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Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

Innovative Precast Concrete Truss Using Adaptive Shape Memory Prestressing System

Project No.: UI-23-RP-02

FINAL REPORT

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Executive Summary:

One approach to improving the sustainability of transportation infrastructure is through optimizing the usage of materials. Carbon emissions can be reduced by using more efficient geometries that decrease the amount of concrete and steel needed for construction. Thus, this research studied the effectiveness of truss-shaped precast bridge girders as a way to increase sustainability.

The unique geometry of the truss becomes more feasible through the use of novel materials like shape memory alloys (SMAs). The SMAs can prestress the slender members of the concrete truss more easily than conventional prestressing methods. These prestressing forces improve structural performance by delaying the onset of cracking. Furthermore, the SMAs can be activated after cracking resulting in the healing of cracked concrete members.

First, truss bridge girders were studied using the Finite Element Method. A full bridge was developed. Different bridge girder geometries were then analyzed in a parametric study to iteratively determine the most optimal design.

Concrete specimens reinforced with SMAs were created to demonstrate the concept. Two were cast using formwork and one was printed using a 3D concrete printer. The results showed that SMAs are effective at prestressing concrete. It also showed that activation of SMAs can close cracks in the specimens, thereby healing the structure and prolonging the service life.

This research was presented at three poster presentations and in a journal paper. The importance of infrastructure sustainability through innovation was also conveyed to the younger generation through the TRIO Upward Bound's summer program and the Grainger College of Engineering's summer camp at the University of Illinois at Urbana-Champaign.

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TRANS-IPIC Final Report:

Problem Statement

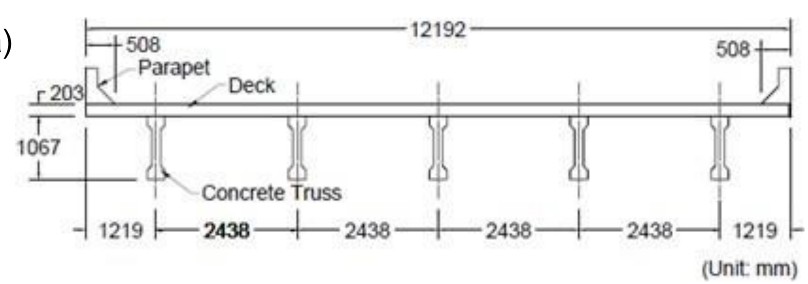
The ever-growing demand for making our transportation infrastructure more sustainable requires serious efforts to reduce carbon emissions associated with the concrete and steel used in transportation infrastructure. One way to achieve sustainability is by optimizing the materials used in transportation infrastructure. This research helps address this issue by studying the application of shape memory alloys (SMAs) in a geometrically optimized (truss) system. The SMAs apply localized prestressing in any direction without mechanical tensioning or special hardware, which is ideal for prestressing short diagonal or vertical members of a truss. The research includes numerical simulation and experimental testing of geometrically complex truss structures with SMAs placed in tension members that are difficult to prestress using conventional methods. The performance of the new truss is compared with traditional bridge girders to prove the feasibility of the new concept.

Design of Full-scale Bridge using Finite Element Method

The finite element method (FEM) was used to analyze full-scale bridges with a superstructure system comprising a truss system reinforced with SMAs and compare its performance with conventional bridge designs. The goal was to numerically examine the feasibility of applying prestressing with SMAs in designing a truss system that can withstand conventional design loads as per the American Association of State Highway and Transportation Officials (AASHTO) Load-and-Resistant Factor Design (LRFD) design specifications.

Concrete bridge girders were chosen as an example application in this study to demonstrate the viability of the concrete truss concept. With five prestressed concrete girders, the example bridge was intended to be a standard single-span mid-range bridge (**Fig. 1a**). Five AASHTO Type-II girders, placed equally apart, supported the 203 mm thick deck. Five concrete trusses support the deck of the same bridge, which was created utilizing the concrete truss method. According to the truss analogy, a common model for concrete behavior in flexure, the concrete truss was constructed as a Howe truss (**Fig. 1b**).

(a)



(b)

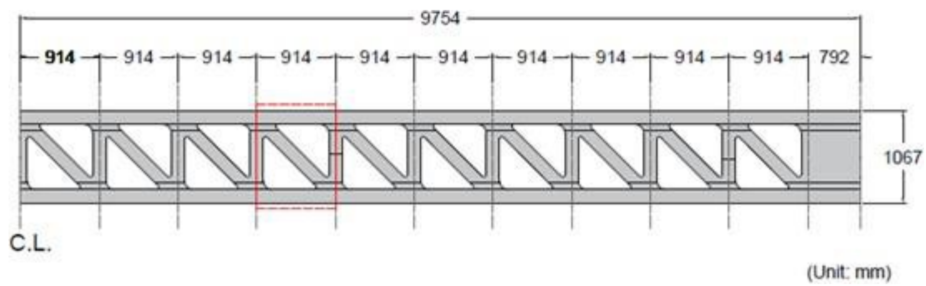


Figure 1. (a) Bridge cross-section and (b) truss layout

The precast concrete truss was prestressed using SMAs in conjunction with a traditional pre-tensioning method. Because the bottom chord could prestress more than its SMA counterpart, it was reinforced with traditional pre-tensioning reinforcements. SMA bars, which can apply targeted prestressing force considerably more easily than the traditional prestressing system, were used to prestress the vertical parts. According to the Load-and-Resistant Factor Design (LRFD) strength limit states of AASHTO, the concrete truss was designed with realistic loading conditions in mind (AASHTO, 2020).

The live load capacity and demand curves for the reference and concrete truss models are displayed in **Fig. 2**. Only the additional load over the factored dead load as per the AASHTO strength I limit state was reported, as the dead load of the two models differs. The additional load represents the reserved capacity for the live load. According to the AASHTO strength I limit state's live load, dashed lines depict the demand curve for the moment (**Fig. 2a**) and shear (**Fig. 2b**) along the distance from the midspan. The reference and truss systems, in every case, surpass the AASHTO strength I limit states. Along the girder's length, the capacities of the concrete truss model range from 60% to 90% of those of the reference model.

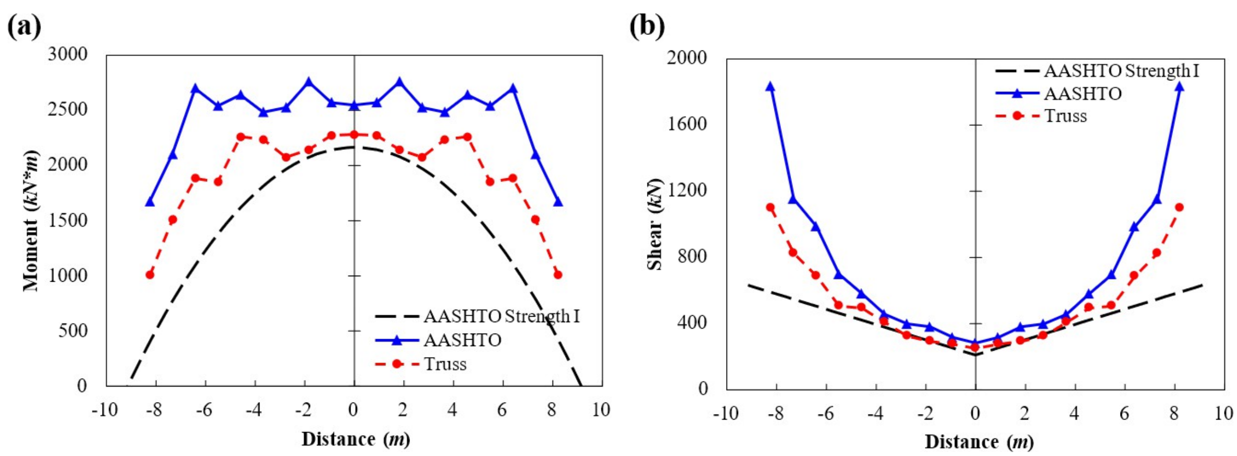


Figure 2. Demand vs. capacity of the truss and reference bridge models for (a) moment and (b) shear

Design of Bridge Girders using Finite Element Method

The design of the bridge girder involved a comprehensive parametric study aimed at optimizing a truss system capable of enabling longer spans while using the same or reduced concrete volume compared to conventional AASHTO I-girders. The parametric study investigated several key design variables, including the length and depth of the truss, the dimensions of the flanges, web thickness, the number and size of voids, and the number and arrangement of SMA bars in the vertical members. Specifically, the lengths of trusses considered ranged from 20 to 35 feet, with depths varying between 36 and 60 inches. The widths of the bottom and top flanges were analyzed at different values to identify the optimal balance between material efficiency and structural performance.

The FEM analyses were conducted to evaluate different configurations of the truss system. The results demonstrated that a truss with a span length of 26 feet was optimal, achieving a 30% increase in span length while using 25% less concrete compared to a conventional 20-feet AASHTO I-girder. This material reduction not only contributes to sustainability goals but also demonstrates the potential of the truss system to enhance structural efficiency without compromising safety or performance. The optimized truss system reinforced with steel rebars is shown in **Fig. 3**.

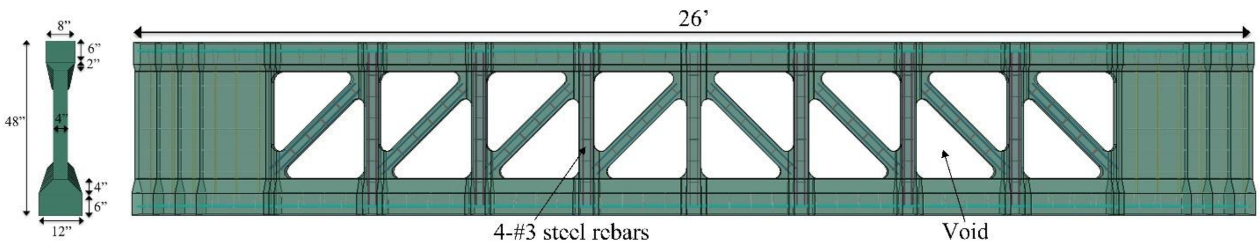


Figure 3. Optimized truss system (vertical members reinforced with steel rebars)

In order to investigate the efficiency of SMA bars as prestressing, the vertical steel bars (2.75% reinforcement ratio) in vertical members were replaced with SMA bars (2.41% reinforcement ratio) as shown in **Fig. 4**. By placing SMA bars in the vertical members, targeted prestressing forces could be applied, thereby improving the load-carrying capacity of the truss and delaying the onset of cracking. The FEA results confirmed that the cracking load was increased by 46% when SMA bars were used compared to the steel bars case. This approach allowed the truss to maintain compliance with AASHTO LRFD design specifications while reducing material usage and extending span capabilities. A shortened version of this truss will be cast and tested next year.

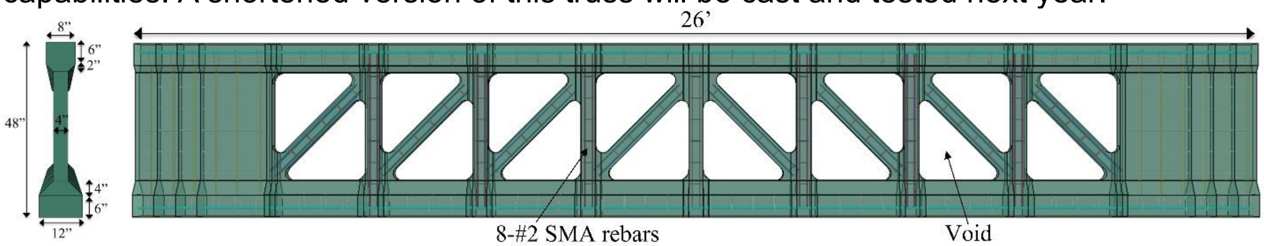


Figure 4. Optimized truss system (vertical members reinforced with SMA rebars)

Fabrication, Instrumentation, and Testing of Flexural Specimen

To understand the behavior of concrete truss members when prestressed with SMA bars under both bending and tension, several experimental tests were carried out. The first test focused on the flexural performance of concrete reinforced with SMAs. A concrete beam was reinforced with two 2 mm diameter SMA wires placed internally near the bottom of the beam (**Fig. 5a**). These wires were prestrained to 6% and the ends were bent into 90-degree hooks. Sheet metal was folded around the hooks as reinforcement, and a thermocouple was attached to the SMAs inside. A Crack Opening Displacement (COD) gauge and a strain gauge were attached to the specimen to monitor crack development (**Fig. 5b**). A notch was added to the center of the beam to ensure the crack developed near the sensors.

(a)

(b)

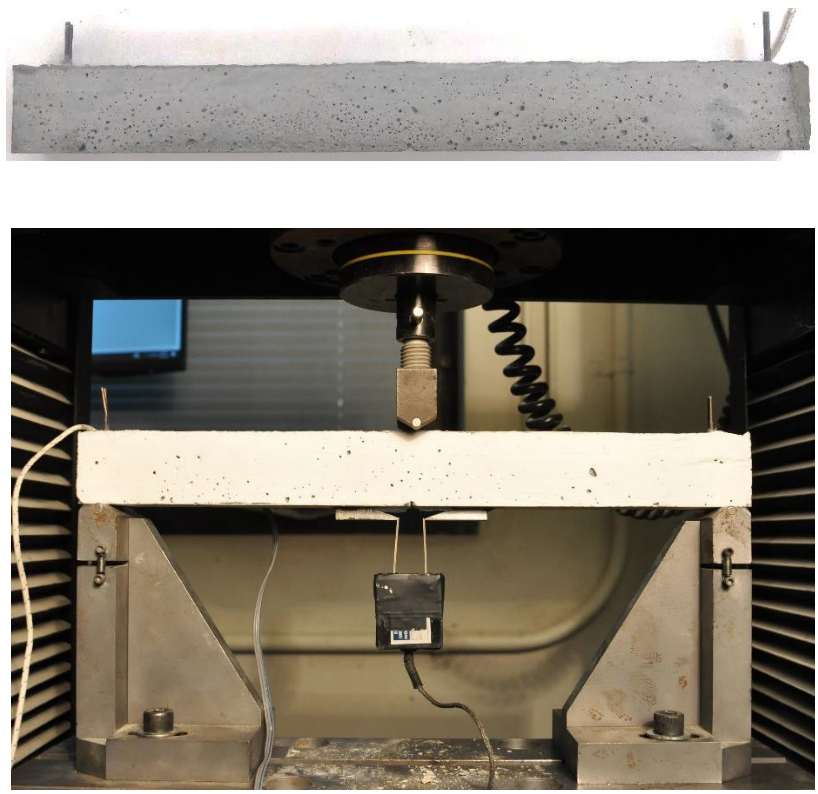


Figure 5. (a) Test specimen after curing and (b) during flexural test

The beam was subjected to a three-point flexure test until the COD gauge read 0.29 mm (**Fig. 6a**). The beam was then unloaded and the exposed SMA ends were connected to a power supply. An electrical current was passed through both SMA wires, triggering the shape memory effect by heating the wires with electrical resistivity. The crack closed completely after the SMA was activated (**Fig. 6b**).

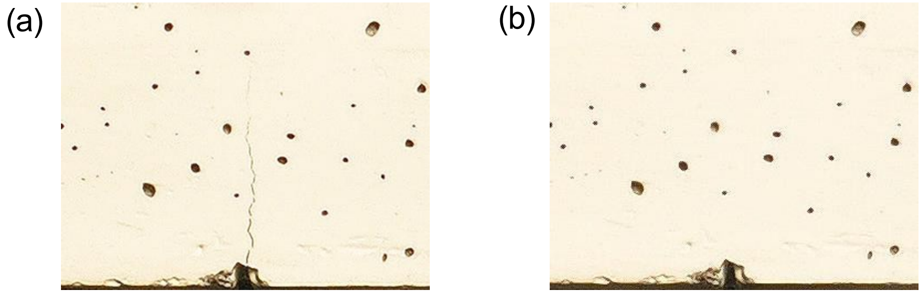


Figure 6. (a) Crack during loading and (b) crack after activation

The beam was loaded again immediately after healing. It was unloaded when the COD gauge read 0.48 mm (**Fig. 7a**). A second activation closed the crack once more (**Fig. 7b**). This demonstrated the effectiveness of SMA in healing cracks in concrete members. This also showed that the healing process is repeatable.

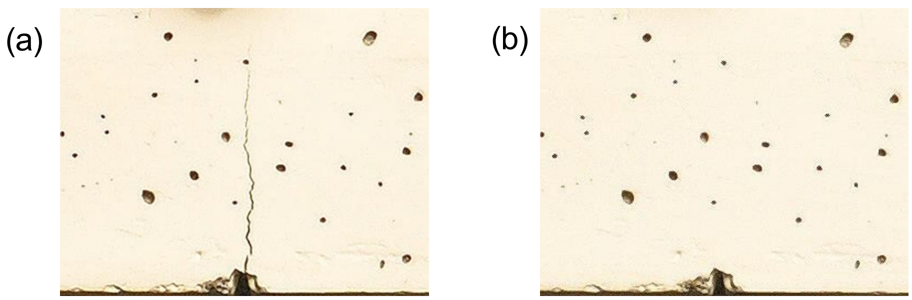


Figure 7. (a) Crack during re-loading and (b) crack after re-activation

<u>Fabrication, Instrumentation, and Testing of Tensile Specimen</u>

The effect of SMA in prestressing and healing a tensile concrete member was studied. A concrete specimen was reinforced with four pre-strained 6.3 mm diameter SMA bars. The bars were sequentially heated with electrical resistivity to trigger the shape memory effect. The strain gauges attached to the center of the specimen (**Fig. 8**) indicated that prestressing was achieved.

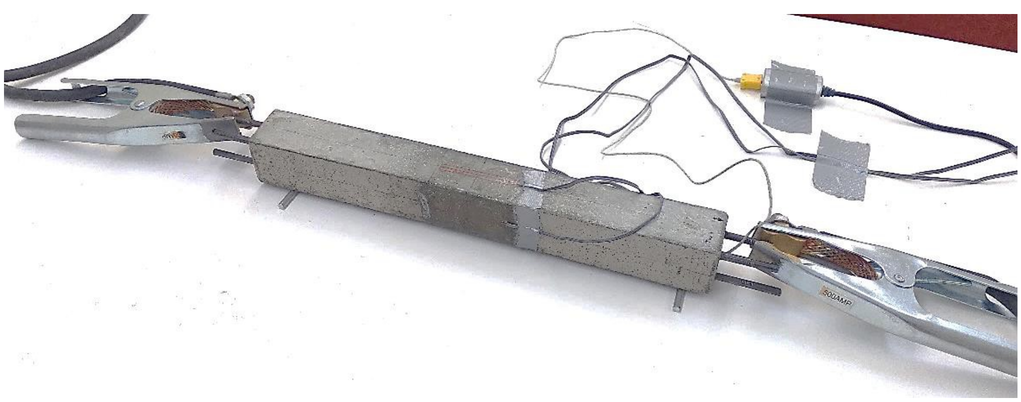


Figure 8. Activation of tensile specimen

Aluminum plates were then attached to the specimen using epoxy to create connection points to the test machine. The specimen was tested under pure tension and stopped when a 0.5 mm wide crack developed near the center of the specimen (**Fig. 9a and 9b**). After unloading, the bars were heated again with electricity to activate the shape memory effect. This caused the cracks to close completely (**Fig. 9c**) and affirmed that SMAs can be used to heal concrete members.

(a) (b) (c)

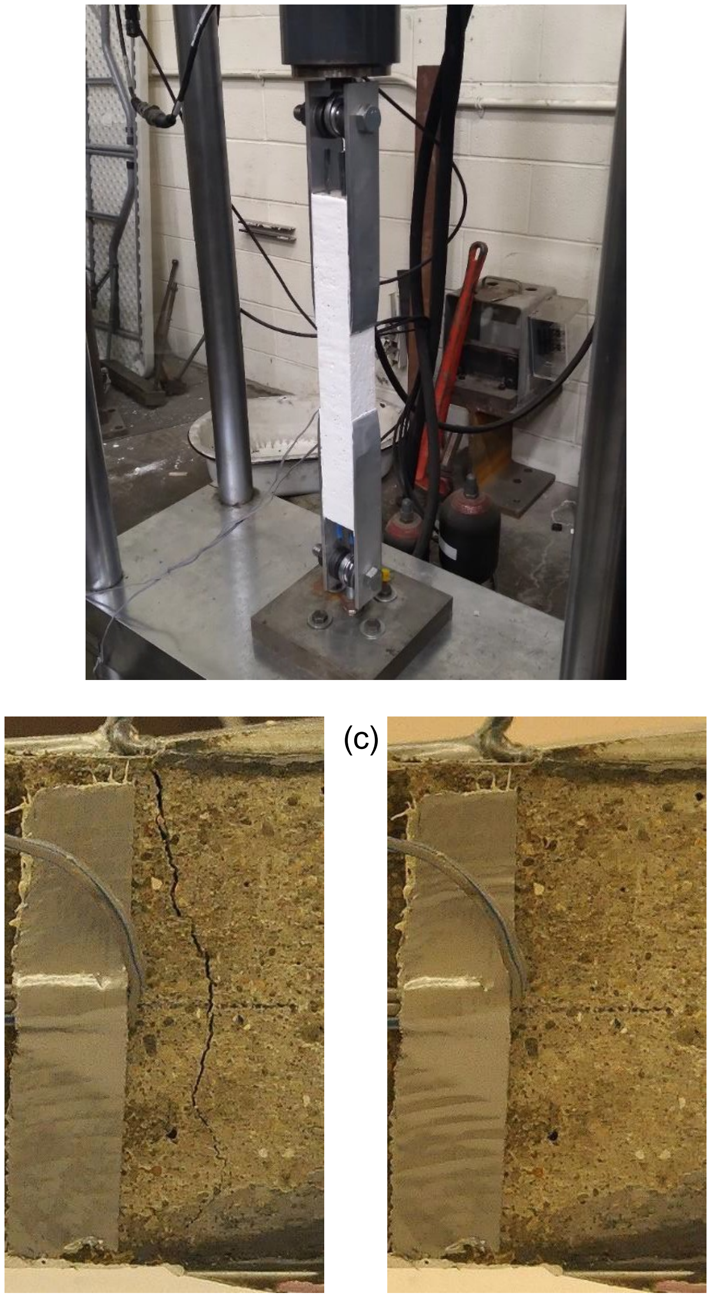


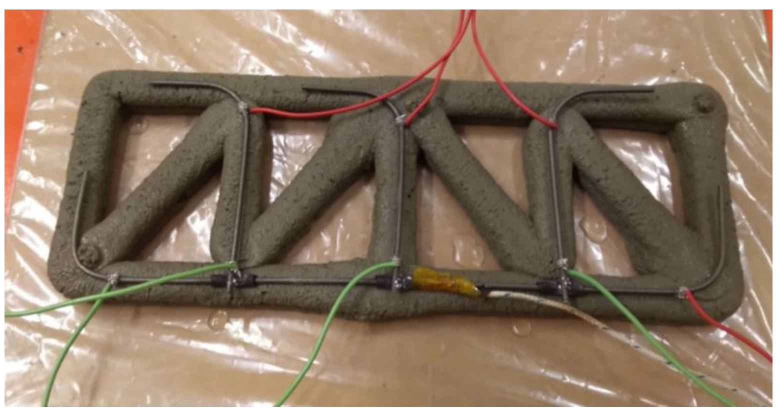
Figure 9. (a) Test setup, (b) crack before healing, and (c) crack after healing

Fabrication, Instrumentation, and Testing of 3D-Printed Specimen

The combination of 3D printed concrete (3DPC) technology with SMA was studied by printing a concrete truss reinforced using 2 mm diameter SMA wires. The SMA was added in between layers of the concrete. The lead wires were needed to allow the use of electricity to activate the SMA after curing. A thermocouple was attached to the lower SMA so that the temperature could be tracked during heating. **Figure 10a** shows the specimen before the final layer was printed on top. The design was based on a Howe truss, so the SMA reinforcement was only added to the tensile members of the truss.

The 3D concrete printer demonstrated advantages over conventional formwork by handling complicated geometry quickly and easily. The voids were created without the need for sacrificial formwork. After curing, a strain gauge was attached, and the specimen was heated using electrical resistivity. The strain gauge detected compression in the bottom chord, indicating that it was prestressed by the SMA. After activation, the specimen was tested under three-point flexure. Digital Image Correlation (DIC) was used to detect the cracks (**Fig. 10b**). The crack developed in the bottom chord where maximum tension was expected. The specimen was then unloaded and the SMA was re-activated to heal the specimen. The crack decreased in size after heating, confirming that healing 3DPC with SMA is viable (**Fig. 10c and 10d**). The effect can be emphasized by increasing the amount of SMA reinforcement.

(a)



(b) (c) (d)

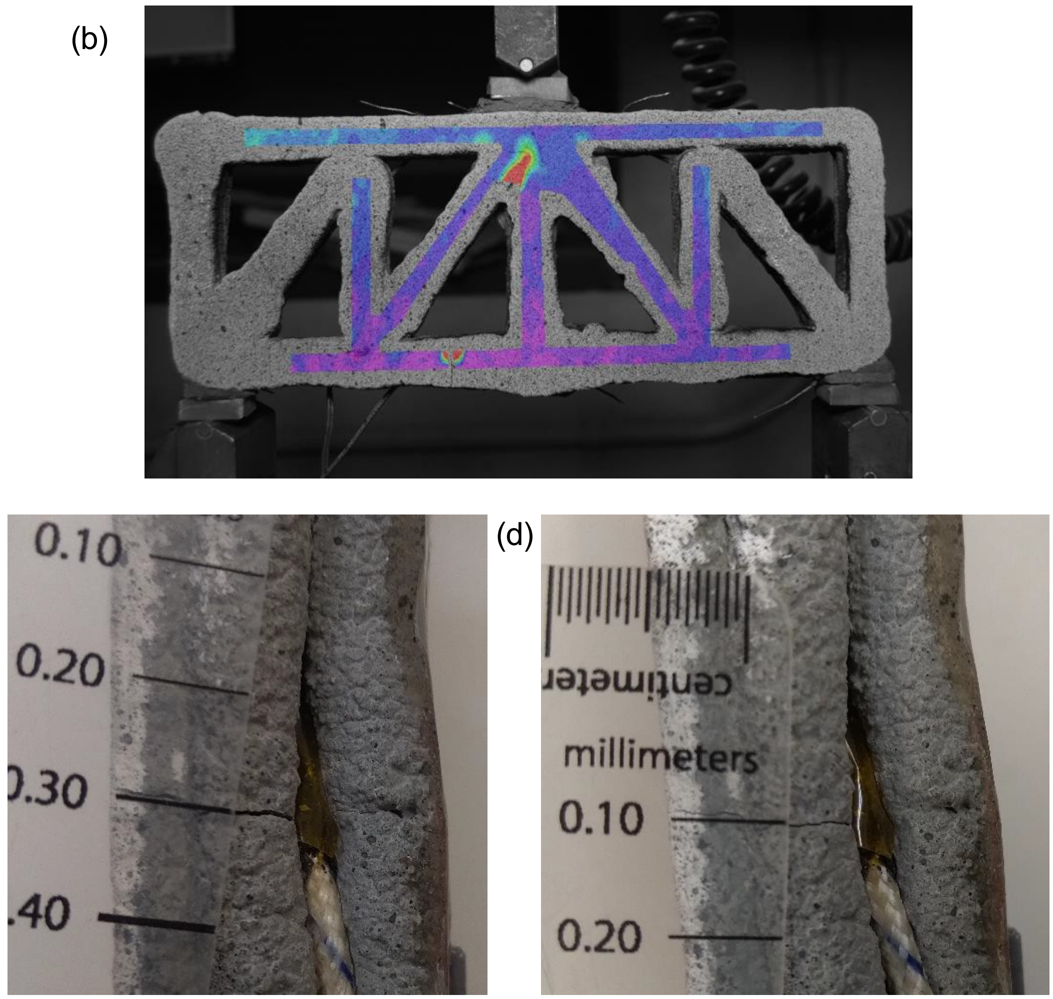


Figure 10. (a) Specimen printing, (b) testing, (c) before healing, and (d) after healing

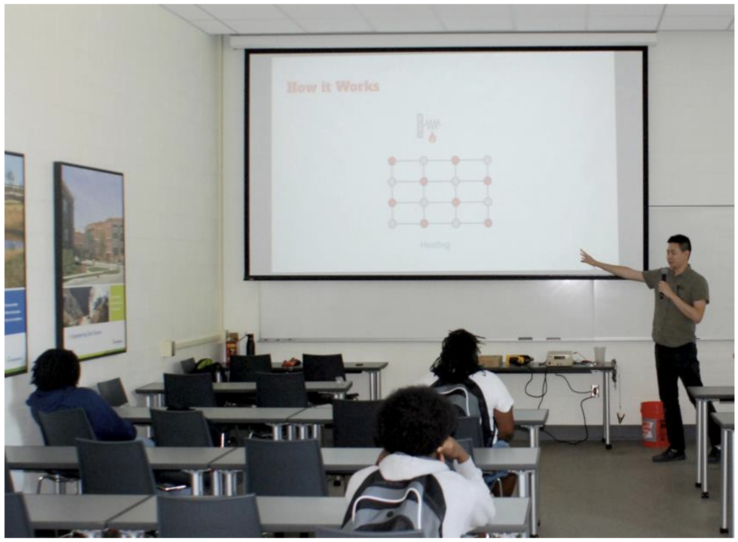
Educational Outreach Activities

It was important to convey the significance of innovation in transportation infrastructure to the younger generation. Therefore, our research group participated in the TRIO Upward Bound's summer program and the Grainger College of Engineering's summer camp.

The TRIO Upward Bound program brings high school students to the University of Illinois Urbana-Champaign campus and encourages enrollment in a post-secondary institution. Our portion of the program was called "Building Bridges with Memory" and introduced the students to the use of shape memory alloys in concrete bridges.

The students attended afternoon activities prepared by our research group throughout June and July. Some afternoons were classroom lessons (**Fig. 11a**) while others were hands-on, such as concrete casting (**Fig. 11b**). There were also days dedicated to tours. For one afternoon, the students were given a tour of the Newmark crane bay and attended one of the experiments of our research group (**Fig. 11c**). For another afternoon, the students were taken on a tour of a local concrete production plant (**Fig. 11d**). There are also certain days spent at a computer lab, so the students could learn computer-aided design (CAD) drawing software and structural analysis software.

(a)



(b)

(c)

(d)

Figure 11. (a) Classroom lesson, (b) concrete casting, (c) tour of Newmark, and (d) tour of concrete plant

As part of our goals of educating the younger generation, our research group hosted high school students during the Grainger College of Engineering's "City Designers and Builders" 2024 Summer Camp. Our session, "Building with Memory," demonstrated the use of shape memory alloys in civil engineering applications. The students were given a tour through the Newmark crane bay and allowed to inspect and inquire about our various research projects (**Fig. 12**).

(a)

(b)

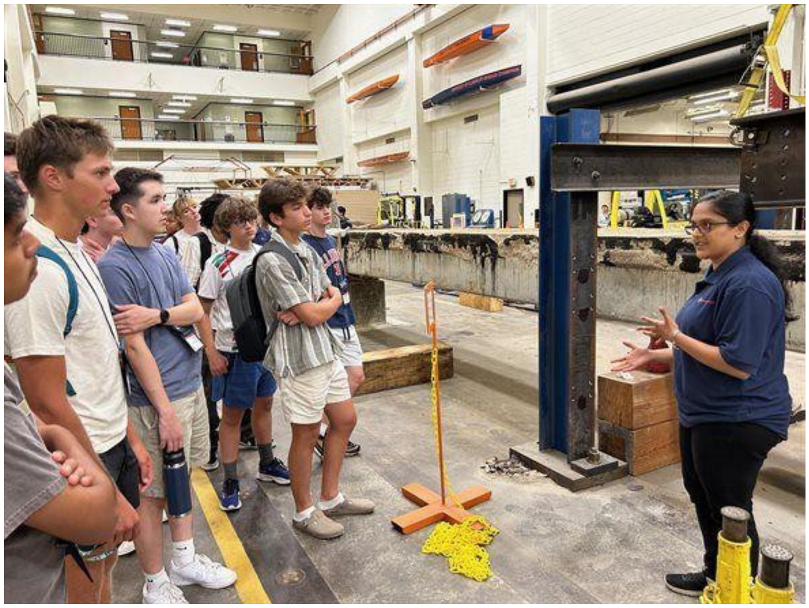


Figure 12. (a) Formwork and equipment for prestressing bridge girders and (b) a bridge girder ready for testing

Papers that Include TRANS-IPIC UTC in the Acknowledgments Section

Sung, M. & Andrawes, B. “Innovative Precast Prestressed Concrete Truss System Using Shape Memory Alloys and Conventional Steel” Journal of Intelligent Material Systems and Structures. (Federal Funds Acknowledgment: Yes)

Presentations and Posters of TRANS-IPIC Funded Research

A poster was presented at the US DOT Future of Transportation Summit held in Washington, DC on August 13th-15th, 2024 (**Fig. 13**).

Figure 13. US DOT Future of Transportation Summit

A poster was presented at the ASCE International Conference on Transportation and Development held in Atlanta, GA on June 16th-18th, 2024 (**Fig. 14**).

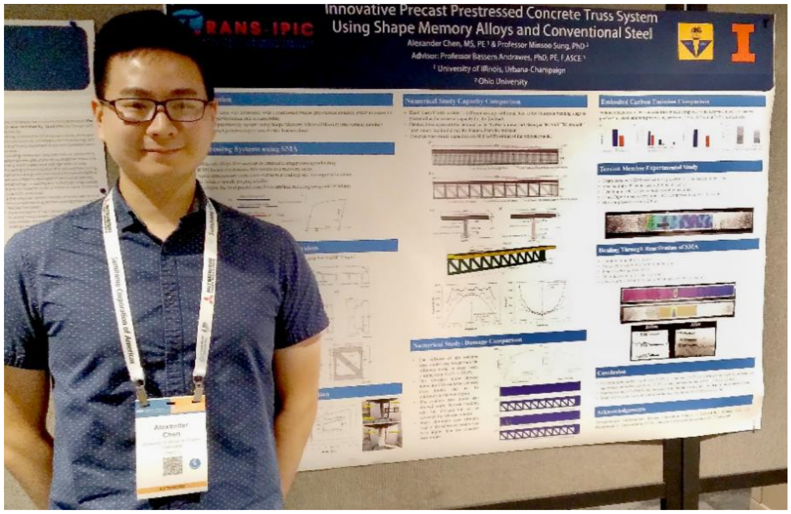


Figure 14. International Conference on Transportation & Development

A poster was presented at the 1st TRANS-IPIC Annual Workshop held in Rosemont/Chicago, IL on April 22nd, 2024 (**Fig. 15**).

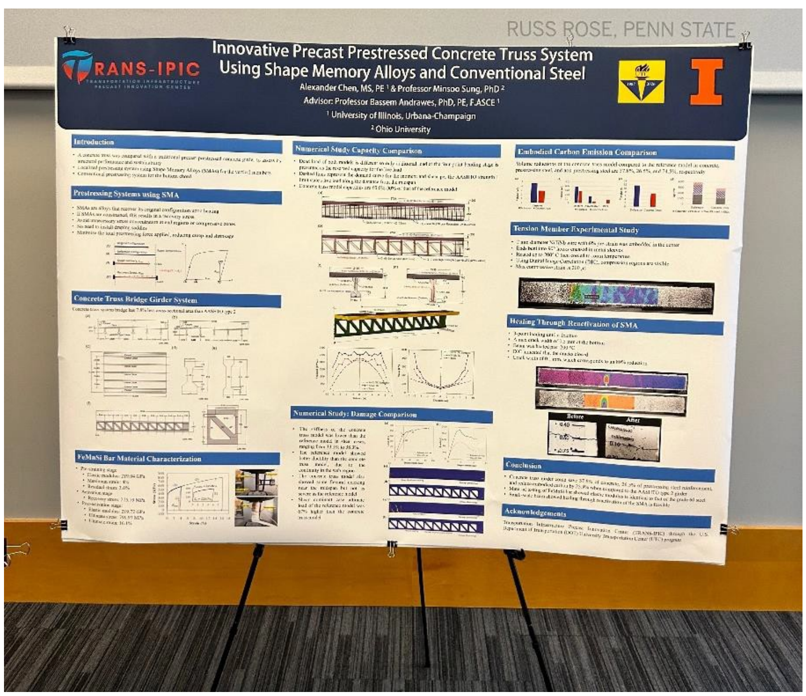


Figure 15. TRANS-IPIC Annual Workshop

A presentation on the experimental work in this final report will take place at the ASCE Structures Congress held in Phoenix, Arizona on April 9th -11th, 2025.