Developing Lightweight and High-Performance Metamaterial Concrete

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Research Problem

For more than a century, concrete technology advances rely mainly on modifying mix compositions

Future performance must be reimagined via internal architectural design

Mechanical metamaterials offer a transformative path, geometry over composition

✓ **Reengineering concrete with tunable strength and energy absorption functionalities in a lightweight, structurally efficient form**

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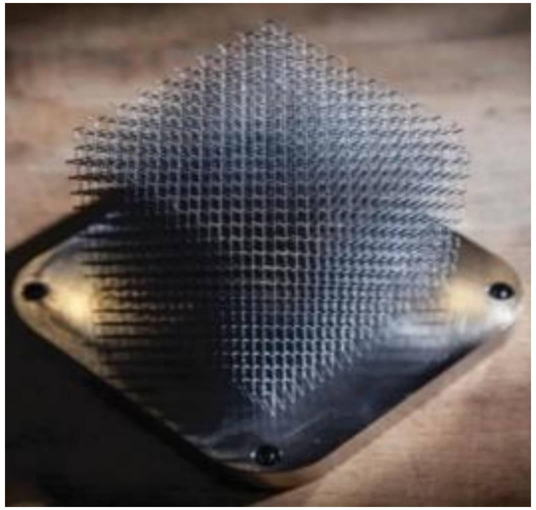
Mechanical Metamaterials

Metamaterials

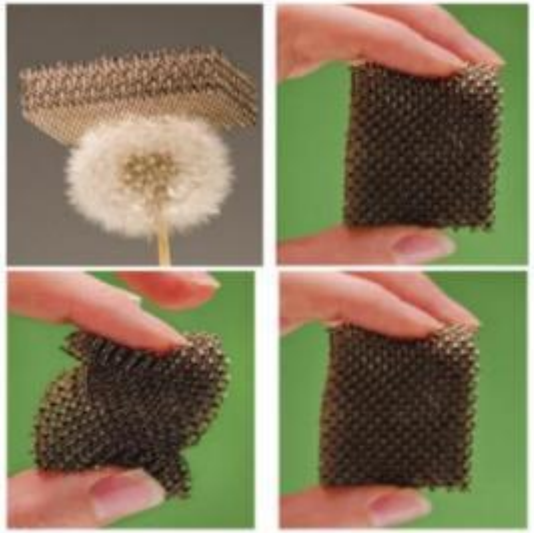
- Artificial structures
- Often arranged in repeated patterns
- Derive their properties from their designed structure
- Shape, geometry, size, orientation and arrangement

Metamaterial Types:

- Electromagnetic Metamaterial
- Photonic or Optical Metamaterial
- Mechanical Metamaterial (MM)
  - Extremal metamaterials
  - Negative metamaterials
  - Ultra-property metamaterials



Zadpoor, 2016, Materials Horizons. DOI: 10.1039/C6MH00065G



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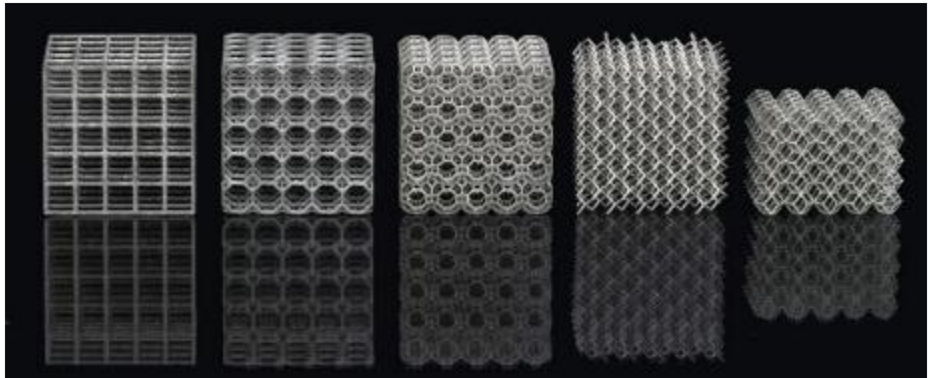

Kolken et al., 2021, Acta Biomaterialia. DOI: 10.1016/j.actbio.2021.03.015

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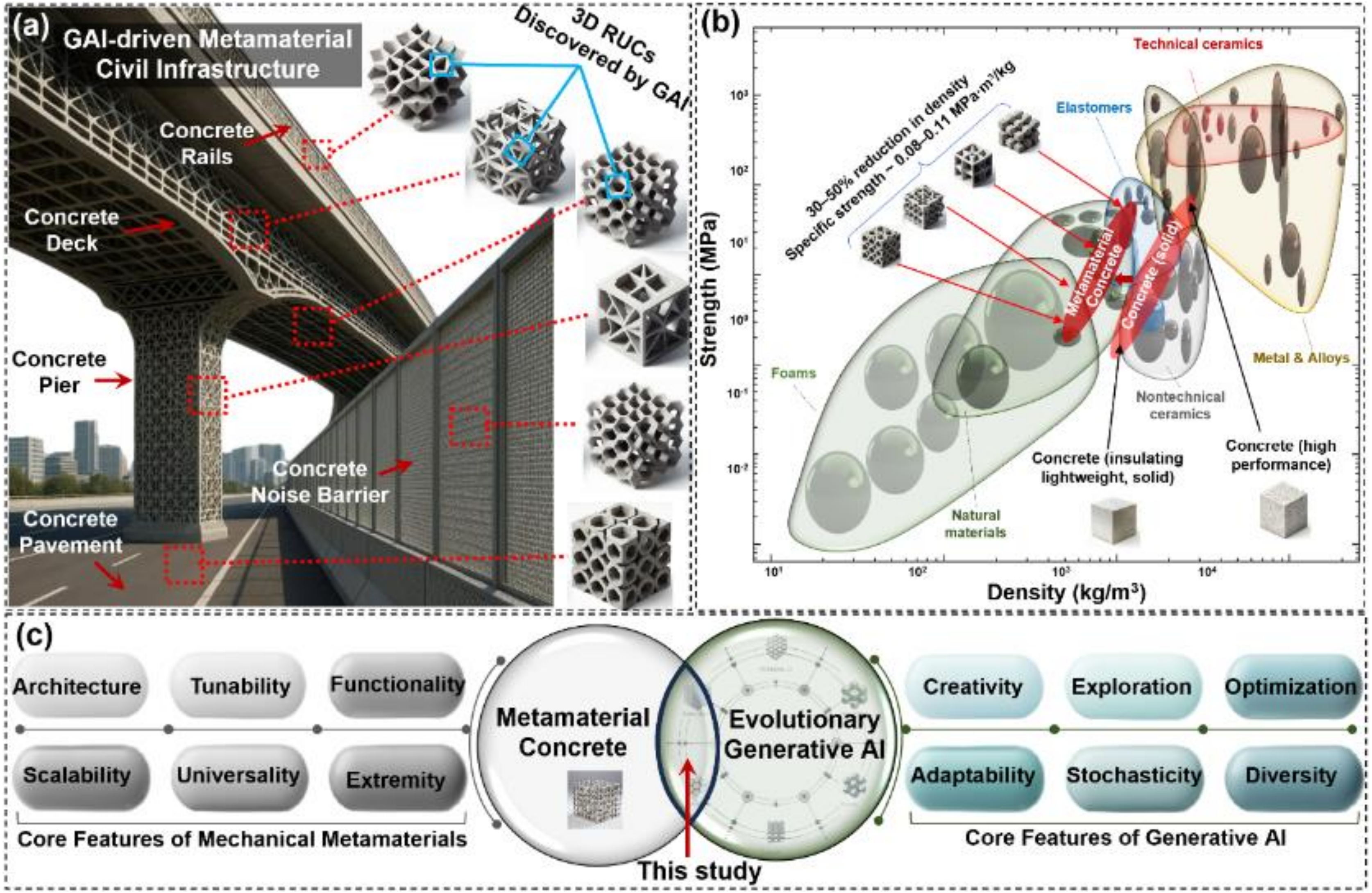
Vision

A **fundamental shift in the science of concrete design**, and more broadly civil infrastructure materials, from **compositionally** defined to **architecturally** defined

“Structure-specific” metamaterial concrete enables tailored solutions for lightweight and high-strength civil infrastructure systems



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Project Objectives & Approach

Objectives:

- ➢ Developing lightweight and high-performance metamaterial concrete

Approach:

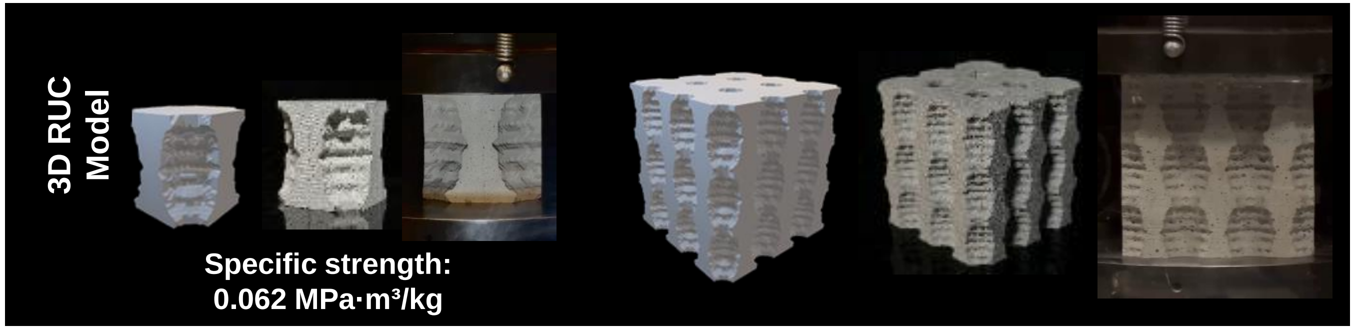
- ➢ Mechanical metamaterial design
- ➢ Evolutionary generative AI
- ➢ Mechanical characterization

Define mechanical objectives to achieve high strength-to-density ratio

$$Objective\ function = -(C^H_{1111} + C^H_{1112} + C^H_{1133} + C^H_{2211} + C^H_{2222} + C^H_{2233} + C^H_{3311} + C^H_{3322} + C^H_{3333})$$

Explore the design space using evolutionary generative AI

Fabricate and test

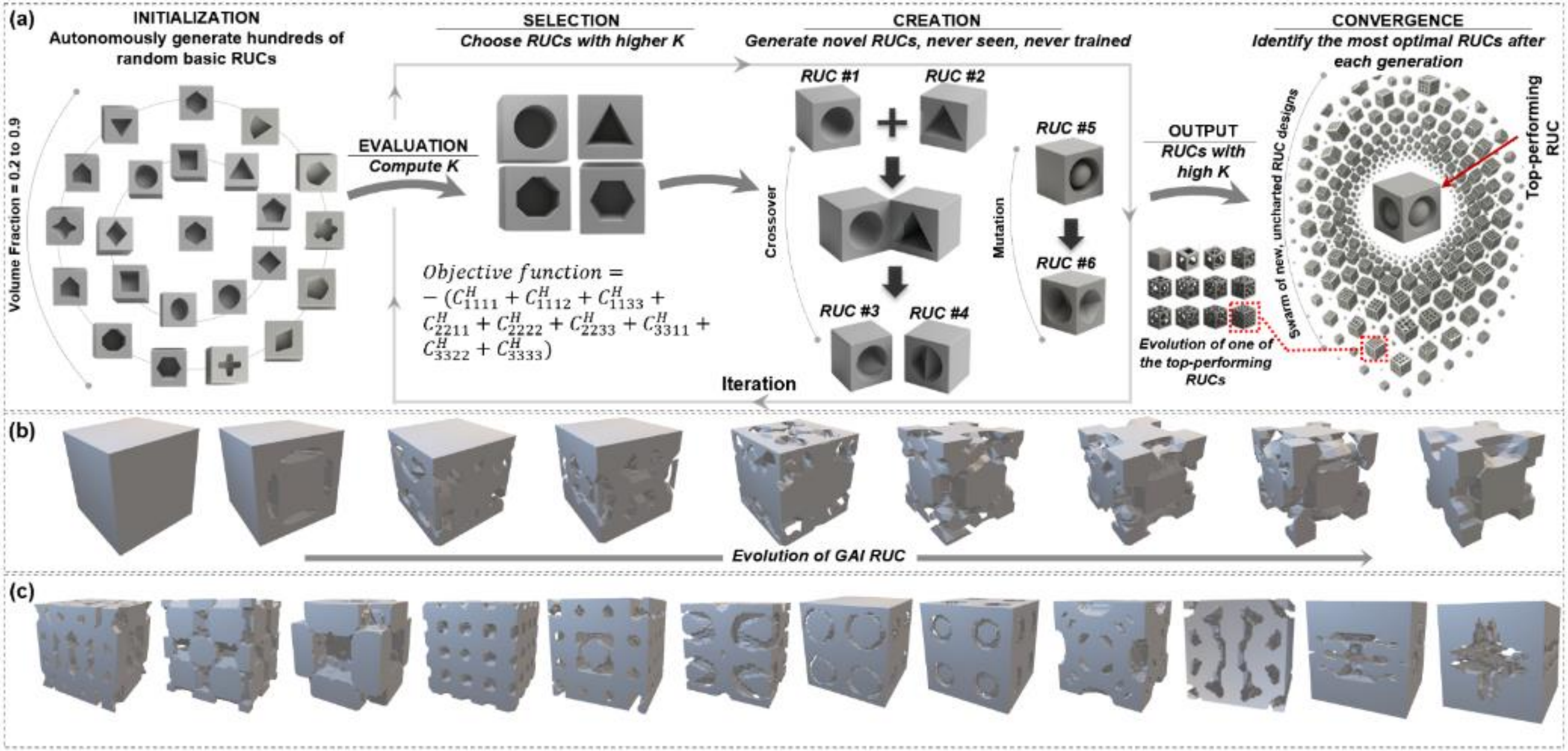


Evolutionary GAI framework

High strength-to-density ratio with unit cells combining high mechanical strength with low density

Bulk modulus (K) served as the objective function

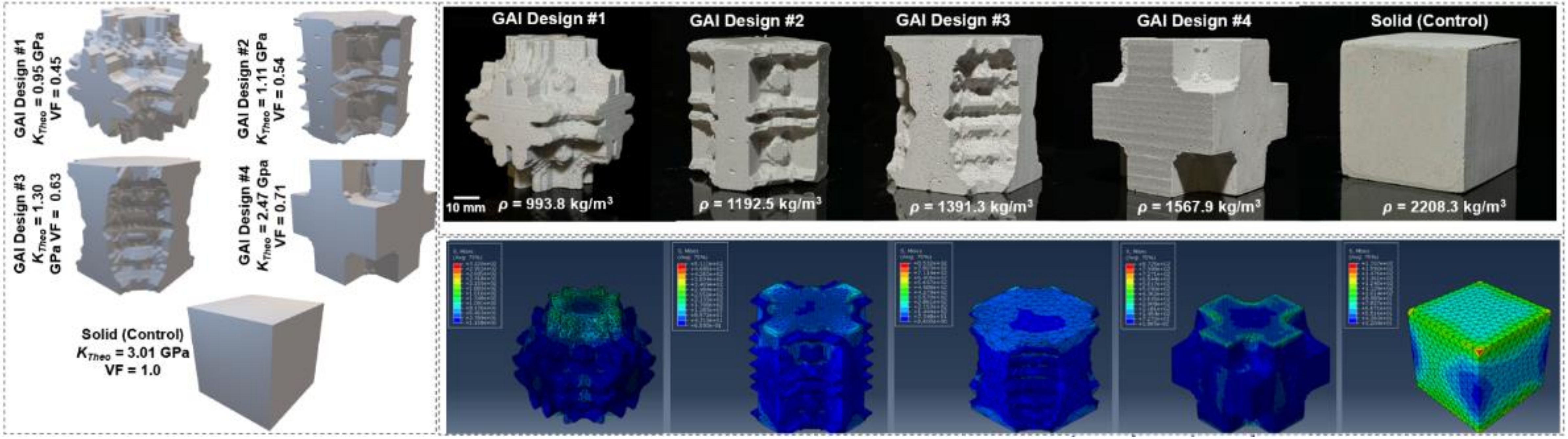
We explored over 10,000 3D designs



Optimal Cementitious Designs

Four representative designs based on their K values, VF, and manufacturability

Ultra-high-performance concrete (UHPC) mix as the parent/bulk material



The density reduction is independent of the type of cementitious bulk materials

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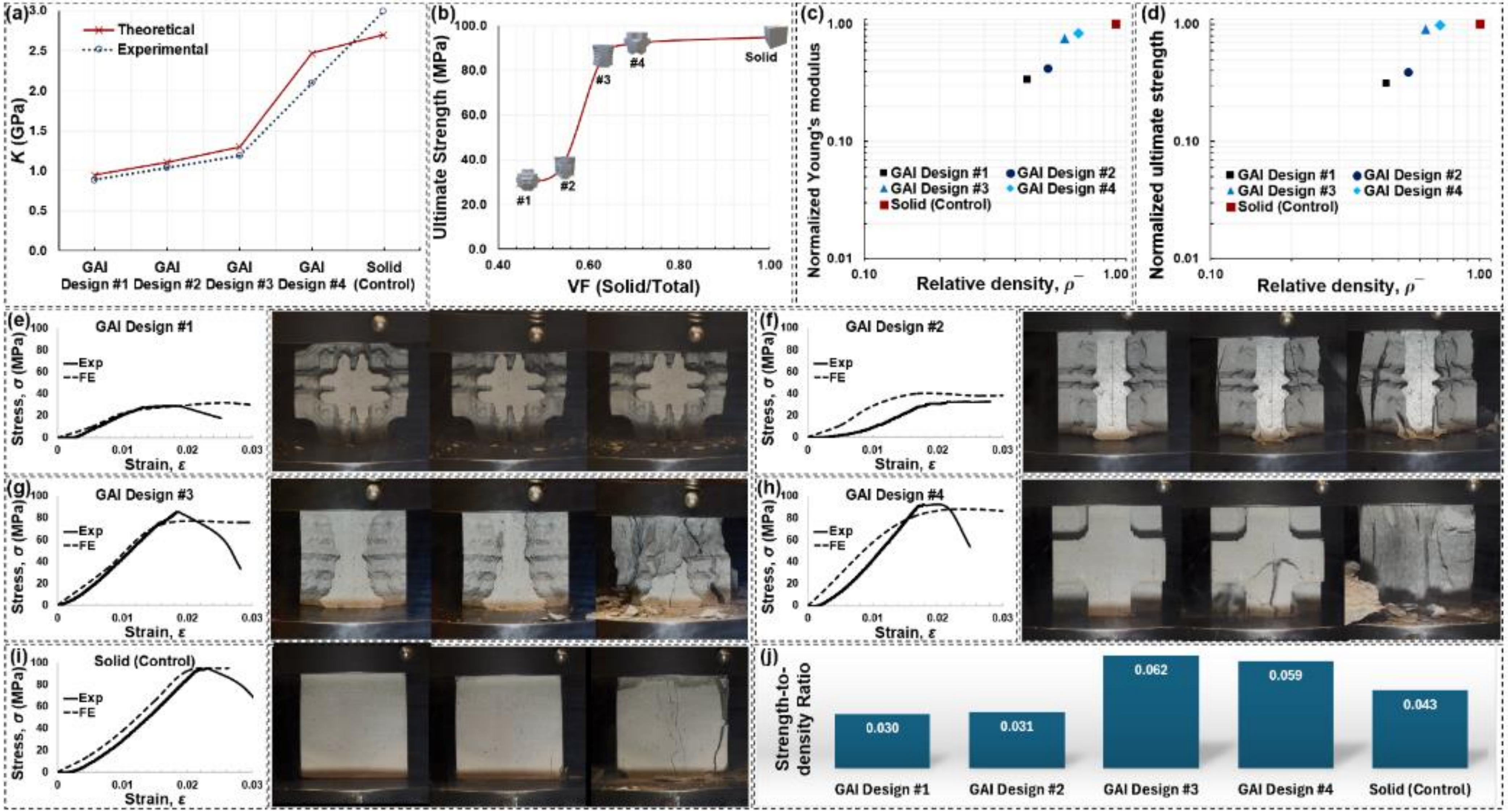
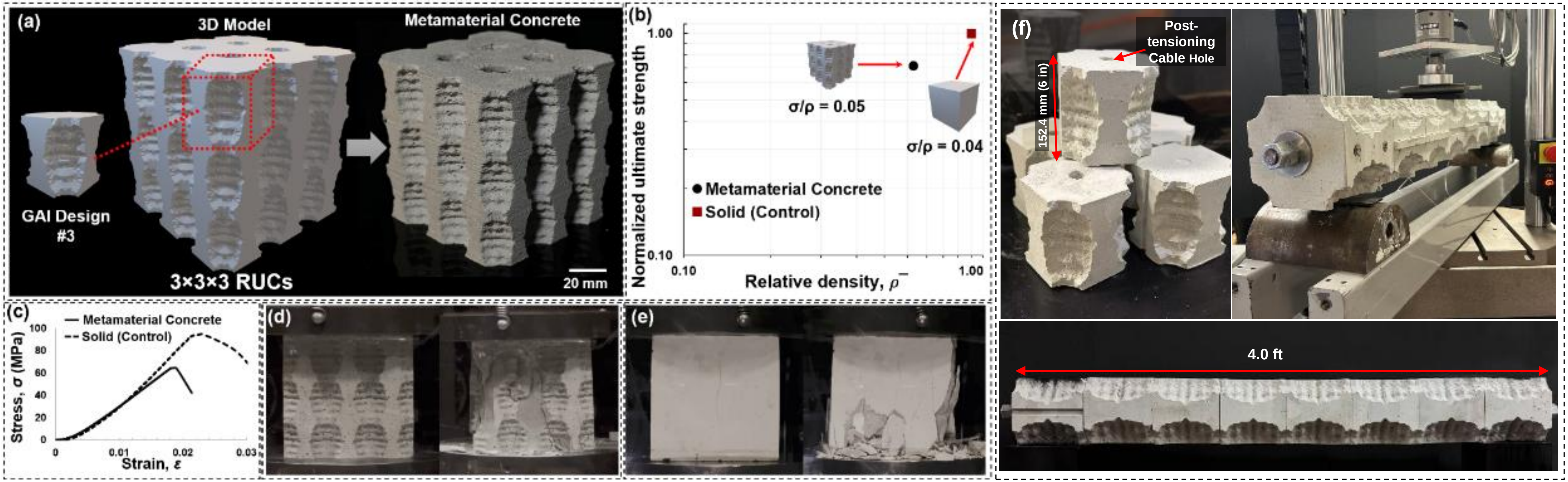
Results



Mild steel (~0.027 MPa·m³/kg), structural steel (e.g., ASTM A36 ~0.025-0.035 MPa·m³/kg), high-strength low-alloy steel (e.g., ASTM A992 ~0.030-0.045 MPa·m³/kg), and common construction aluminum alloys (e.g., 6061-T6 ~0.040-0.065 MPa·m³/kg)

Large-scale implementation

The transition from laboratory-scale research to large-scale implementation is a crucial step



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Impact

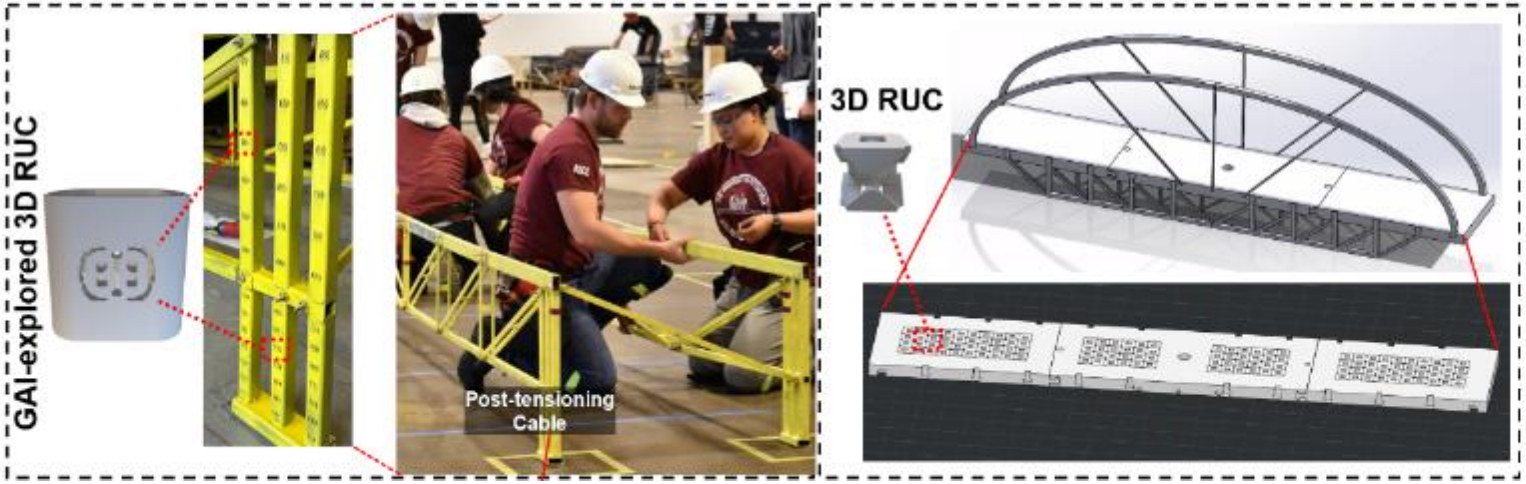
Engaging students in hands-on projects with advanced materials inspires broader interest in the future of civil infrastructure design

• Our Pitt ASCE Student Chapter developed bridge prototypes using GAI-designed metamaterials

• Achievements in the 2025 ASCE Mid-Atlantic East & West Student Symposium at Penn State:

- 2nd place in structural efficiency & stiffness (Steel Bridge)
- 1st place in structural efficiency (3D Printed Bridge)

• First-ever academic use of mechanical metamaterials in a civil engineering competition



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Conclusion & Further Works

- **Demonstrated Feasibility:** Successfully validated GAI-driven structure-specific metamaterial concrete as a strong, lightweight alternative to conventional concrete

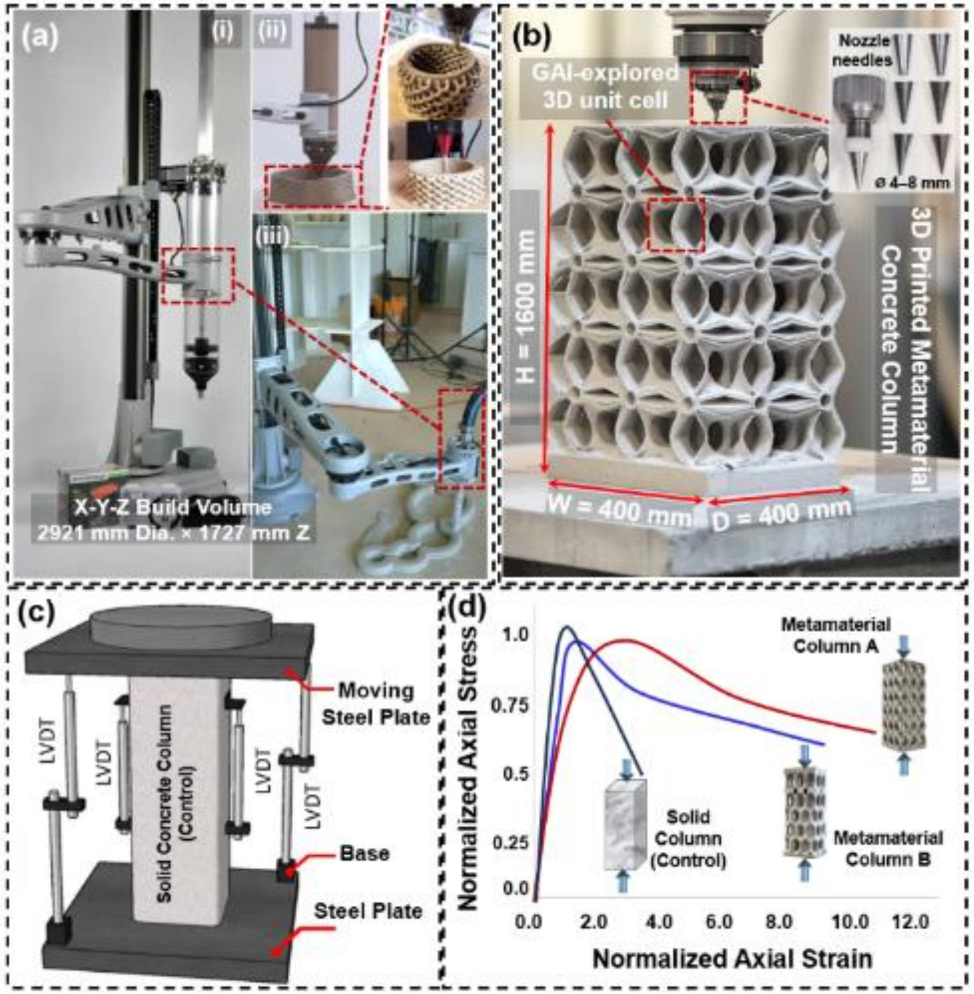
- **Enhanced Performance:** Showed significant improvements in strength-to-weight ratio with metamaterial concrete

- **Future Directions:**

  ✓ Clear protocols for material selection, 3D printing, and modular prefabrication ensure their efficiently into construction workflows

  ✓ Flexural performance can be improved using strategies like post-tensioning, external reinforcements, and grout encapsulation tailored to their geometry

  ✓ Field testing and regulatory code development are critical for scaling structure-specific metamaterial concrete in bridges, pavements, and modular infrastructure



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Thank You

We are the "Intelligent Structures and Architected Materials Research and Testing (ISMART)" Laboratory at the University of Pittsburgh

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