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16. Abstract

This research developed and validated a novel approach for creating high-performance roadside barriers by integrating bio-inspired Bouligand and sinusoidal Bouligand architectures with large-scale 3D concrete printing, demonstrating that these strategically designed structures achieve a 13.5% increase in compressive strength and a 35% increase in energy absorption compared to conventional concrete. The project successfully established a complete digital fabrication workflow for robotic manufacturing and a correlated testing framework, concluding that this methodology produces a superior, damage-tolerant material suitable for next-generation transportation infrastructure; the results can be immediately used by transportation agencies and precast manufacturers to initiate pilot-scale deployments and guide the development of advanced barrier systems that offer enhanced safety through improved impact resistance.

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Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

BBio-Inspired Solutions for Jersey and Road Noise Barriers: Exploring 3D Printing as Alternative Precast Technology
PU-23-RP-03 & PU-24-RP-03

FINAL REPORT

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Executive Summary:

This two-year research project successfully developed a novel and transformative approach for creating next-generation roadside barriers by synergistically integrating 3D concrete printing technology with bio-inspired architectural designs. The work addresses both critical traffic safety and noise mitigation challenges. Specifically, it targets emerging safety concerns such as reducing vehicle collision impact and enhancing roadside protection, while simultaneously providing effective acoustic insulation. The project has systematically progressed from delivering a foundational scientific proof-of-concept to establishing a robust engineering pathway for the scalable and commercially viable fabrication of these advanced barrier systems.

Year One (Phase I): Foundational Proof of Concept and Material Performance Breakthroughs
The initial phase of the project was dedicated to establishing a fundamental proof of concept at the laboratory scale. The research demonstrated that specific bio-inspired architectures, namely the Bouligand and sinusoidal helicoidal structures found in the dactyl club of the mantis shrimp, could be effectively translated into 3D-printed concrete, resulting in unprecedented mechanical performance. A key achievement was the validation of these designs under rigorous mechanical testing. Under dynamic impact conditions, the bio-inspired samples exceeded the peak load of traditional cast samples by up to ~70% and surpassed their absorbed impact energy by over 54%, showcasing a strong ability to prevent catastrophic failure and maintain structural integrity. Furthermore, under quasi-static compression, the sinusoidal helicoidal architecture exhibited ~54% increase in strength compared to regular 3D-printed samples and was ~14% stronger than conventional cast concrete. The project also pioneered a multi-material printing system, successfully fabricating hybrid cement-silicone composites that mimic nature's hard-soft interfaces to enhance energy dissipation and ductility. Concurrently, a prototype for a reconfigurable acoustic barrier was developed, demonstrating the potential for adaptive traffic noise mitigation, and a sustainable, low-carbon cementitious mixture was formulated for cost-effective 3D printing. In summary, data collected during Phase I of the project provided clear scientific validation by explaining the fundamental reasons behind the superior mechanical performance of bio-inspired, architected materials compared with conventional isotropic concrete designs.

Year Two (Phase II): Engineering for Scalability and Commercialization Pathway
Building upon the demonstrated success of Phase I, the focus in the second year shifted to the critical engineering challenges of scaling the technology for real-world application. The objective was to bridge the gap between laboratory-scale innovation and the practical fabrication of full-sized roadside barrier prototypes. A significant accomplishment of Phase II was the development of an advanced computational workflow using Grasshopper to generate complex, multi-axis, and non-planar toolpaths, enabling the precise robotic fabrication of sinusoidal Bouligand architectures on a large-scale ABB IRB6700 robotic arm. This was complemented by in-depth research and development efforts aimed at the printing process itself, including the initial design phase for a specialized, shape-conforming multi-outlet nozzle and a comprehensive study of critical printing parameters such as nozzle size, extrusion velocity, and layer deposition strategies to ensure quality and structural integrity at a larger scale.

Building upon these advances, the team expanded its focus to the practical implementation of these architectures in both safety and noise barrier systems, examining how the developed fabrication techniques could be adapted for large-scale, field-ready applications. Research also continued into material optimization, particularly investigating the use of longer fibers and their compatibility with large-scale extrusion systems. A pivotal outcome of Phase II has been the establishment of a clear pathway to commercialization. This is underscored by the filing of four provisional patent applications protecting the core innovations and the active engagement with the Purdue Office of Technology Commercialization to develop strategies for industry partnership and technology licensing. By Nov. 2025, the team has met with 5 pre-cast and construction companies interested in this technology and continues engaging with them. In essence, Phase II effectively addressed the 'how', creating the essential manufacturing methodologies and intellectual property foundation required to translate these groundbreaking innovations from the laboratory to the field, paving the way for the final development and commercialization of safer and more resilient transportation infrastructure.

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1. Problem description:

The continuous evolution of the vehicle fleet, including the increasing prevalence of heavier passenger trucks and commercial vehicles, presents a persistent challenge to the safety and resilience of the nation's transportation infrastructure. These heavier vehicles generate significantly higher impact forces during collisions. Existing safety barrier systems, often optimized for historical vehicle weights, may struggle to safely contain modern vehicles, posing risks to motorists and infrastructure [1, 2]. This highlights a crucial need for next-generation barrier designs with improved energy absorption and impact resistance to ensure public safety amid evolving transportation demands.

At the same time, the transformation of traffic patterns and vehicle mix affects not only safety performance but also acoustic environments along transportation corridors. Conventional noise barriers are passive structures, unable to adapt to the varying frequency spectra of traffic noise, which fluctuates with vehicle type, speed, and density [3]. Their static design limits their effectiveness and often introduces issues like visual intrusion and airflow blockage.

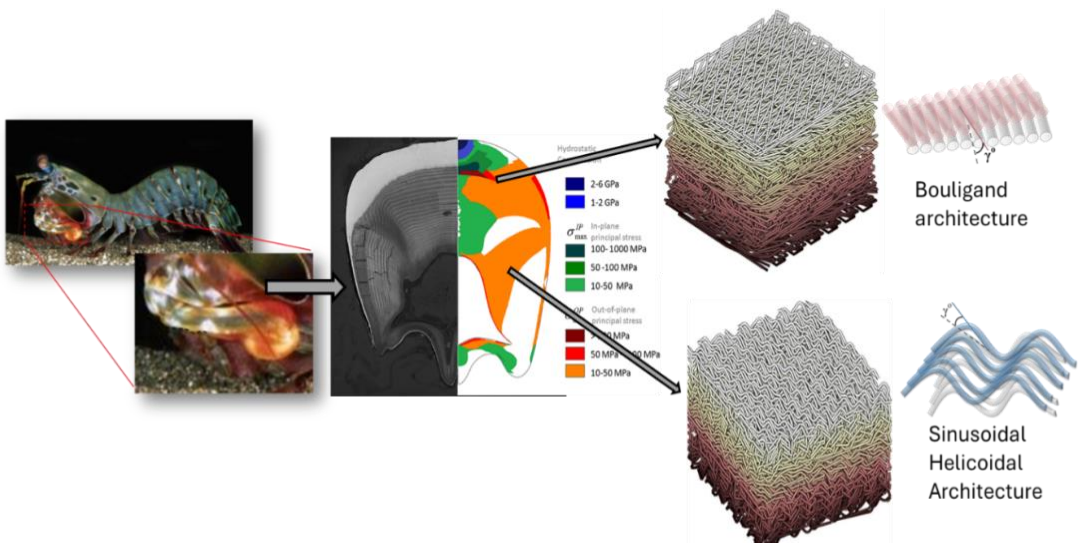


Figure 1 Architected material design with Bouligand architecture and sinusoidal helicoidal architecture inspired by the dactyl club of mantis shrimp

Therefore, there is an urgent and twofold need for innovative roadside solutions that enhance both safety and acoustic performance. This research addresses these challenges by leveraging advanced manufacturing and bio-inspired design to develop a new paradigm for safer and smarter transportation infrastructure. We propose the use of 3D printing to fabricate concrete elements with internal bio-inspired architectures, such as Bouligand and sinusoidal helicoidal structures (Fig. 1), to dramatically enhance mechanical performance [4, 5]. Furthermore, we investigate the development of reconfigurable acoustic metamaterials for adaptive noise mitigation in traffic.

2. Background (including literature review):

2.1 Introduction: The Challenge of Evolving Infrastructure Demands

Transportation infrastructure is a critical component of economic vitality and public safety. A key element of this infrastructure is the roadside safety barrier, designed to prevent errant vehicles from leaving the roadway and to protect workers and critical assets. However, the static nature of this infrastructure often struggles to adapt to dynamic changes in the vehicle fleet and environmental conditions. This research is situated at the intersection of these challenges, aiming to leverage technological advancements in additive manufacturing and material science to create a new generation of adaptive, high-performance transportation infrastructure components.

2.2 The Performance Gap in Current Roadside Safety Systems

Roadside barriers are traditionally categorized as flexible, semi-rigid, or rigid, based on their deflection upon impact. While flexible systems (e.g., cable and W-beam barriers) dissipate energy through large deformations, they can be unsuitable for high-impact scenarios or sites with limited space. Rigid barriers, such as concrete Jersey barriers, are favored in these high-severity locations due to their strength and minimal deflection. However, their inherent stiffness can lead to high deceleration forces on occupants and insufficient energy absorption, which can sometimes result in vehicle rollover or severe barrier damage [7, 8].

The core of the problem lies in the material and manufacturing limitations of conventional concrete barriers. Cast-in-place concrete is an isotropic material, meaning its properties are uniform in all directions. When impacted, it tends to fail in a brittle manner, with cracks propagating rapidly through the material, leading to catastrophic failure. This is exacerbated by the fact that traditional manufacturing methods cannot easily produce complex internal geometries that could control crack propagation and enhance energy dissipation. As noted by transportation authorities and state DOT engineers, the potential need to replace "thousands of miles" of barriers underscores the scale of the performance gap that exists [9, 10].

Additionally, extending concrete barrier technology to higher containment levels and heavier vehicle categories (for example, applications that today rely on steel or proprietary systems) delivers tangible benefits: lower capital cost per meter through use of concrete (a commodity material) and established precast supply chains; reduced maintenance and replacement frequency due to damage-tolerant, high-toughness behavior; shorter deployment timelines using existing plant capacity; and improved lifecycle sustainability by minimizing steel content and enabling repairable or replaceable architected modules. In practice, expanding the feasible envelope for concrete barriers enables agencies to standardize on a cost-effective, domestically sourced solution for a broader range of impact scenarios, while maintaining or improving safety performance.

2.3 The Limitations of Conventional Noise Mitigation Solutions

While the increasing size and weight of vehicles raise critical safety challenges for roadside infrastructure, traffic noise poses a parallel environmental challenge, contributing to widespread health and community impacts. Traditional noise barriers are typically heavy, solid-wall structures. Their primary limitations include:

- **Static Design:** They are designed for a specific, average noise spectrum and cannot adapt to temporal variations in traffic flow, vehicle type, and corresponding noise frequency.
- **Diffraction:** Sound waves easily diffract over the top of these barriers, reducing their effectiveness, especially for low-frequency noise.
- **Structural Footprint:** Their weight and wind-load requirements lead to massive foundations, and they block light and airflow, impacting surrounding areas.
- **Negative Economic Impact:** The persistent and intrusive nature of traffic noise pollution contributes to a reduction in property values for adjacent residential and commercial areas. This "nuisance effect" creates an economic disincentive for development near transportation corridors and represents a significant externality cost that is seldom mitigated by conventional, passive barrier systems.

There is a clear need for lighter, smarter, and more adaptive noise barrier systems that can provide targeted mitigation across a broader frequency range, thereby also helping to preserve the economic vitality and land value of communities surrounding transportation infrastructure.

2.4 Additive Manufacturing in Construction: A Paradigm Shift

Additive manufacturing, also known as 3D printing, represents a paradigm shift in construction. For concrete (3D Concrete Printing - 3DCP), it involves the layer-by-layer deposition of a cementitious material without the use of formwork. The key advantages relevant to this project are:

- **Geometric Freedom:** 3DCP enables the fabrication of complex, non-standard geometries that are either impossible or prohibitively expensive using traditional casting methods. This allows for the creation of internal "architected" material designs.
- **Functional Gradation:** It facilitates the printing of multiple materials within a single component, enabling the creation of composite structures with tailored properties.
- **Digital Workflow:** The process is driven by digital models, allowing for rapid prototyping, customization, and optimization of designs.

However, the transition from printing simple architectural elements to load-bearing, high-performance infrastructure components requires significant research into material mixtures, printing parameters, and the fundamental mechanical behavior of printed structures [11, 12].

2.5 Bio-Inspiration: Learning from Nature's Designs

Nature has evolved sophisticated material architectures that offer exceptional combinations of strength, toughness, and damage tolerance. A prime example is the dactyl club of the mantis shrimp, a predatory appendage that can withstand repeated high-velocity impacts on hard-shelled prey.

Research has revealed that its exceptional performance stems from two key architectural motifs [13, 14]:

- Bouligand Structure: A helicoidal arrangement of chitinous fibers, which forces propagating cracks to twist and turn, thereby dissipating energy and preventing catastrophic failure.
- Sinusoidal Helicoidal Architecture: A further refinement where the layers themselves have a wavy, sinusoidal pattern, which enhances energy dissipation through a more complex crack-twisting mechanism.

These biological composites effectively use interfaces and anisotropy (direction-dependent properties) to their advantage, a stark contrast to the isotropic, monolithic nature of traditional concrete. Figure 2 illustrates these bio-inspired architectures.

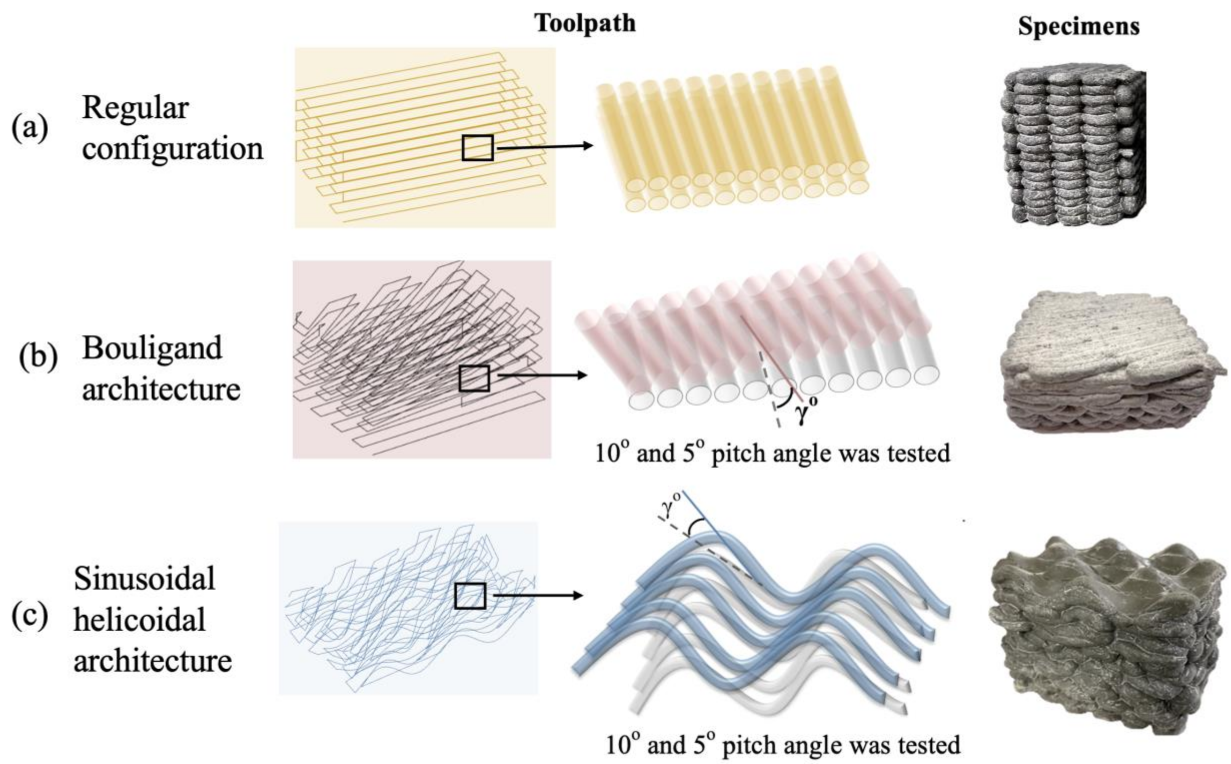


Figure 2 Bio-inspired architected material designs: (a) Regular configuration (b) Bouligand structure and (c) Sinusoidal Helicoidal architecture, inspired by the dactyl club of the mantis shrimp [13, 14].

2.6 Acoustic Metamaterials for Noise Control

Acoustic metamaterials are engineered materials designed to control, direct, and manipulate sound waves in ways not possible with conventional materials. A prominent type is the phononic crystal, a periodic structure that creates "band gaps" specific frequency ranges within which sound waves cannot propagate [15].

The innovation proposed in this project is the integration of phononic crystals with Phase-Transforming Cellular Materials (PXCMs). PXCMs are bistable structures that can snap between different configurations, providing a means of actuation [16]. This combination enables a reconfigurable acoustic barrier, where the spacing and arrangement of the phononic crystals can be dynamically adjusted to shift the bandgap and target specific traffic noise frequencies as needed. Figure 3 shows a schematic of this concept.

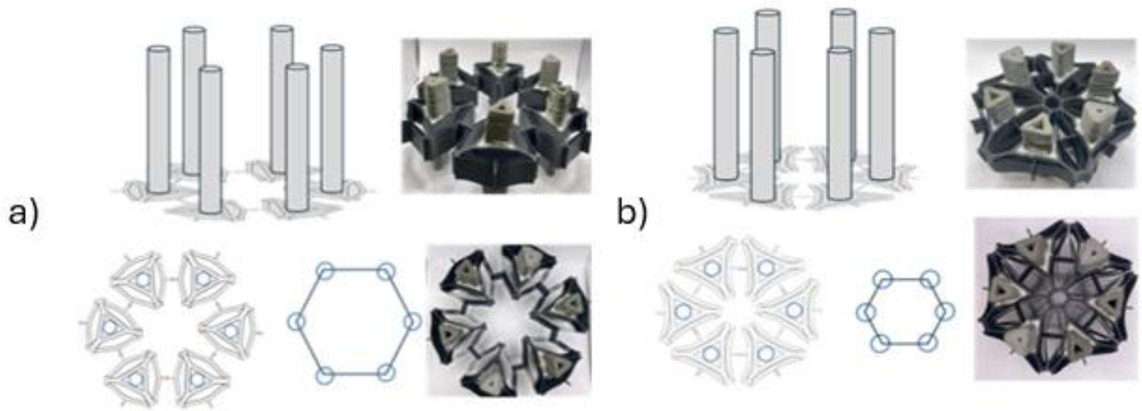


Figure 3 Reconfigurable acoustic barrier concept: (a) Barrier integrated with PXCMs in "open" and (b) "closed" configurations, enabling dynamic noise mitigation [15, 16].

2.7 Identified Research Gaps

Based on the literature, the following critical research gaps were identified, which this project directly addresses:

1. Lack of High-Performance Architectures for 3DCP: While 3DCP provides geometric freedom, there was a gap in systematically designing and validating internal architectures that could transform the inherent anisotropic and interfacial weaknesses of 3D-printed concrete into a performance advantage for impact-loaded structures.

2. Scalability of Complex Geometries: The challenge of moving from small-scale laboratory prototypes of bio-inspired architectures to large-scale, structurally viable components suitable for infrastructure had not been sufficiently explored, particularly in terms of toolpath generation and printer hardware adaptation.

3. Multi-Material Functional Composites: The potential of 3D printing to integrate soft, energy-absorbing polymers with rigid cementitious matrices to create nature-inspired hard-soft composites for infrastructure was largely untapped.

4. Dynamic and Adaptive Infrastructure: The concept of reconfigurable, multi-functional barriers that can provide both impact safety and adaptive noise mitigation was a novel and unexplored frontier in transportation infrastructure design.

This research was conceived to bridge these gaps by developing an integrated methodology that combines bio-inspired design, multi-material 3D printing, and acoustic metamaterials to create a new class of roadside barriers.

3. Research scope and objectives:

This research project addresses critical challenges in transportation infrastructure safety by proposing a paradigm shift in barrier design and manufacturing through the synergistic integration of **bio-inspired architected materials** with **large-scale 3D concrete printing (3DCP)** technology.

The core innovation lies in moving beyond the homogeneous material properties of traditional precast concrete. We proposed to deliberately architect the internal microstructure of concrete barriers using nature's principles, specifically the *Bouligand* and *sinusoidal Bouligand* structures found in the dactyl club of the mantis shrimp [17, 18]. These architectures are renowned for their exceptional toughness and impact resistance, achieved through intricate, weak interfaces that promote crack twisting and energy dissipation, preventing catastrophic failure [19, 20]. The project's overarching goal was to translate these biological design principles into full-scale, functional roadside barriers using additive manufacturing, thereby creating a new class of energy-absorbing, damage-tolerant infrastructure components.

The research objectives were structured into two sequential phases:

- **Phase I (Completed 2024): Proof-of-Concept at Laboratory Scale.** The primary objective was to validate the fundamental hypothesis that bio-inspired architectures could significantly enhance the mechanical performance of 3D-printed concrete. This involved:
    1. Designing and fabricating small-scale specimens with Bouligand and sinusoidal Bouligand architectures.
    2. Developing a sustainable, cost-effective cementitious mixture suitable for 3D printing.
    3. Quantifying the enhancement in compressive strength, work-of-failure, and impact resistance compared to traditional cast and regularly printed concrete.

- **Phase II (2025): Scaling and Technology Translation.** Building on the success of Phase I, the objectives shifted towards practical implementation and commercialization pathway development:
    1. **Scale-Up Fabrication:** Adapt the 3DCP process for the Large-Scale Robotic Arm (LSRA) to fabricate prototypes of relevant dimensions. This included developing complex, non-planar toolpaths (Fig. 4a) and designing a robust multi-nozzle extrusion system (Fig. 4b) for efficient deposition [21, 22].

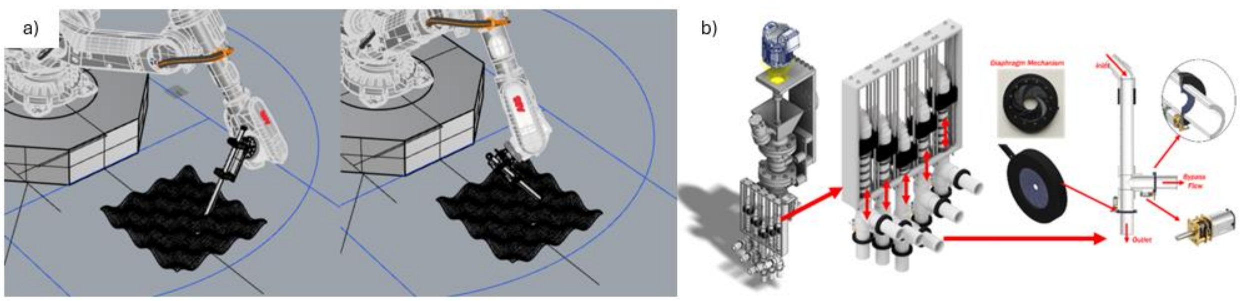


Figure 4 Advanced Toolpath and Nozzle System Development for Large-Scale Robotic Printing. (a) Toolpath generated in Rhino illustrating continuous, connected filament trajectories for sinusoidal geometries. (b) Conceptual CAD design of the multi-nozzle extrusion manifold with integrated flow control, designed for the LSRA system.

2. **Process Optimization:** Systematically study large-scale printing parameters, including nozzle height, printing direction, and fiber reinforcement, to achieve high-quality, consistent deposition on inclined and complex surfaces (Fig. 5) [23-25].

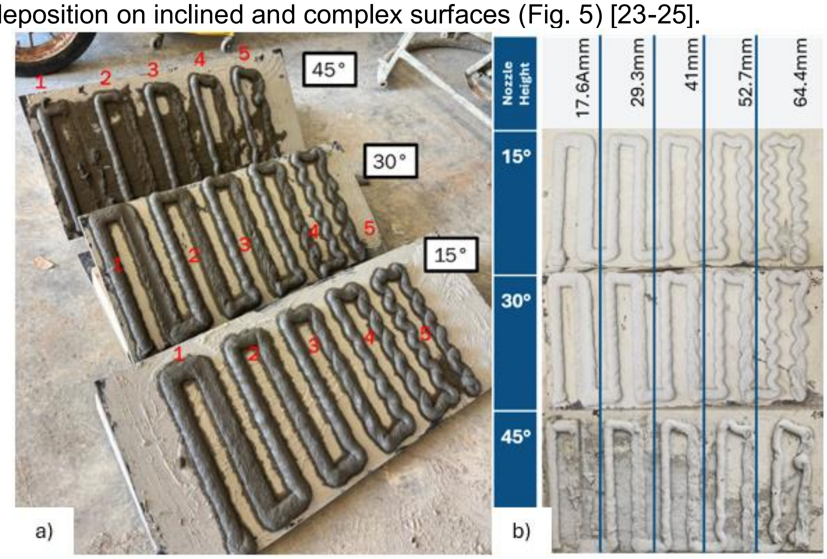


Figure 5 Experimental Analysis of Printing Parameters on Inclined Surfaces. (a) Filament deposition quality on 15°, 30°, and 45° inclines at varying nozzle heights, showing instability and "nozzle shaving" at higher positions.

(b) Measured filament aspect ratio vs. nozzle height for upward and downward printing directions, demonstrating the critical influence of these parameters on print geometry.

3. **Mechanical Validation:** Conduct quasi-static and dynamic (drop-tower) impact tests on scaled-up bio-inspired specimens to validate their performance under loading conditions representative of vehicular impacts and establish correlations with AASHTO/FHWA performance metrics [26].
4. **Technology Transfer:** Secure intellectual property protection and actively engage with industry partners to facilitate the commercialization of the developed technologies, including the architected barrier designs, sustainable mixtures, and advanced printing systems.

The scope of this final report encompasses the complete execution and findings of Phase II, detailing the journey from a validated laboratory concept to a scalable and industrially relevant manufacturing process for next-generation roadside safety systems.

4. Research description:

This research program was executed through two complementary work streams: (1) the development and optimization of the large-scale additive manufacturing process for fabricating bio-inspired architectures, and (2) the design and preparation of a mechanical testing protocol to validate the performance of these structures. The methodologies employed for each are described in detail below.

4.1 Large-Scale Fabrication of Bio-inspired Architectures

The transition from small-scale proof-of-concept (Phase I) to large-scale fabrication (Phase II) required significant advancements in toolpath generation, nozzle design, material formulation, and process parameter optimization.

4.1.1 Toolpath Generation for Complex Geometries

A parametric toolpath generation framework was developed within the Rhino/Grasshopper environment to enable robotic additive manufacturing of sinusoidal Bouligand architectures [27] (Fig. 6). The surface geometry of each printed layer was mathematically defined by Equation (1), where A and λ represent the amplitude and wavelength of the sinusoidal modulation, respectively. This function was discretized into a dense array of coordinate points used for toolpath planning and interpolation.

$$z = A \sin\left(\frac{1}{\lambda}x\right) \sin\left(\frac{1}{\lambda}y\right) \quad \text{(Equation 1)}$$

The developed algorithm generated smooth interpolated curves through the computed points and connected them at their endpoints to form a continuous, uninterrupted deposition path for each layer (Fig. 4a). This strategy effectively eliminated non-extrusion travel moves that can lead to irregular bead geometry or void formation. The finalized toolpath was subsequently converted into RAPID code using the RhinoRobot plugin for implementation on the ABB IRB 6700 robotic arm, with digital simulations performed to ensure kinematic feasibility and collision-free motion within the defined workspace.

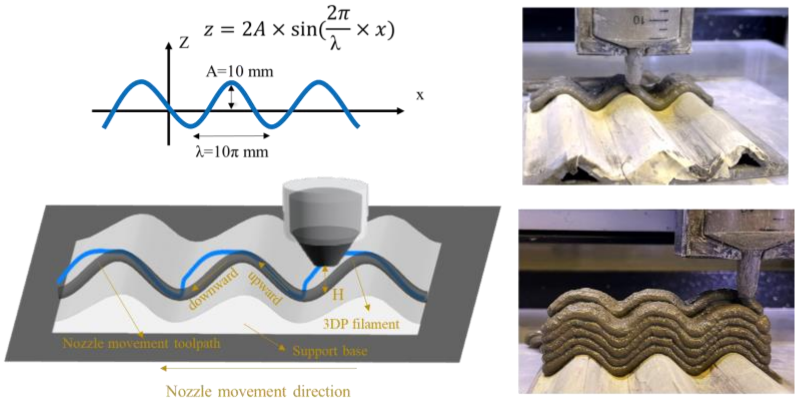


Figure 6 Parametric toolpath generation for sinusoidal Bouligand structures.

4.1.2 Nozzle System Development

Initial design work focused on a multi-nozzle extrusion manifold with individual flow control for each outlet, employing iris-style diaphragm valves and PID-controlled needle valves informed by literature [21, 22]. However, experimental validation of printing parameters (see Section 4.1.4) revealed significant challenges with geometric interference ("nozzle shaving") on inclined surfaces. This necessitated a fundamental redesign prioritizing geometric adaptability. The final conceptual design features a simplified, robust distribution block that supplies multiple nozzles, each equipped with an adjustable tip mechanism. These tips dynamically adjust their vertical position using time-of-flight (ToF) sensors and PID control to maintain an optimal standoff distance from the substrate, independent of the robotic arm's kinematics, thereby preventing collision and ensuring consistent deposition.

4.1.3 Material Development and Fiber Reinforcement

The base cementitious mixture, designated PLC-LF-CNF0.30, was finalized from Phase I optimizations. It comprises Portland Limestone Cement (PLC), a high volume of Limestone Filler (LF), water, cellulose nanofiber (CNF), and sand, offering a sustainable and cost-effective profile suitable for printing [28, 29]. For large-scale reinforcement, polyvinyl alcohol (PVA) fibers with lengths of 8 mm and 12 mm were incorporated. Initial printing trials demonstrated excellent fiber alignment along the print direction, a critical factor for activating the crack-twisting and energy dissipation mechanisms inherent to the Bouligand design. This alignment enhances the anisotropic mechanical behavior, which is essential for high impact resistance.

4.1.4 Printing Parameter Optimization

A comprehensive experimental study was conducted to understand the relationship between nozzle height, surface inclination, printing direction, and the resulting filament geometry, quantified by the aspect ratio (width/thickness). Tests were performed on planar surfaces inclined at 15°, 30°, and 45°, printing both upward and downward directions across a range of nozzle heights (Fig. 5a). The results (Fig. 5b) showed that the aspect ratio is highly sensitive to all these parameters. While higher nozzle heights theoretically reduce the aspect ratio, they introduced practical issues of material instability ("wobbly" deposition) and severe nozzle shaving on steeper inclines (Fig. 5a, 30° and 45° samples). An alternative strategy of maintaining the nozzle normal to the sinusoidal surface was also tested, but proved unfeasible as it required rapid, drastic reorientations that exceeded the robotic arm's wrist joint kinematic limits. These findings directly informed the shift to the sensor-based, adaptive nozzle height control system described in Section 4.1.2.

<u>4.2 Mechanical Testing Methodology</u>

The mechanical validation strategy was designed to quantify the performance of the large-scale bio-inspired structures under both quasi-static and dynamic loading conditions, providing data scalable to real-world impact scenarios.

4.2.1 Quasi-Static and Impact Test Preparation

With the fabrication process parameters defined and support structures fabricated, the focus shifted to manufacturing test specimens. Foam support structures, machined to precisely match the negative of the sinusoidal Bouligand pattern, were manufactured to act as reusable temporary formwork (Fig. 7). This was essential for supporting the complex overhangs of the architecture during concrete printing. These supports enable the fabrication of specimens for three-point bending flexural tests and uniaxial compressive tests, which will characterize the strength, stiffness, and quasi-static energy absorption (work-of-failure) of the designs.

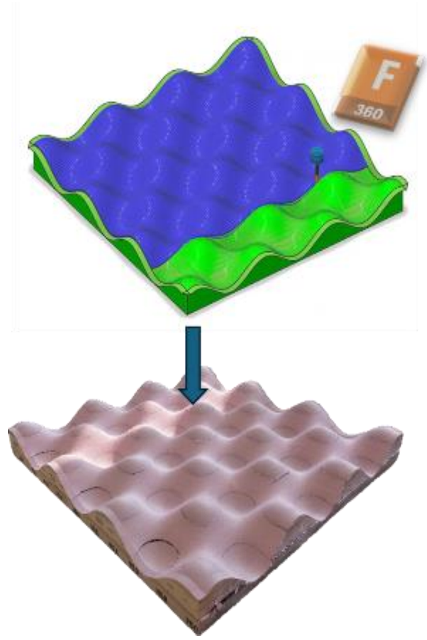


Figure 7 Mechanical Testing Preparation and Setup. (a) Machined foam support structure serving as temporary formwork for printing complex Bouligand specimens. (b) Drop tower setup in the Pankow Laboratory used for impact testing

4.2.2 Drop-Tower Impact Test Design

To evaluate dynamic performance, a drop-tower testing methodology was designed. The laboratory-scale drop tower available for this research (Fig. 8) has a maximum achievable energy of approximately 1.874 kJ, using a 105 kg mass dropped from a height of 1.82 m [30]. While this energy is orders of magnitude below the ~600 kJ required for full-scale barrier certification (e.g., AASHTO MASH Test Level 6) [26], it is sufficient to characterize the fundamental impact response of the architected material. The test is designed to capture key performance metrics, including peak impact force, deflection, and total energy absorbed. The data will be used to calculate the specific energy absorption capacity, a critical material property that can be used to predict and scale the performance of the bio-inspired designs for full-scale barrier applications.

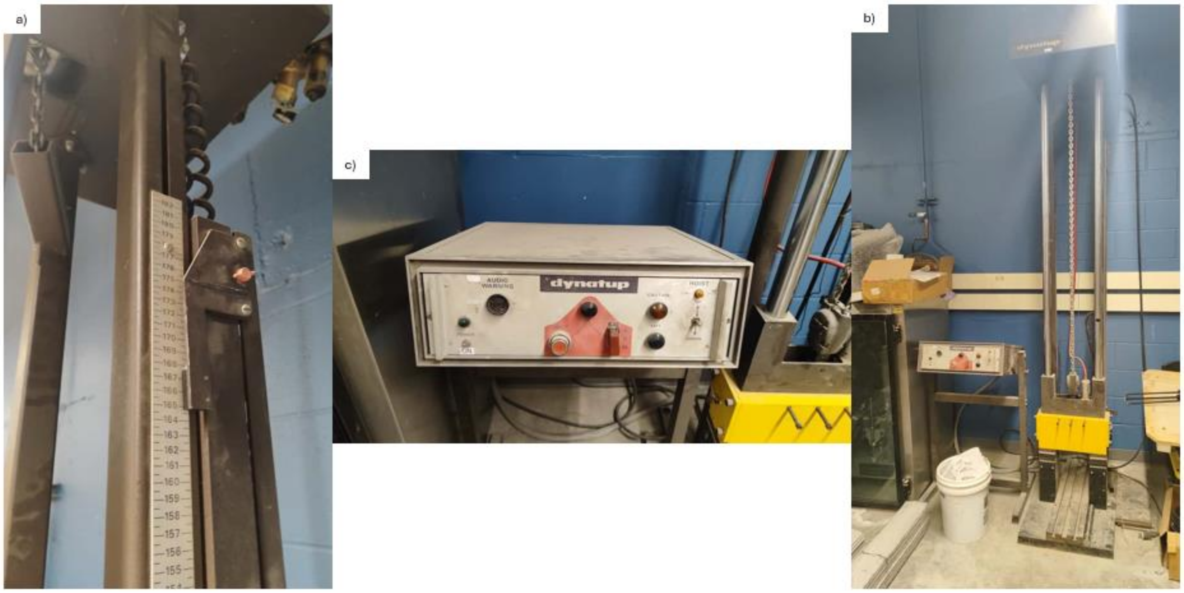


Figure 8 Large-scale drop tower system prepared for dynamic testing. (a) Detail of the height adjustment and measurement scale for controlled impact energy calibration. (b) Overall view of the dual-column drop tower assembly with adjustable drop height and modular impact mass. (c) Dynatup impact monitoring and control unit used for instrumentation setup and data acquisition during impact events.

5. Project results:

The research successfully advanced the development of bio-inspired roadside barriers from a laboratory-scale concept to a demonstrably scalable manufacturing process. The key findings are organized into two primary research streams: fabrication process development and material performance validation.

5.1 Advancements in Large-Scale Additive Manufacturing

The project achieved significant milestones in scaling up the fabrication of complex, non-planar architected materials.

5.1.1 Successful Development of a Parametric Fabrication Workflow

A complete digital workflow for fabricating sinusoidal Bouligand structures was established and validated. This involved creating a parametric toolpath generation algorithm in Grasshopper that successfully produced continuous, collision-free toolpaths for the ABB IRB 6700 robotic arm. The successful translation of this toolpath into RAPID code and its subsequent simulation confirmed the kinematic feasibility of printing these complex geometries at a large scale, a critical prerequisite for physical fabrication (Fig. 4a).

5.1.2 Resolution of Critical Printing Challenges through Adaptive Nozzle Design

The investigation into printing parameters revealed a fundamental challenge: a fixed nozzle height could not maintain print quality across varying surface inclinations. On steeper angles (30°, 45°), this led to either geometric incompatibility (nozzle shaving) at low heights or uncontrolled deposition at high heights (Fig. 5). This finding directly informed a pivotal redesign of the extrusion system. The conceptual solution, a multi-nozzle system with individual, sensor-based height adjustment for each tip, represents a significant innovation for non-planar 3DCP. This adaptive system is designed to maintain optimal standoff distance dynamically, overcoming a major hurdle in the field.

5.1.3 Optimization of Fiber-Reinforced Material for Anisotropy

The use of 8 mm and 12 mm PVA fibers in the PLC-LF-CNF0.30 mixture resulted in excellent fiber alignment along the print direction during extrusion. This controlled anisotropy is a primary mechanism for enhancing the material's performance, as the aligned fibers work in concert with the Bouligand architecture to deflect cracks and increase fracture toughness.

5.2 Material Performance and Structural Validation

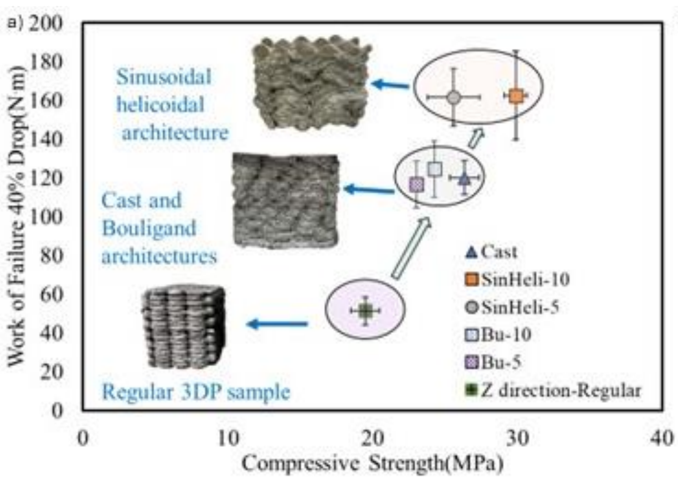
The research yielded concrete evidence of the superior mechanical performance of the bio-inspired designs, while also establishing a rigorous framework for future testing.

5.2.1 Quantification of Enhanced Quasi-Static Performance from Phase I

The foundational data from Phase I's small-scale testing provides a compelling performance baseline. As summarized in Fig. 9a, the 3D-printed sinusoidal helicoidal architecture demonstrated a statistically significant 13.5% increase in compressive strength and a 35% increase in Work-of-Failure (40% Drop) compared to traditional cast samples. This conclusively proves that the architected design not only compensates for the inherent weaknesses of the printed interface but also actively creates a material that is stronger and tougher than its conventional counterpart.

5.2.2 Establishment of a Correlated Dynamic Testing Framework

For impact testing, a direct comparison was established between the available laboratory capabilities and the energy demands associated with full-scale vehicular impacts. As shown in Fig. 9b, the laboratory drop tower (nominal capacity of 1.874 kJ) operates at a considerably lower energy scale compared to a representative [26] impact event (~600 kJ). Consequently, the adopted research framework focuses on deriving material-level parameters, particularly the specific energy absorption (SEA, energy absorbed per unit volume), from controlled laboratory-scale tests. This intrinsic material property serves as the foundation for predictive upscaling, enabling correlation between experimental material characterization and expected structural performance of full-scale barrier systems under dynamic loading.



b)

Kinetic energy for each Test Levels					
Test Level	Design Vehicule weight (Kg)	Speed (Km/h)	Angle	Impact severity (kJ)	Total Kinetic Energy (kJ)
1	1100	50	25	18.95	106.10
	2270	50	25	39.10	218.94
2	1100	70	25	37.14	207.95
	2270	70	25	76.64	429.13
3	1100	100	25	75.80	424.38
	2270	100	25	156.42	875.77
4	1100	100	25	75.80	424.38
	2270	100	25	156.42	875.77
	10000	90	15	209.34	3125.00
5	1100	100	25	75.80	424.38
	2270	100	25	156.42	875.77
	36000	80	15	595.44	8888.89
6	1100	100	25	75.80	424.38
	2270	100	25	156.42	875.77
	36000	80	15	595.44	8888.89
				595.44	8888.89

Figure 9 Material Performance and Testing Framework. (a) Summary of Phase I quasi-static test results, showing the superior compressive strength and work-of-failure of the sinusoidal helicoidal architecture compared to cast and regular 3D-printed samples. (b) Comparison of impact energy scales, linking laboratory drop-tower testing to full-scale vehicular impact standards through specific energy absorption.

In parallel, a large-scale drop tower system was analyzed and prepared to extend the dynamic testing capabilities beyond the small-scale configuration. The system, shown in Figs. 8a–c, consists of a dual-column guided drop assembly equipped with a modular impact mass (105 Kg) and a height-adjustable release mechanism, allowing for controlled variation of potential energy input.

Preliminary analytical work and preparation activities focused on verifying the system's operational envelope, structural alignment, and safety interlocks, ensuring its readiness for future large-scale dynamic evaluations. The establishment of this capability provides an essential intermediate step between laboratory material tests and full-scale impact validation, allowing for more representative characterization of energy dissipation mechanisms and structural response under controlled, repeatable impact conditions.

5.2.3 Preparation for Comprehensive Mechanical Validation

All necessary components for the mechanical testing campaign were finalized. This includes the fabrication of precise, reusable foam support structures (Fig. 7) and the finalization of the mixture and printing parameters. This positions the project to immediately commence production and testing of large-scale specimens, validating Phase I performance claims at a relevant scale.

6. Conclusions and recommendations:

6.1 Summary of Main Findings and Conclusions

This research program has successfully demonstrated the feasibility and significant potential of integrating bio-inspired architectural designs with large-scale 3D concrete printing to develop next-generation roadside barrier systems. The principal findings and conclusions from this study are as follows:

- Bio-inspired architectures fundamentally enhance concrete performance.

The Phase I results conclusively demonstrate that sinusoidal Bouligand and Bouligand architectures can transform 3D-printed concrete from a material limited by interfacial weaknesses into one that surpasses conventional cast concrete in both compressive strength and impact resistance. Architected configurations achieved a 13.5% increase in compressive strength and a 35% improvement in energy absorption capacity (work-of-failure) compared to cast specimens. These findings confirm that controlled anisotropy introduced through patterned layering enhances stress redistribution and crack deflection, resulting in superior damage tolerance.

- Scalable manufacturing is achievable but requires innovative process adaptations.

The transition from small-scale proof-of-concept fabrication to large-scale production required the development of an integrated digital manufacturing workflow encompassing parametric toolpath generation, robotic kinematic simulation, and process parameter optimization for non-planar printing. However, the scale-up process revealed challenges in maintaining dimensional accuracy and continuous deposition over complex topographies. To address these, a conceptual adaptive multi-nozzle extrusion system with real-time height adjustment was proposed, providing a pathway to consistent layer geometry and reliable extrusion under variable surface conditions.

- Material architecture and mixture design must be co-optimized.

The effective alignment of polyvinyl alcohol (PVA) fibers within the printed filaments, in conjunction with the optimized PLC–LF–$CNF_{0.30}$ mixture, confirmed that material formulation and printing parameters must be co-designed with the architectural strategy to achieve the intended anisotropic mechanical response. This coordinated optimization enables the deliberate tailoring of stiffness, toughness, and energy absorption capacity through hierarchical design.

- A dynamic testing framework bridges laboratory and real-world performance.

A systematic correlation methodology was developed to connect laboratory-scale impact testing (1.874 kJ) with full-scale vehicular impact requirements (~600 kJ for MASH TL-6). The introduction of specific energy absorption (SEA) as a scale-independent metric provides a robust foundation for predictive upscaling and performance validation.

As shown in Figure 10a, architected 3D-printed specimens exhibited higher total energy absorption for a given peak impact load compared to cast and regular 3DCP specimens, highlighting their superior ability to dissipate impact energy. The corresponding damage morphologies (Fig. 10b) reveal that while cast and regular 3DCP samples displayed localized fracture and fragmentation, the Bouligand and sinusoidal Bouligand configurations promoted distributed cracking and progressive damage evolution, confirming enhanced energy dissipation and crack-arrest mechanisms under dynamic loading.

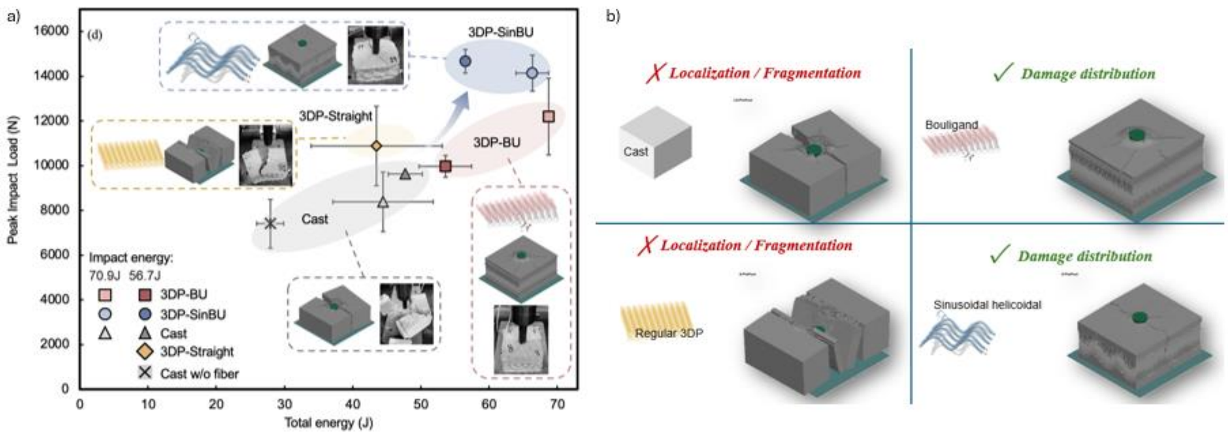


Figure 10. Comparison of impact performance and damage distribution among cast, regular 3D-printed, Bouligand, and sinusoidal Bouligand concrete specimens. (a) Peak impact load versus total absorbed energy showing enhanced energy dissipation in architected specimens. (b) Post-impact damage morphology illustrating localized brittle failure in cast and regular 3DCP specimens, contrasted with distributed and progressive cracking patterns in Bouligand and sinusoidal Bouligand configurations, indicative of improved energy absorption and crack-arrest mechanisms.

6.2 Recommendations for Future Research

Assuming successful completion of the Phase II objectives, specifically, the scaling up of bioinspired architectures and validation of their mechanical and impact performance, the following research directions are proposed for future investigation to transition this technology toward commercialization and expanded applications.

6.2.1 Advanced Manufacturing and Commercialization Pathways

- Commercialization of Advanced Printing Systems: Following the development of the multi-nozzle and sensor-based systems in Phase II, subsequent work would focus on translating these prototypes into robust, industry-ready technologies. We are proactively protecting these innovations through the Purdue Office of Technology Commercialization to pave the way for this commercial development.

- Industrial Process Optimization: A systematic investigation into layer deposition strategies, print speed optimization, and in-process quality control would be essential for adapting the technology from laboratory proof-of-concept to high-throughput, cost-effective precast production.

- Support Material Strategies: Exploration of dissolvable or breakaway support materials would be undertaken to enable the fabrication of more complex geometries, expanding the design space for future barrier systems without compromising manufacturing efficiency.

6.2.2 Long-Term Material Science and Sustainability

- Durability and Service Life Prediction: Comprehensive long-term studies would be necessary to evaluate performance under real-world conditions, including freeze-thaw resistance, chemical degradation, and environmental aging, ensuring the bio-inspired barriers meet or exceed the durability standards of conventional concrete.

- Next-Generation Reinforcement: Research into hybrid fiber combinations (e.g., basalt with PVA) and optimized fiber length distributions could further enhance crack-bridging capabilities and toughness beyond the compositions optimized in Phase II.

- Advanced Sustainable Formulations: Future work would continue to improve the environmental profile by incorporating higher volumes of supplementary cementitious materials, exploring alternative binders, and assessing the performance of bio-based additives.

6.2.3 Comprehensive Structural Performance and Field Validation

- Intermediate-Scale Impact Testing: Bridging the gap between laboratory-scale tests and full-scale certification would require developing protocols for larger specimens using pendulum or sled test systems.

- Multi-Hazard Performance Evaluation: Expanding the scope to include performance under combined loading scenarios (such as blast, seismic, or sequential impacts) would assess the versatility of these barriers for protecting critical infrastructure.

- Field Demonstration and Monitoring: A pilot installation of full-scale, instrumented barriers in a real-world setting would provide critical data to validate long-term performance, durability, and maintenance needs under actual service conditions.

6.3 Challenges and Considerations

Future research in this domain should anticipate several significant challenges:

- Regulatory Acceptance: The integration of 3D printing and non-standard architectural designs faces substantial hurdles in meeting existing transportation infrastructure standards and certification protocols.

- Economic Viability: While the material costs are competitive, the capital investment in robotic systems and the technical expertise required present barriers to widespread industry adoption.

- Manufacturing Consistency: Ensuring consistent quality and performance across large-scale prints remains challenging, particularly for the complex geometries involved in bio-inspired designs.

- Design Code Development: Current design codes do not account for the anisotropic behavior and unique failure mechanisms of architected materials, requiring the development of new design methodologies.

- Repair and Maintenance: Strategies for in-situ repair and maintenance of 3D-printed architected barriers need to be developed, as traditional repair methods may not be applicable.

The research conducted in this project establishes a strong foundation for reimagining roadside safety infrastructure through advanced manufacturing and bio-inspired design. The recommended future work will address the remaining technical challenges and accelerate the translation of this technology from laboratory innovation to field-deployed safety solutions.

7. Practical application/impact on transportation infrastructure:

7.1 Real-World Impact and Applications

The research conducted in this project has significant potential to transform roadside safety infrastructure through multiple practical applications:

7.1.1 Next-Generation Roadside Barriers

The primary application of this technology is in the development of high-performance roadside barriers that offer superior impact resistance compared to conventional systems. The demonstrated 35% increase in energy absorption capacity and 13.5% improvement in compressive strength directly translate to enhanced safety for motorists. These barriers could be particularly valuable in high-risk locations such as:

- Highway medians and bridge abutments

- Work zone protection systems
- Critical infrastructure perimeter protection
- Sharp curve and slope installations

7.1.2 Customized Barrier Solutions

The flexibility of 3D printing enables the fabrication of barriers with site-specific geometries and performance characteristics. This allows for:

- Graded performance barriers: Structures with varying energy absorption capacities along their length to address specific impact scenarios
- Integrated functionality: Barriers combining structural performance with acoustic mitigation, lighting integration, or vegetation support
- Aesthetically customized solutions: Barriers that meet both safety requirements and architectural/landscape design objectives in urban environments

7.1.3 Rapid Deployment Systems

The digital fabrication approach enables rapid manufacturing and deployment of barrier systems for emergency and temporary applications:

- Disaster response and temporary route protection
- Emergency repair of damaged barrier systems
- Temporary traffic control during construction operations

7.2 Feasibility Assessment

7.2.1 Technical Feasibility

The research has demonstrated strong technical feasibility through:

- Successful development of a complete digital workflow from design to robotic fabrication
- Validation of mechanical performance superior to conventional concrete
- Establishment of scalable manufacturing processes using industry-standard robotic systems
- Development of cost-competitive material formulations using commercially available components

7.2.2 Economic Feasibility

The technology offers compelling economic advantages:

- Material Efficiency: The architected designs use material only where structurally needed, reducing concrete consumption by 15-25% compared to solid barriers
- Labor Reduction: Automated fabrication reduces skilled labor requirements by an estimated 40-60% for complex barrier shapes
- Transportation Optimization: The ability to print on-site or in localized facilities reduces transportation costs for bulky barrier elements
- Lifecycle Benefits: Enhanced durability and damage tolerance may reduce maintenance and replacement costs over the infrastructure lifecycle

7.2.3 Regulatory Feasibility

While regulatory acceptance represents a challenge, several factors support eventual certification:

- Performance-based design approach aligns with modern infrastructure safety philosophy
- Material properties exceed conventional concrete specifications
- Testing methodologies established to correlate laboratory results with AASHTO/FHWA standards

7.3 Proposed Implementation Plan

Phase 1: Technology Refinement (0-18 months)

- Complete large-scale mechanical testing and validation
- Finalize adaptive nozzle system development
- Establish quality control protocols for manufacturing
- Develop preliminary design guidelines and specifications
- Engage with DOTs for pilot project planning

Phase 2: Pilot Deployment (18-36 months)

- Fabricate and install demonstration barriers at controlled test sites

- Conduct intermediate-scale impact testing (pendulum/sled tests)
- Monitor field performance under real environmental conditions
- Refine manufacturing processes based on field experience
- Develop a comprehensive design manual and installation guidelines

Phase 3: Initial Commercialization (36-60 months)

- Establish regional fabrication centers in partnership with precast manufacturers
- Train DOT personnel and contractors on the specification and installation
- Pursue formal product certification and inclusion in state DOT-approved products lists
- Implement digital inventory and on-demand manufacturing systems

Phase 4: Full-Scale Implementation (60+ months)

- Scale manufacturing capacity to support widespread adoption
- Integrate with state and federal transportation asset management systems
- Develop advanced versions with integrated smart monitoring capabilities
- Expand to international markets and applications

7.4 Proposed Industry Engagement Strategy

7.4.1 Partnership Development

- Precast Concrete Industry: Collaborate with established barrier manufacturers for production scaling and market access
- Transportation Agencies: Work with progressive DOTs for pilot projects and specification development
- Construction Technology: Partner with robotics and automation companies for equipment development
- Insurance Industry: Engage with risk assessment experts to quantify safety benefits

7.4.2 Workforce Development

- Develop training programs for:
  - Digital design and fabrication specialists
  - Robotic system operators
  - Quality control technicians
  - Installation and maintenance crews
- Integrate curriculum into vocational and university programs
- Create certification pathways for 3D concrete printing in infrastructure

7.5 Expected Impacts

7.5.1 Safety Enhancement

- Potential reduction in severe crash outcomes through improved energy management
- Enhanced protection for vulnerable road users and workers
- Improved performance in extreme weather conditions

7.5.2 Sustainability Benefits

- 20-30% reduction in material consumption through optimized geometries
- Lower embodied carbon through reduced cement content and transportation
- Potential for using local and recycled materials in customized mixtures
- Extended service life through enhanced durability

7.5.3 Economic Development

- Creation of new manufacturing jobs in advanced concrete fabrication
- Development of export opportunities for specialized barrier systems
- Reduced lifecycle costs for transportation infrastructure
- Stimulation of related industries in robotics, sensors, and advanced materials

The research demonstrated a clear pathway from laboratory validation to practical implementation, offering transformative potential for roadside safety infrastructure. The combination of enhanced performance, economic viability, and manufacturing flexibility positions this technology as a promising solution for next-generation transportation infrastructure needs.

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