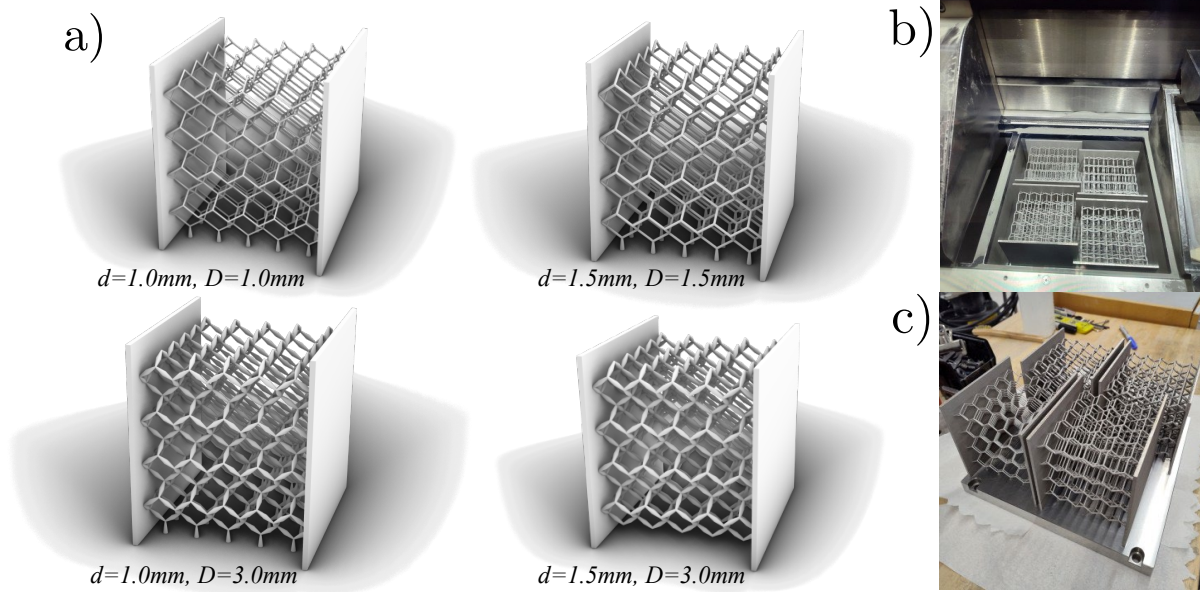


Figure 2.3: a) Renders of the selected experimental specimens for fabrication using laser powder bed fusion (LPBF) additive manufacturing. b) Specimens inside the EOS M290 laser chamber during the cleanup of the fabrication process. c) Base plate with specimens after removal from the machine.

As previously mentioned, the four specimens that were chosen for fabrication were geometrical property combinations of D1-d1, D3-d1, and D1.5-d1.5 which possessed varying geometrical properties leading to distinct mechanical properties under small strains. The

dimensions of all specimens were selected as 98 x 98 x 104.53 mm to ensure compatibility with the 125 x 125 mm fixture plates. For the orthogonal unit cells, the lattice constant, a , was set to 19.6 mm, while the lattice height was 26.133 mm. These parameters resulted in a composite specimen with an overall bounding box measuring 100 x 100 x 106 mm. The results of the DMLS fabrication process can be observed in Figure 2.3, with the specimens being captured right after the metal sintering process inside the EOS M290 machine (Figure 2.3b) and in the post-removal condition before separating them from the base plate with the means of an electrical discharge machining (EDM) process. It must be noted that the final specimens produced didn't present any imperfections or broken struts. To facilitate uniform load transfer and connection to the experimental apparatus, the top and bottom horizontal interfaces of the composite matrix are bounded by approximately 3mm thick rigid external stiffening plates that were printed fused to the specimens.

The experimental mechanical characterization of the fabricated interpenetrating phase composite specimens relies on a high-precision, Instron ElectroPuls E10000 universal dynamic testing frame, which is equipped with a 10 kN dynamic load cell to accurately capture the force response [33]. The E10000 system is engineered to perform both quasi-static and high-frequency dynamic testing, relying on a high-stiffness, precision-aligned twin-column load frame to maintain stringent load string alignment even when lateral or offset loads are induced. To evaluate the uniaxial compressive properties of the composite specimens—such as their effective compressive stiffness, yield threshold, and macroscopic strain limits—the test frame is fitted with rigid 20 kN-capacity fixed compression platens [34]. Quasi-static, displacement-controlled compression tests are executed, following ASTM D575, using these platens to reliably map the compressive stress-strain behavior and establish the linear elastic limits of the architected metamaterial. Typical tensile jaws are used to mount the specimens when testing polymeric dumbbell specimens to for their bulk material properties in tension, following ASTM D412.

The experimental determination of the effective shear modulus and the evaluation of the bearings' horizontal isolation capabilities necessitate the application of dynamic shear stress states [35, 36, 37]. Standard testing equipment is insufficient for this coupled loading profile; therefore, a specialized shear apparatus must be machined and assembled. To accurately replicate the kinematic boundary conditions experienced by bridge bearings in service, this in-house experimental setup is engineered to apply lateral shear displacements through vertical displacement of the actuator. Bridge bearings in service experience horizontal deformation while supporting sustained vertical compressive loads from the bridge superstructure. The shear testing apparatus used in this study could not apply a simultaneous vertical compressive load. The cyclic shear tests were therefore conducted without the compressive loading present in an operating bridge bearing. This limitation should be considered when interpreting the measured shear stiffness, hysteretic response, interface behavior, and failure mechanisms.

The specialized shear apparatus incorporates a fixed base on which an adjustable linear rail is mounted upon that holds the lower part of the shear fixture. The top part of the fixture that connects to the specimen is directly and rigidly attached to the frame's vertical linear actuator. The composite specimen is firmly connected to both this top plate and the bottom plate, by using precision fabricated metallic plates that were printed attached to it (Figure 2.3). The frame's load cells and LVDTs continuously record the applied vertical (shear) force and resulting shear strain.

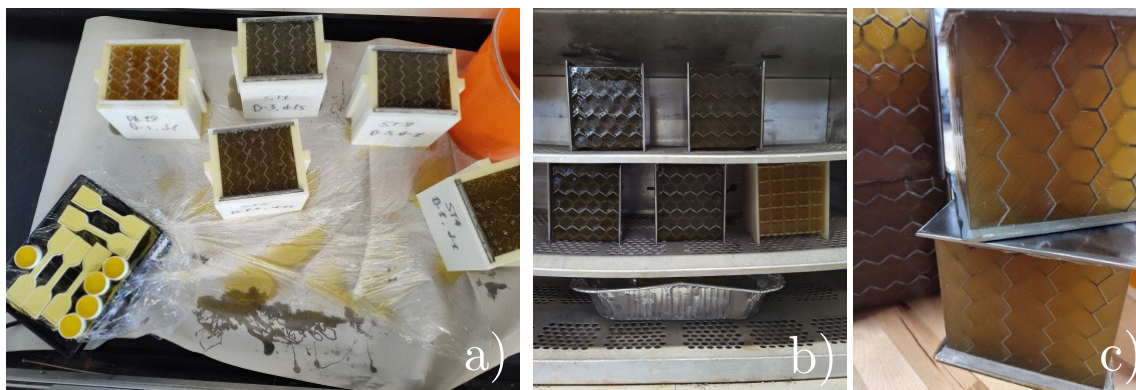


Figure 2.4: a) Casting of specimens in the 2-part elastomeric matrix, before the 48hr air curing. Dumbbell-shaped tensile specimens and round compressive specimens for acquiring the bulk material properties in tension (ASTM D412) and compression (ASTM D575) are observed. b) Post-curing treatment of the elastomer inside an industrial oven at 150°F (65°C) for 8hrs. c) Closeups of cured specimens before experimental testing.

3.0 Results

3.1 Bulk Material Characterization

The mechanical characterization of the elastomer matrix is essential for defining its bulk physical properties and is achieved through rigorous standardized compressive and tensile testing.

To acquire the bulk compressive properties, testing is conducted following ASTM D575, which establishes empirical procedures for determining the compression-deflection characteristics of rubber compounds. Standard test specimens for this procedure are cylindrical, featuring a continuous diameter of 28.6 ± 0.1 mm (yielding a 650 mm^2 cross-sectional area) and a nominal thickness of 12.5 ± 0.5 mm (Figure 3.1). The standard delineates two primary procedures for testing. Test Method A evaluates the compressive force required to achieve a predefined specified deflection. In this method, the specimen is subjected to three successive loading and unloading cycles at a deflection rate of 12 ± 3 mm/min, with the definitive readings recorded during the third application of force to account for initial material conditioning. Conversely, Test Method B determines the specific deflection that results from the application of a specified constant mass or compressive force. During both compressive test procedures, sheets of sandpaper are typically inserted between the elastomeric surfaces and the testing machine platens to resist lateral slippage, ensuring accurate uniaxial compression measurements. In this work test method A was used for the quantification of the compressive properties of the 2-part bulk elastomer matrix. The results of these tests are presented in Figure 3.2.

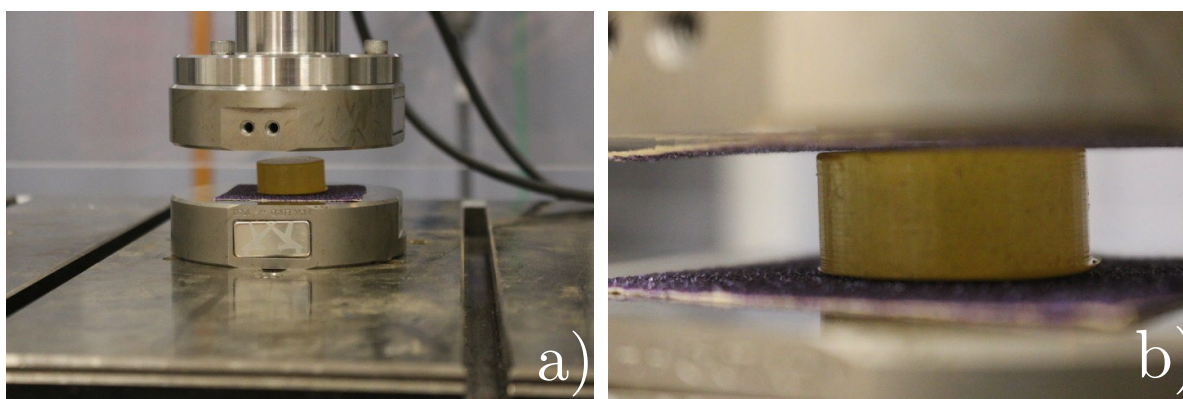


Figure 3.1: a) ASTM D575 compliant compressive specimens tested to characterize the bulk properties of the elastomer matrix. b) Compressive specimens tested with sand paper on both sides per specification recommendations.

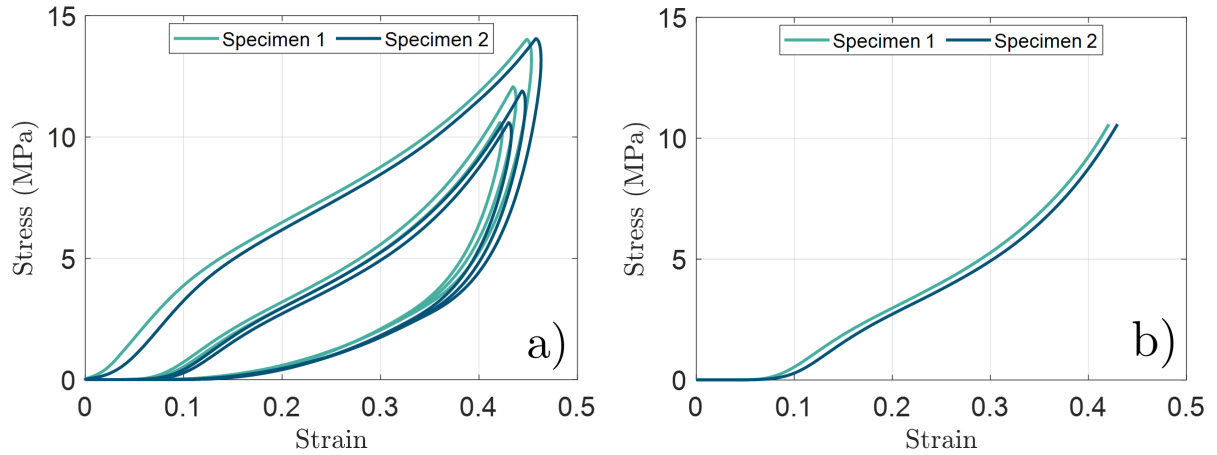


Figure 3.2: a) Stress-strain curves illustrating the agreement from the testing of 2 compressive specimens. Three cycles of loading are performed to condition the specimen. b) The compressive properties of the elastomer matrix are determined by using the data captured during the third cycle.

The Mullins effect is a mechanical phenomenon observed in elastomeric materials characterized by a pronounced stress softening, where the stress required to reload the material is significantly lower than the stress required during the initial virgin loading at the same strain level. This reduction in stress is most significant during the first few loading cycles and gradually stabilizes into a constant hysteresis loop after several additional cycles. This complex nonlinear behavior is primarily attributed to microstructural alterations, specifically the internal sliding and friction of macromolecular chains and their interactions with reinforcing filler particles.

To physically characterize this damage accumulation and stress-softening behavior, cyclic loading-unloading tests were performed on a single elastomer specimen subjected to monotonic compression. The experimental protocol consisted of 80 total cycles, during which the maximum applied displacement was incrementally increased in discrete steps every ten cycles. During these tests, the specimen was evaluated up to a maximum strain of approximately 0.55 and a peak compressive stress of roughly 14 MPa. By comparing the strain-induced relaxation between the first and tenth cycle of each displacement increment, the tests successfully quantified the progressive accumulation of damage and the stabilization of the elastomer's cyclic response.

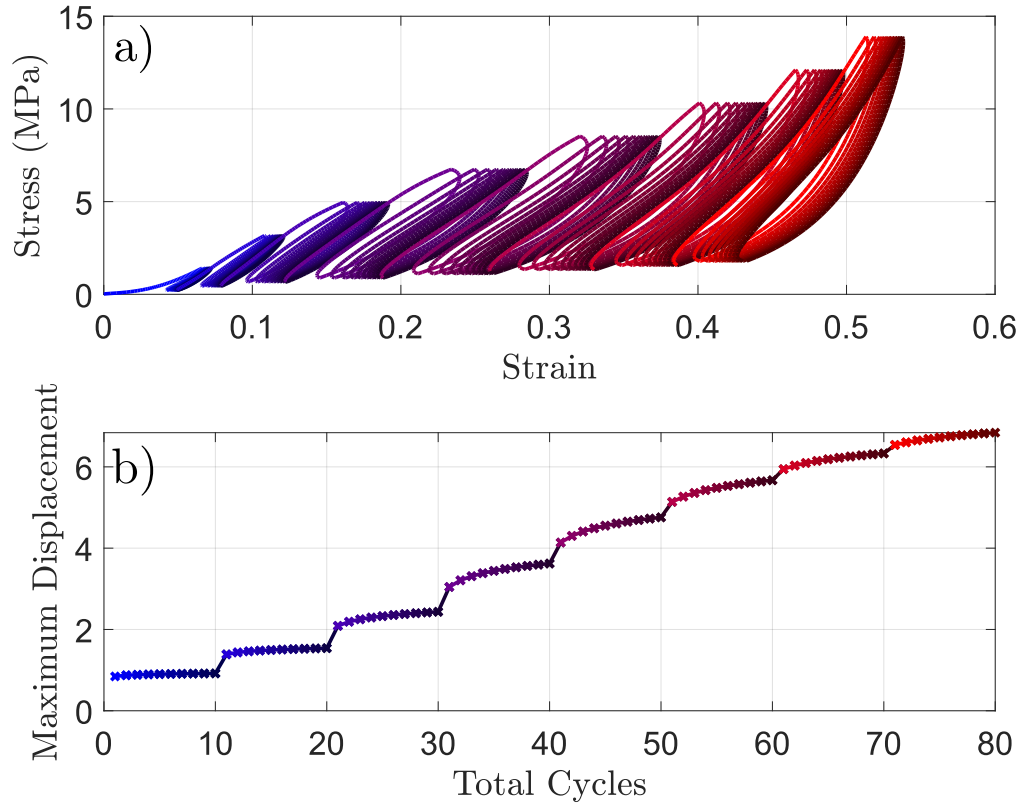


Figure 3.3: Cyclic loading-unloading of a single elastomer specimen at 225lbf (1kN) intervals under monotonic compression for the characterization of the Mullins damage effect in the elastomer.

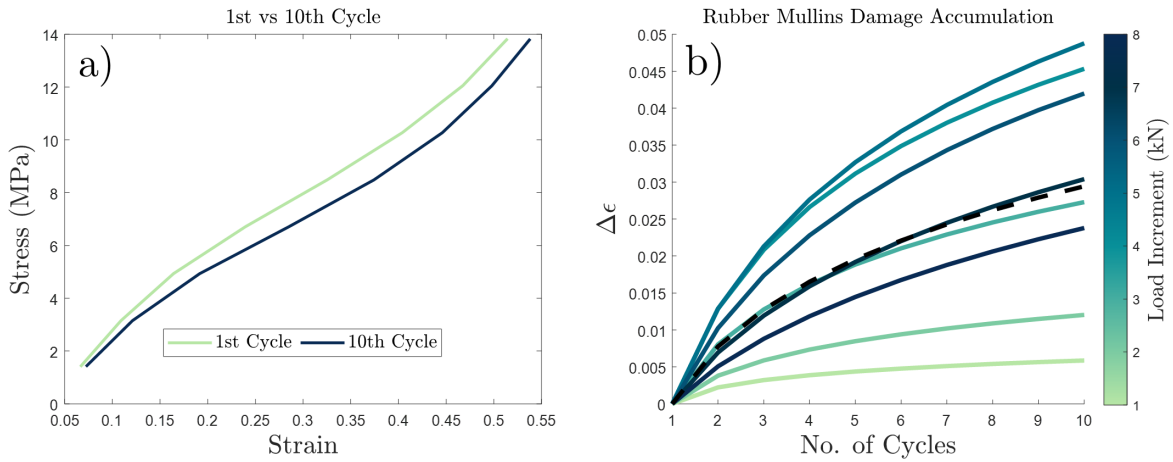


Figure 3.4: a) Comparison of the strain induced relaxation of the specimen between the 1st and the 10th cycle for the characterization of the Mullins damage effect. b) Damage accumulation in progressive cycles. The dashed line represents the average damage accumulation during the first ten cycles.

Tensile properties are evaluated in accordance with ASTM D412, which outlines the standard test methods for vulcanized thermoset rubbers and thermoplastic elastomers. Specifically, Test Method A per D412 is employed for assessing dumbbell and straight section specimens, while a second method, Method B mandates the use of cut ring specimens. In these experiments shown in Figure 3.5, method A was utilized with standardized tensile dumbbell specimens that were cast in place, following the same procedure that was used for the fabrication of composite bearing specimens. The tensile testing apparatus utilizes a power-driven machine that applies a uniform rate of grip separation, typically specified at 500 ± 50 mm/min for a specified distance. This standardized protocol enables the accurate extraction of critical mechanical parameters, including tensile stress, tensile stress at a given elongation, ultimate tensile strength, yield point, and ultimate elongation. These tensile properties are calculated based on the original cross-sectional area of the specimen's uniform cross-section prior to any prestressing. Per D412, if an elastomeric material exhibits a yield point (yield strain) at less than 20% elongation when tested at the standard 500 ± 50 mm/min rate, the required rate of elongation must be formally reduced to 50 ± 5 mm/min. Should the material continue to display a yield point under 20% elongation at this reduced rate, the displacement rate must be further decreased to 5 ± 0.5 mm/min. This provision was applicable during the testing of the liquid 2-part elastomer matrix and the experimental findings are reported below in Figure 3.5.

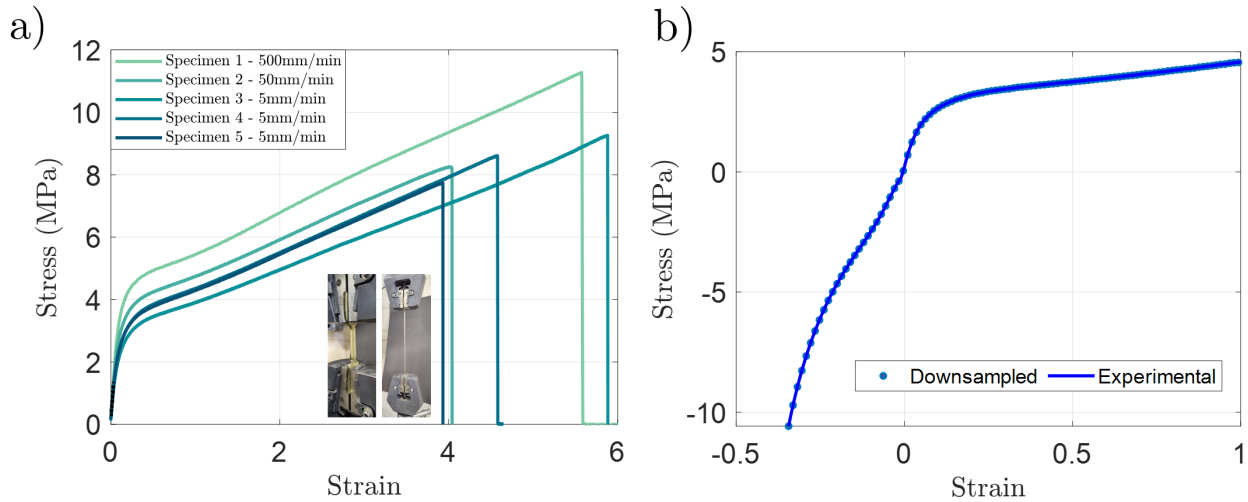


Figure 3.5: a) Tensile specimens tested at varying strain rates for the characterization of the tensile properties of the rubber matrix. b) Synthesized stress-strain response in tension and compression mapping the mechanical properties of the elastomer matrix.

3.2 Composite Lattice Bearings

Following this material level characterization, the composite specimens were subjected to small strain axial and shear testing followed by progressively increasing cyclic shear loading.

The small strain tests were used to estimate the compressive and shear moduli of the three configurations. The cyclic tests were used to characterize the measured hysteretic response and stiffness evolution within the displacement and force ranges achieved during testing. The D1-d1 and D3-d1 specimens were tested until interfacial failure, while testing of the D1.5-d1.5 specimen was terminated when the required force reached the capacity of the testing frame.

The experimental apparatus used in these tests utilizes the Electropuls E10000 mechanical testing frame equipped with an actuator capable of applying controlled forces and deformations across vertical degrees of freedom. The system is highly modular and is configured to capture the mechanical properties of the specimens under pure axial compression as well as in planar shear by using the as-built attached to the specimen plates. During the shear testing configurations, the bottom bounding plate of the composite specimen is rigidly clamped to a fixed lower horizontal rail, while the top bounding plate is secured to a movable upper fixture connected directly to the mechanical actuator. This boundary condition allows the actuator to drive the top plate into positive and negative ordinate maximum displacements while maintaining structural stability. Furthermore, the built-in rectangular plate design allowed the apparatus to evaluate the anisotropic shear response of the bearings by testing them in two orthogonal shear orientations, specifically denoted as the G12 and G13 shear planes.

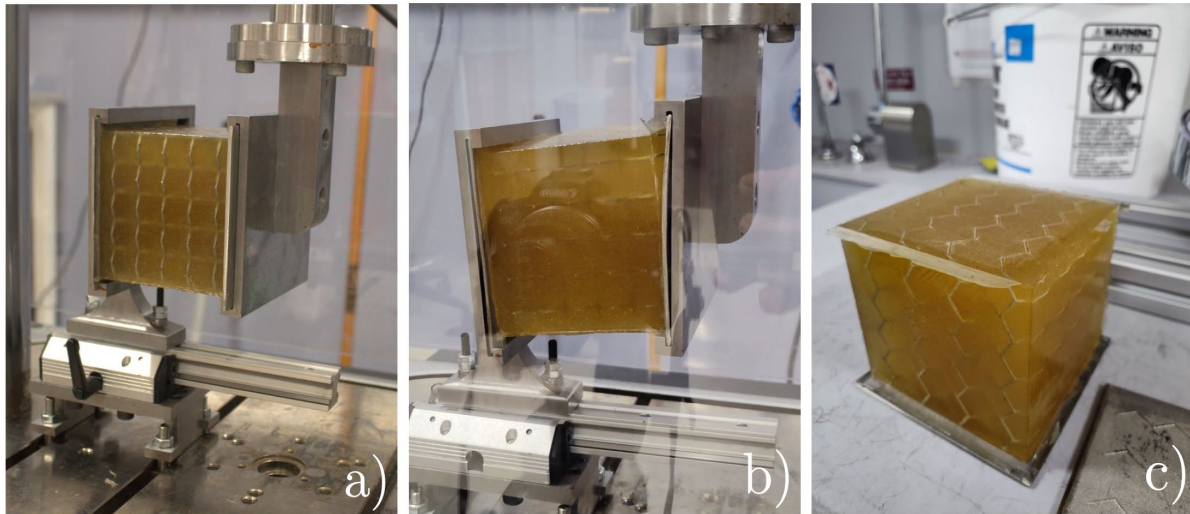


Figure 3.6: a) Photo of the experimental setup with the specimen placed in the shear testing apparatus. b) Snapshot during the experiment with the actuator reaching the negative ordinate maximum displacement. c) Specimen after the debonding failure of the interface at the end of the test.

The loading protocol was systematically divided into two distinct testing phases: a non-destructive small-strain characterization and a destructive large-displacement cyclic test. Initially, a linear elastic perturbation loading of 0.5mm was applied using a 0.1mm/min displacement rate, yielding very small strain amplitudes. This initial phase was utilized to accurately isolate and capture the fundamental elastic properties of the composite bearings under both axial compression and the orthogonal shear directions (G12 and G13) without inducing irreversible internal damage. Any kinks that are observed within the shear testing curves at very early strain levels represent relative displacement of the plate inside the slotted

fixture, due to fabrication and fitting tolerances. Elastic property measurements are taken beyond that point (shown as dashed lines in Figure 3.8).

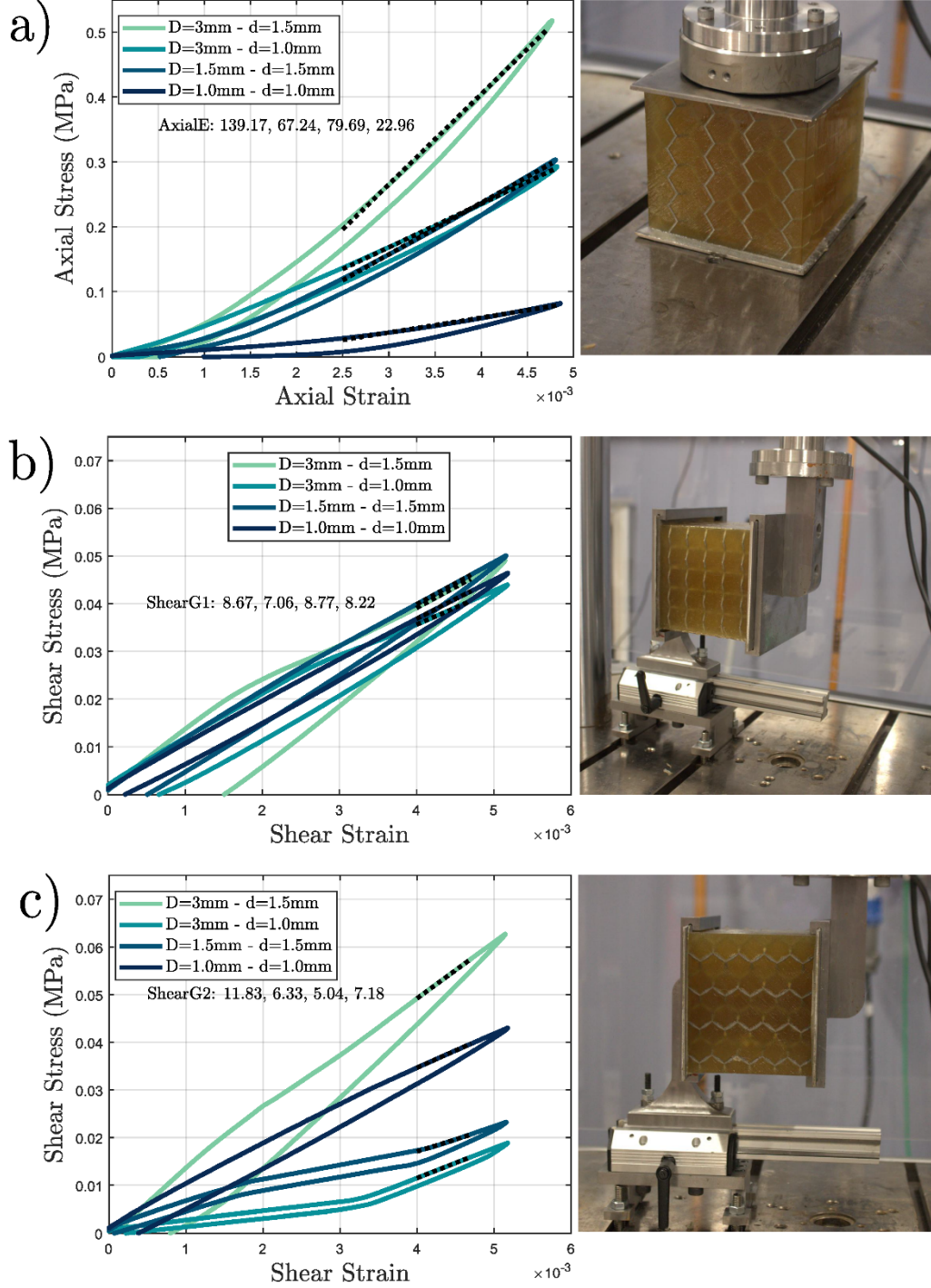


Figure 3.8: Linear elastic perturbation loading at small strains for capturing the elastic properties of the composites. a) Testing under axial compression. b) Testing under shear G12. c) Testing under shear G13.

Within the small strain range evaluated, the measured axial compressive stiffness varied substantially among the three lattice configurations, while the measured shear moduli remained within a comparatively narrower range. These results provide initial evidence that lattice geometry can influence the relationship between axial and shear stiffness in the prototype composite system. Because the specimens were small scale, used a prototype elastomer, and were not evaluated under combined service loading, the results do not establish that the tested configurations satisfy the stiffness or movement requirements of conventional or seismic bridge bearings.

A comparison between the macroscopic experimental characterization under linear elastic perturbation loads and the explorative Representative Volume Element (RVE) numerical findings presented in Figure 2.1 reveals both fundamental property alignments and distinct numerical discrepancies driven by varying boundary conditions.

Both the experimental testing and periodic RVE simulations showed the same qualitative trend of greater variation in axial stiffness than in shear stiffness across the configurations considered. The parametric RVE study demonstrates that increasing the structural dimensions of the internal lattice—specifically the main strut thickness (D) and the unit cell nodal dimension (d)—results in an exponential increase in the effective axial modulus, E_3 . Concurrently, the effective transverse shear modulus, G_{12} , remains remarkably stable and bounded near the baseline stiffness of the unreinforced matrix material. This behavior is directly corroborated by physical experiments; for example, modifying the embedded lattice from a D1-d1 to a D3-d1 geometry yielded a substantial increase in the experimental axial modulus from 22.96 MPa to 67.24 MPa, while the experimental shear modulus G_{12} effectively remained in the same range.

Although the experimental and RVE results show similar qualitative trends, their quantitative agreement is limited. For example, the D1.5-d1.5 configuration had a measured axial modulus of approximately 79.69 MPa, compared with an RVE prediction of approximately 30 MPa for similar geometric parameters. The measured value was therefore approximately 2.7 times the RVE prediction. This discrepancy represents an important limitation of the current numerical analysis and indicates that the RVE model should not be used to quantitatively predict the stiffness of the finite bearing prototypes without further calibration.

The discrepancy is likely influenced by differences between the idealized RVE boundary conditions and the physical constraints of the experimental specimens. The RVE analysis represents an unconfined, infinitely periodic lattice, while the experimental specimens were finite composite blocks bonded to rigid top and bottom plates. These plates restrained lateral expansion of the nearly incompressible elastomer and introduced confinement and shape factor effects that were not represented in the RVE model. The specimen boundaries, lattice to elastomer interaction, plate geometry, interface conditions, and nonlinear elastomer behavior may also have contributed to the difference. Therefore, the RVE analysis should be interpreted primarily as a design space exploration tool that identified qualitative relationships between lattice geometry and effective properties, rather than as a calibrated model of the tested specimens.

A calibrated finite element model incorporating the complete specimen geometry, rigid bounding plates, lattice to elastomer interfaces, experimentally characterized elastomer

behavior, and the actual loading and boundary conditions is needed for quantitative comparison with the experiments. Such a model would help separate the contributions of lattice geometry, elastomer confinement, shape factor, and interface behavior to the measured composite response.

Following the elastic characterization, the specimens were subjected to cyclic shear loading at progressively increasing displacements to evaluate their nonlinear hysteresis, stiffness evolution, and, where reached, failure mechanisms. The cyclic loading was governed by a strictly constant displacement rate at 5mm/min, utilizing a time-history profile where the structural displacement progressively and symmetrically increased in amplitude over time (Figure 3.7). The actuator cycled the specimens through progressively increasing positive and negative displacement amplitudes until either specimen failure occurred or the required force reached the capacity of the testing frame. For the D1-d1 and D3-d1 configurations tested to failure, the observed failure mode was macroscopic debonding at the interface between the internal composite volume and the rigid external bounding plates. However, for the bearing configuration designated as D1.5-d1.5, the cyclic shear testing protocol was abruptly terminated prior to interfacial debonding because the forces required to displace the specimen exceeded the maximum load capacity of the testing frame.

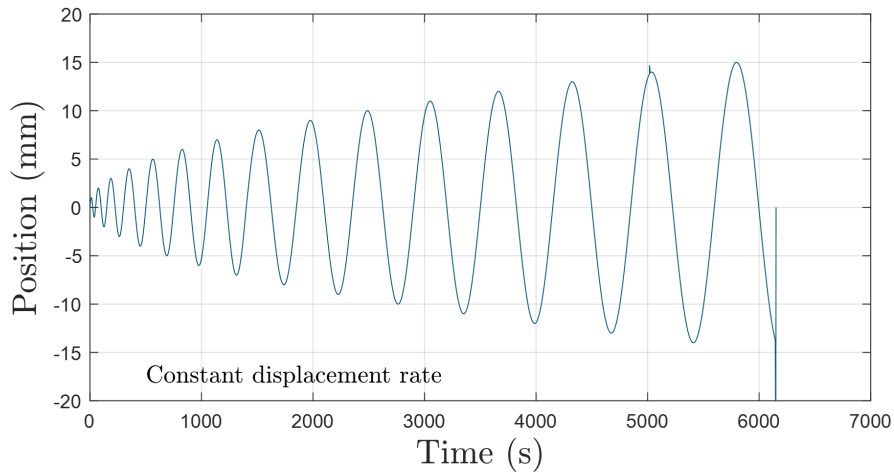


Figure 3.7: Loading protocol used in the cyclic shear loading of the composite bridge bearing specimens.

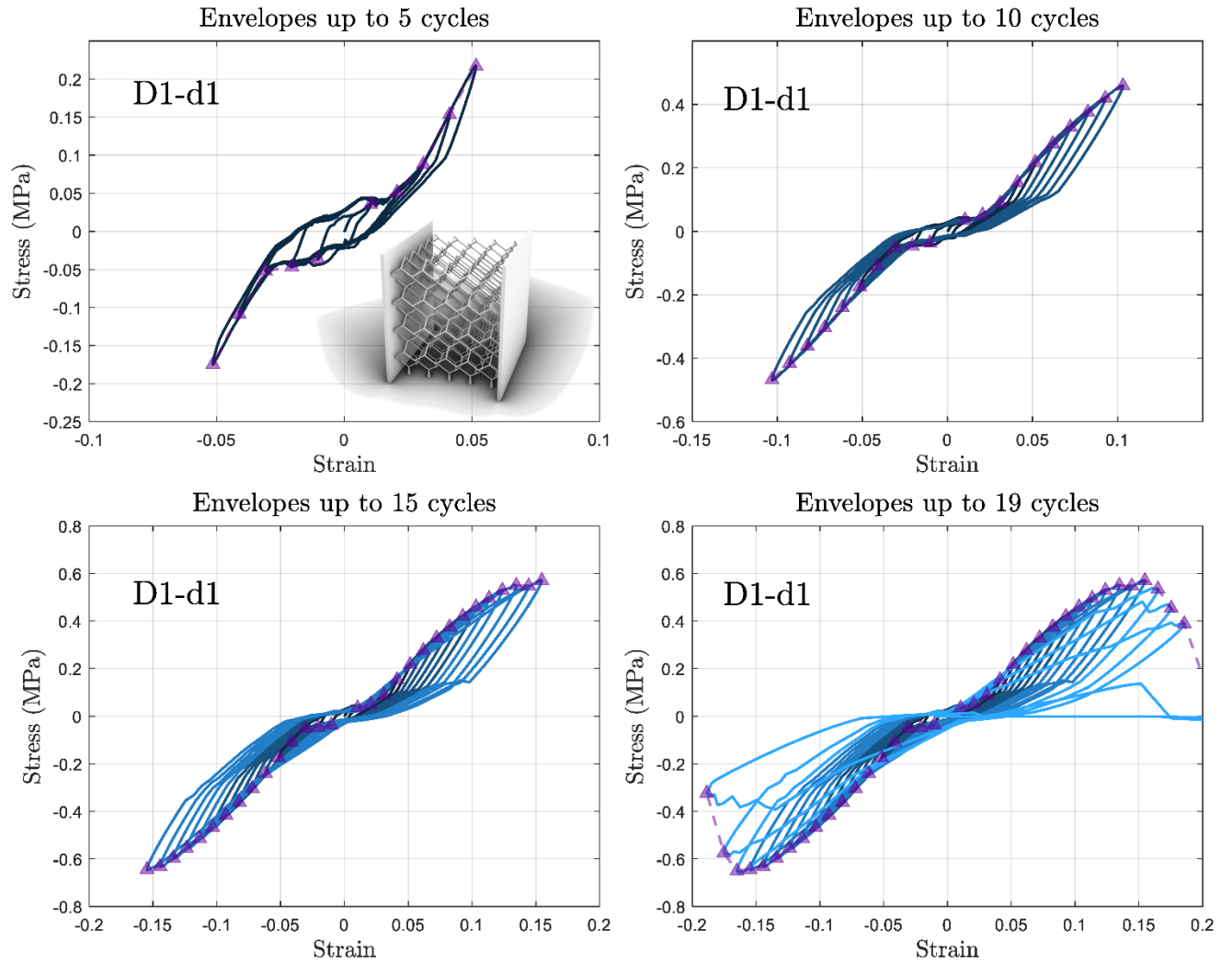


Figure 3.9: Cyclic shear loading of the D1-d1 composite bridge bearing at large displacement until failure.

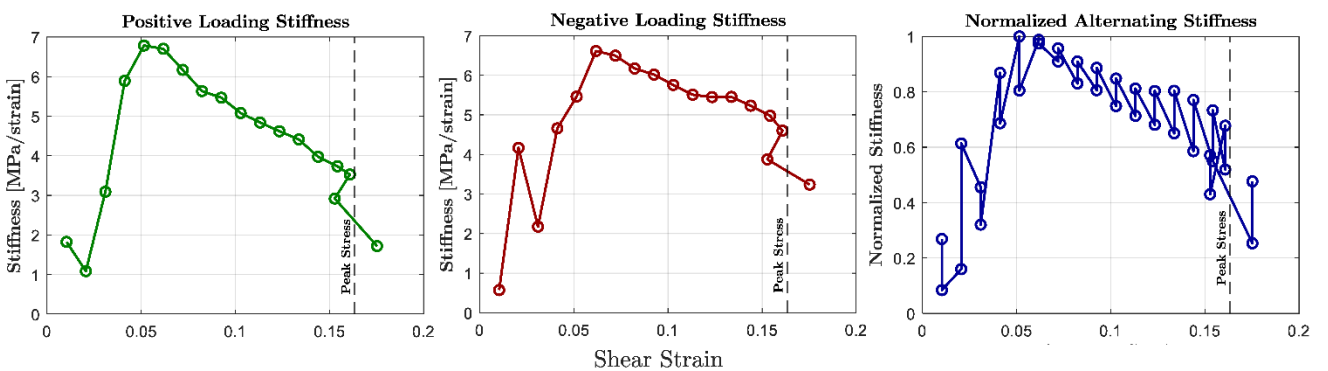


Figure 3.10: Progressive stiffness deterioration during the cyclic shear loading of the D1-d1 specimen.

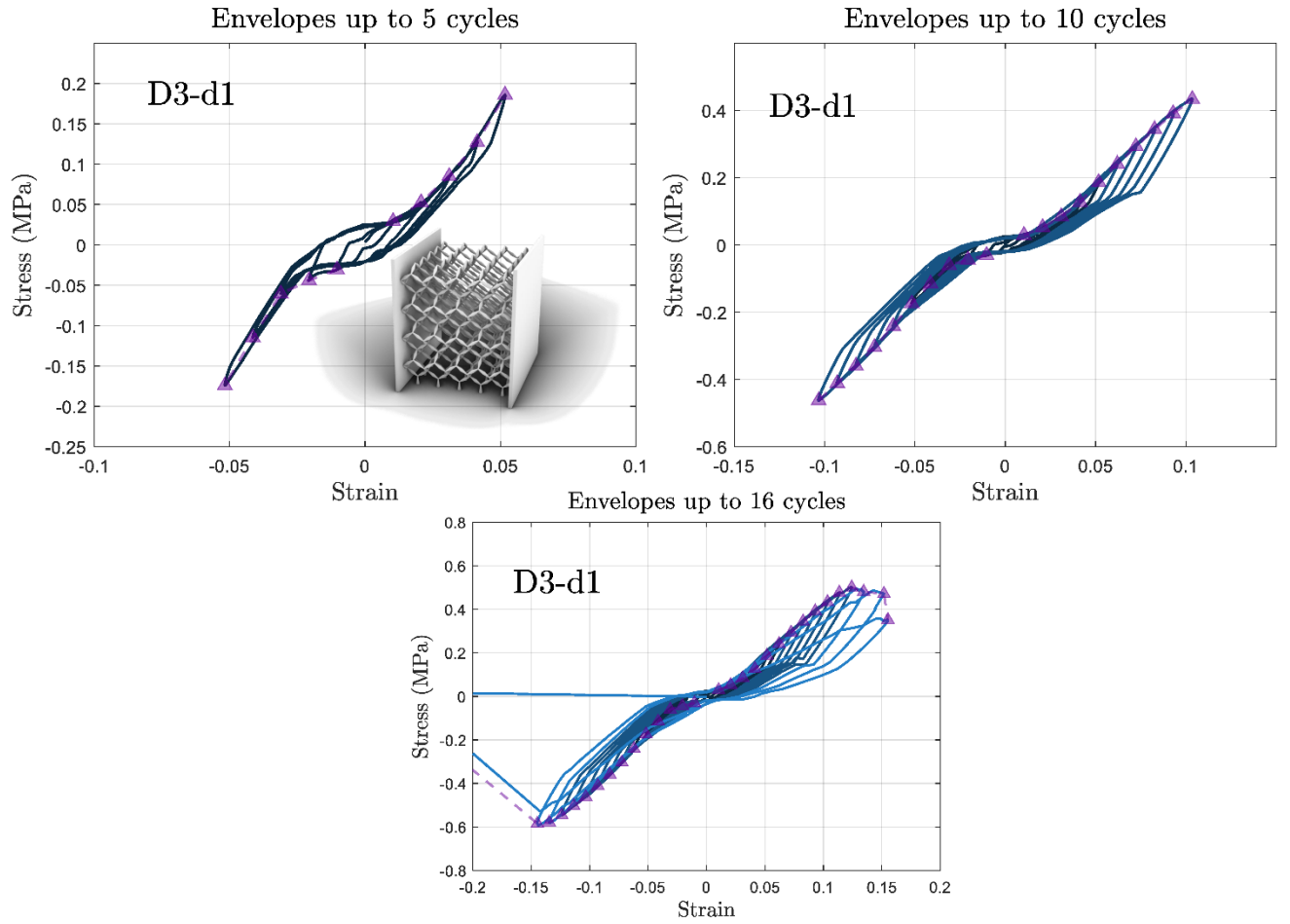


Figure 3.11: Cyclic shear loading of the D3-d1 composite bridge bearing at large displacement until failure.

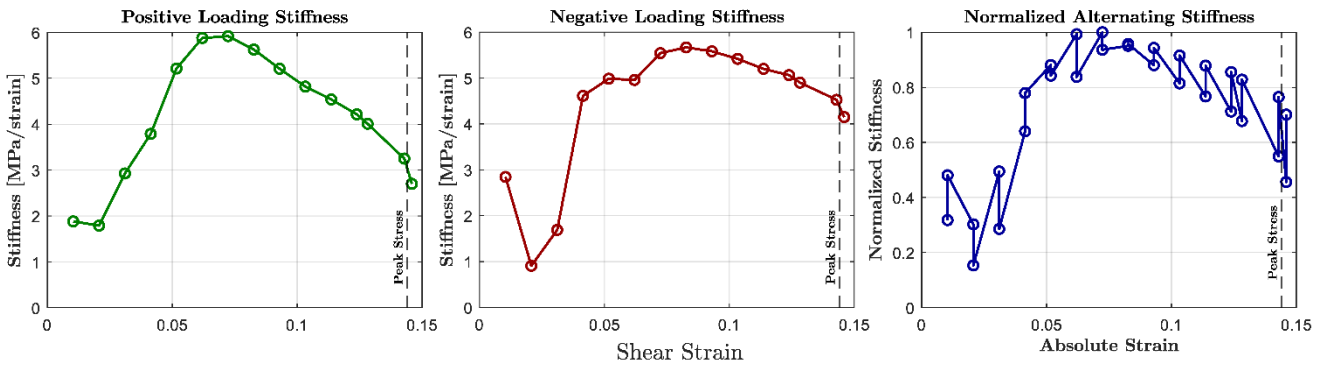


Figure 3.12: Progressive stiffness deterioration during the cyclic shear loading of the D3-d1 specimen.

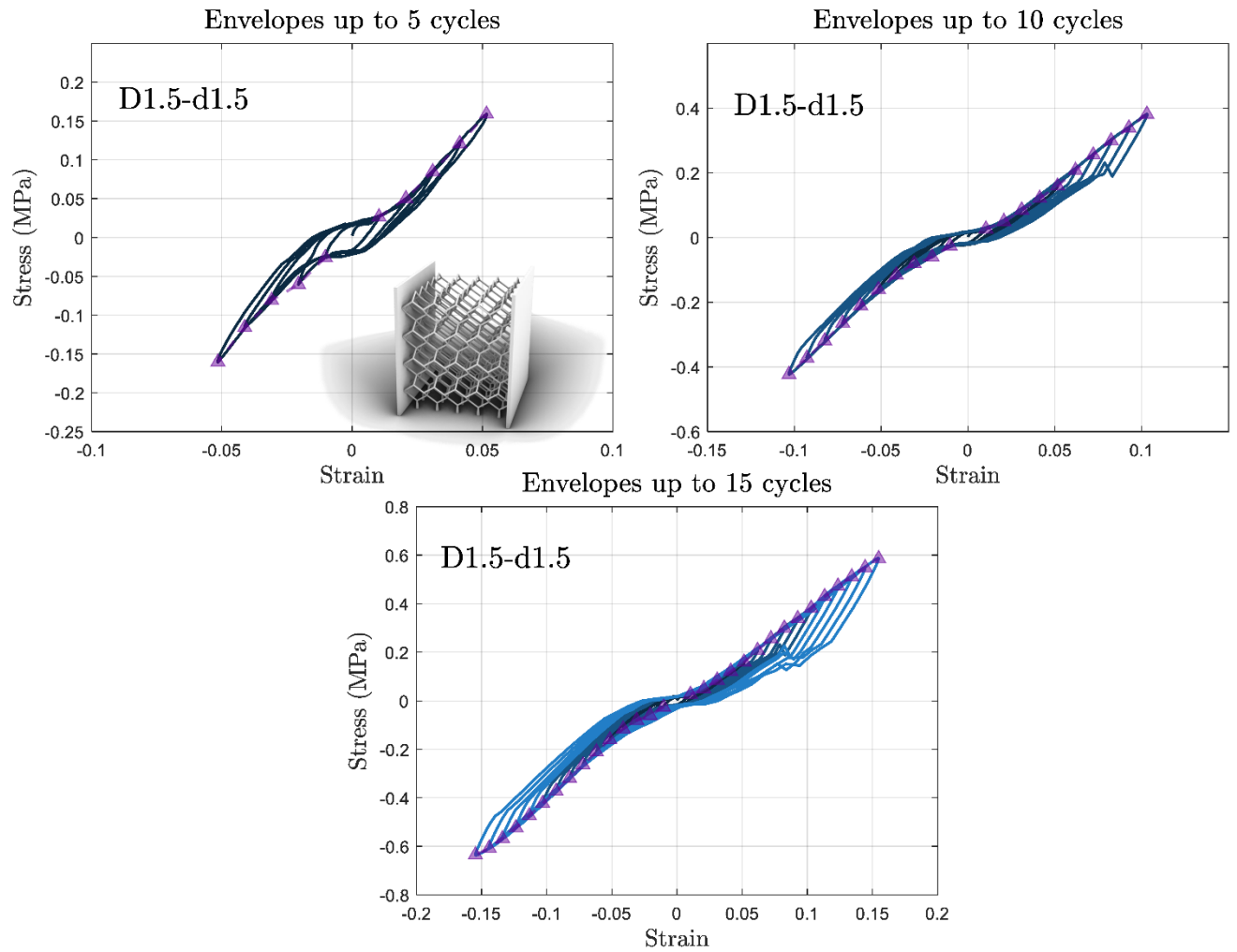


Figure 3.13: Cyclic shear response of the D1.5-d1.5 composite bearing within the tested displacement range. Testing was terminated when the required force reached the capacity of the testing frame, before specimen failure.

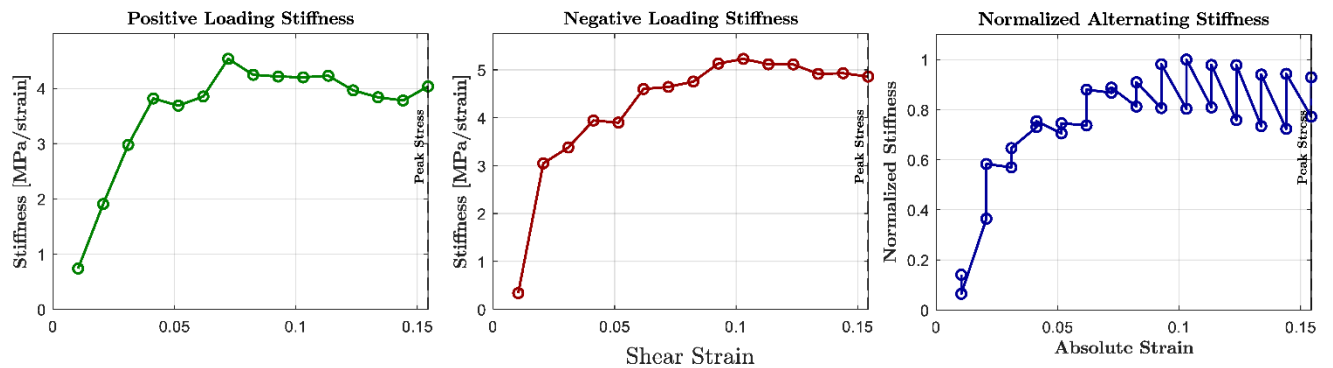


Figure 3.14: Stiffness evolution of the D1.5-d1.5 specimen within the tested range. Testing was terminated when the required force reached the capacity of the testing frame, before specimen failure.

Following the non-destructive characterization, the specimens were subjected to progressively increasing cyclic shear displacements to characterize their nonlinear hysteresis, stiffness evolution, and, where reached, failure mechanisms.

For the highly flexible D1-d1 configuration, the composite bearing successfully withstood up to 19 loading cycles prior to catastrophic interfacial debonding between the composite volume and the rigid bounding plates. The structural deterioration profile indicated a rapid initial increase in the positive loading stiffness, peaking at approximately 6.8 MPa/strain, followed by a severe, monotonic degradation down to roughly 2.0 MPa/strain at peak stress. The resulting hysteresis envelopes demonstrated substantial energy dissipation but an accelerated rate of stiffness degradation highly correlated with the bulk steel's yield curve, likely due to the higher internal stress concentrations transferred by the stiffer internal lattice to the bounding plate interface. Eventually, the interfacial surface fails due to the tensile stresses induced on the interface, as a resultant of the significant coupling of the pentamode phase properties to the properties of the bulk material. Functional grading at the plate/lattice interface could help resolve this issue.

The D3-d1 configuration, featuring much thicker primary struts, reached macroscopic failure after 16 cycles under the progressively increasing displacement protocol. Its positive loading stiffness peaked at approximately 6.0 MPa/strain before deteriorating to roughly 3.0 MPa/strain near ultimate failure.

Conversely, the D1.5-d1.5 configuration presented a markedly different structural response under large deformations. The test was abruptly terminated after 15 cycles prior to the specimen achieving ultimate failure or interfacial debonding, strictly because the reaction forces required to impose further shear displacements exceeded the maximum load capacity of the mechanical testing frame. Within the tested range, the positive loading stiffness reached approximately 4.5 MPa/strain and subsequently remained between approximately 3.8 and 4.0 MPa/strain up to test termination. These results indicate that the D1.5-d1.5 configuration exhibited comparatively stable stiffness within the range evaluated. Because the specimen did not reach failure, its ultimate capacity, failure strain, and performance under additional loading cycles were not established. The available results therefore do not support a definitive comparison of its ultimate or fatigue performance with the other configurations.

For the configurations tested to failure, the observed large strain response suggests that the tensile elongation capacity of the steel pentamode phase may limit the lateral deformation capacity of the composite. Because the D1.5-d1.5 specimen did not reach failure, this behavior could not be confirmed for that configuration. This represents a potential limitation that should be investigated through additional testing.

Decoupling of the large strain behavior from the bulk material's elongation at fracture remains an open research question that could hypothetically be achieved by further exploration of various interfacial configurations of the pentamode phase. Ultimately delocalizing structural damage at large strains could be achieved by the adoption of separated layers of the pentamode phase inside the composite or creation of internal lattice interfaces that could act as fuses.

In summary, the experimental results indicate that the embedded stainless steel lattice influenced the measured stiffness evolution, yielding response, and observed failure behavior of the tested composite prototypes, even at relative densities below 3 percent. The results also suggest that strut tapering had a less pronounced influence on the measured large strain response

than anticipated from the small strain RVE analysis. These observations are limited to the tested configurations and loading ranges and should not be interpreted as establishing ultimate, fatigue, or in service performance.

3.3 Study Limitations

This study was conducted as a laboratory scale proof of concept to evaluate the feasibility of fabricating and mechanically testing elastomeric composite bearings reinforced with additively manufactured pentamode lattices. The results demonstrate that changes in lattice geometry can influence the measured axial and shear response of the prototype specimens. Several limitations, however, should be considered when interpreting the findings and assessing their applicability to bridge bearing systems.

The cyclic shear testing apparatus could not apply a sustained vertical compressive load while imposing horizontal displacement. In service, bridge bearings experience shear deformation while supporting the gravity load of the superstructure. The absence of simultaneous compression may affect the measured shear stiffness, hysteretic response, interface behavior, and failure mechanisms. Consequently, the cyclic shear results should not be interpreted as representative of the behavior of these bearings under actual bridge loading conditions.

The experimental program was also limited to small scale prototypes, a limited number of specimens, and three lattice configurations. The dimensions, fabrication process, and boundary conditions of these specimens were selected to support an initial feasibility evaluation and do not represent a full scale bearing design. In addition, the capacity of the testing frame limited the range over which the D1.5 d1.5 specimen could be evaluated. Testing was terminated when the required force reached the capacity of the frame, before failure of the specimen. Therefore, the ultimate capacity, failure strain, and comparative fatigue performance of this configuration were not established.

PMC 790 was selected primarily because its low viscosity and room temperature casting characteristics enabled reliable encapsulation of the complex lattice geometry during prototype fabrication. Its Shore A hardness of 90 is substantially greater than the hardness commonly used for conventional bridge bearing elastomers. The measured response of these prototypes therefore should not be interpreted as demonstrating equivalence to elastomers currently specified for MassDOT bridge bearings.

Finally, the study did not include long duration fatigue testing, environmental conditioning, corrosion exposure, thermal aging, creep, relaxation, full scale testing, or field testing. The investigation also did not directly evaluate seismic isolation performance, uplift resistance, durability, constructability at production scale, or lifecycle cost. These topics require additional experimental and analytical investigation before the proposed bearing concept can be evaluated for implementation on bridge structures.

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4.0 Conclusions

4.1 Key findings of this work

This study established the laboratory feasibility of fabricating elastomeric composite bearing prototypes reinforced with additively manufactured stainless steel pentamode lattices. The findings represent proof of concept and do not establish that the tested prototypes are suitable for deployment on MassDOT bridge structures.

First, the fabrication process successfully integrated laser powder bed fused lattice structures with a cast polyurethane matrix and rigid external plates. This demonstrates the manufacturability of the proposed composite concept at the prototype scale.

Second, within the small strain range evaluated, changes in lattice geometry produced substantial differences in measured axial stiffness while the measured shear stiffness varied within a comparatively narrower range. This provides initial evidence that architected reinforcement may offer a means of influencing the axial and shear response of elastomeric composite systems through geometric design.

Third, the progressively increasing cyclic shear tests demonstrated that lattice geometry and interface behavior influenced the measured hysteretic response and stiffness evolution. The D1-d1 and D3-d1 configurations ultimately experienced interfacial debonding. The D1.5-d1.5 configuration exhibited comparatively stable stiffness within the tested range, but its test was terminated when the required force reached the capacity of the testing frame. Its ultimate capacity, failure strain, and comparative fatigue performance were therefore not established.

The study did not directly evaluate performance as either a conventional bridge bearing or a seismic isolation bearing. It also did not directly evaluate uplift resistance, sustained gravity load combined with shear, seismic energy dissipation, fatigue resistance, environmental durability, corrosion resistance, aging, or lifecycle cost. Accordingly, no conclusions regarding these performance characteristics or advantages over conventional bearings can be drawn from the current testing program.

The proposed concept is not intended to represent a single bearing design that could be used interchangeably as both a conventional bridge bearing and a seismic isolation bearing. Rather, it is an architected composite platform whose lattice geometry, elastomer, dimensions, and connection details could potentially be tailored for different bearing applications. Conventional bridge bearings and seismic isolation bearings have different stiffness, displacement, damping, strength, and qualification requirements. The prototypes evaluated in this study were not designed or tested to demonstrate compliance with either system. Additional application specific design and testing would therefore be required to determine whether future configurations could be developed for conventional bearing applications, seismic isolation applications, or both.

Further research is required to determine whether the observed geometric tunability can be translated into a full scale bearing that satisfies applicable material, strength, movement, fatigue, durability, constructability, and economic requirements.

4.2 Steps towards future implementation

This preliminary study was limited to understanding the stress states developed in small scale bearing prototypes, pertaining to the fundamental mechanics that govern their behavior. To advance the practical implementation of pentamode mechanical metamaterials and composite elastomeric bearing systems, several research and developmental steps must be undertaken. These future initiatives encompass advancements in computational modeling, material optimization, experimental validation, and damage characterization.

1. *Further Analytical and Computational Modeling* - The RVE models used in this study were developed for preliminary design space exploration and were not calibrated to reproduce the response of the finite experimental specimens. Future work should develop and calibrate a finite element model that incorporates the complete specimen geometry, rigid bounding plates, lattice to elastomer interface conditions, experimentally characterized nonlinear elastomer behavior, and the actual experimental loading and boundary conditions. This model would support a more rigorous evaluation of confinement, shape factor, interface behavior, and geometrically nonlinear response under combined compression and shear loading.
2. *Experimental Validation and Dynamic Testing* - While numerical models have provided substantial insights, the fabrication and rigorous laboratory testing of a larger volume of real-scale physical models of pentamode composite bearing prototypes are required. The addition of a vertical load during these experiments could be beneficial for the extensive understanding of their on-site behavior. Further vibration/damping analysis would be mandatory to understand the equivalence of these materials to the existing conventional bearings. These full-scale models, manufactured via advanced additive techniques, must be subjected to dynamic/fatigue loading. Pilot testing these materials in real operating conditions and under the environmental exposure of a bridge would facilitate the next step towards making them feasibly available for construction. These large-scale studies will advance a prescriptive design methodology for novel bearings that can be easily adopted in state codes and standards without the need of advanced numerical analysis and simulations. Furthermore, a comprehensive study of their corrosion and aging characteristics is necessary.
3. *Financial and Manufacturing Feasibility Study* - Additive manufacturing may offer time savings during the design and prototyping of customized bearings by allowing lattice geometries to be modified digitally and fabricated without developing unique tooling for each internal reinforcement configuration. This approach could also support the production of application specific bearing geometries and reduce the number of separate reinforcement components that require assembly. However, laser powder bed fusion currently involves substantial material, equipment, postprocessing, inspection, and quality control costs. The present study did not compare fabrication time, production cost, installation cost, or lifecycle cost with those of conventional bearings. A detailed manufacturing and economic study is therefore required to determine whether the potential time savings/design flexibility can produce a cost-effective solution at full scale.

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