Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

3D Printed Smart Permanent Concrete Formwork for Precast Structural Component-Structural Performance – Phase 2: Large Scale Testing
LS-24-RP-02

Quarterly Progress Report
For the performance period ending October 1st 2026

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TRANS-IPIC Quarterly Progress Report:

Project Description:

1. Research Plan - Statement of Problem

   Tens of thousands of bridges and more than 40% of all the roads and highways in the US are in urgent need of rehabilitation [1]. Structural health monitoring (SHM) has gained importance in detecting, measuring severity, and locating the early damage in concrete infrastructure. However, issues such as durability, material compatibility, and cost challenge the wider adoption of this technology. Tackling these challenges by infusing additional functionalities into precast concrete (PC) will yield enhanced resilience and extended lifespan. In our previous research, self-sensing cementitious composites (SSCC) demonstrated the capability for producing smart formwork, the fabrication of which depended on additive manufacturing technology [2]. In this phase of our research, our aim is to evaluate the structural performance of large-scale 3D-printed smart formwork and validate its feasibility in real-world applications.

2. Research Plan - Summary of Project Activities (Tasks)

   Task 1: Literature Review and Test Matrix Design
   Task 2: Specimen Fabrication
   Task 3: Load Testing
   Task 4: Data Analysis and Multiphysics Modeling

Project Progress:

3. Progress for each research task

Task 2: Specimen Fabrication [80% completed to date]

Task 2.2: Test Specimen Design

Figure 1. shows the schematic of the self-sensing 3D printed reinforced concrete (SS-3DPRC) column as well as the eccentric axial loading setup. The self-sensing bands are 3D printed in the top, middle, and bottom sections of the column. The eccentric loading will be achieved through a pinned-pinned boundary condition. These boundary conditions will be achieved by preparing a custom steel collar that will house the specimen during loading. The free rotation of the column at the supports will be achieved by applying the axial compressive force via the round knife hinges.

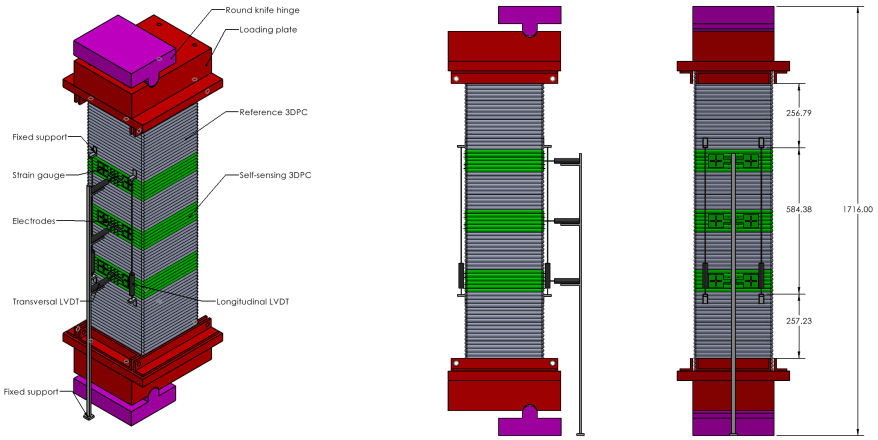


Figure 1. Perspective, front and side view from the CAD model of self-sensing 3D printed reinforced concrete column and boundary conditions

Task 2.3: 3DPC Specimen Fabrication

During this quarter, short SS-3DPRC column segments (Figure 2) and one full-height column (Figure 3) were printed. Printing was done with a KUKA robotic arm paired with a portable concrete pump. The printed shells serve as permanent (stay-in-place) molds and were grouted with the reference concrete mixture 24 hours after printing.



Figure 2. 3D printed self-sensing segment

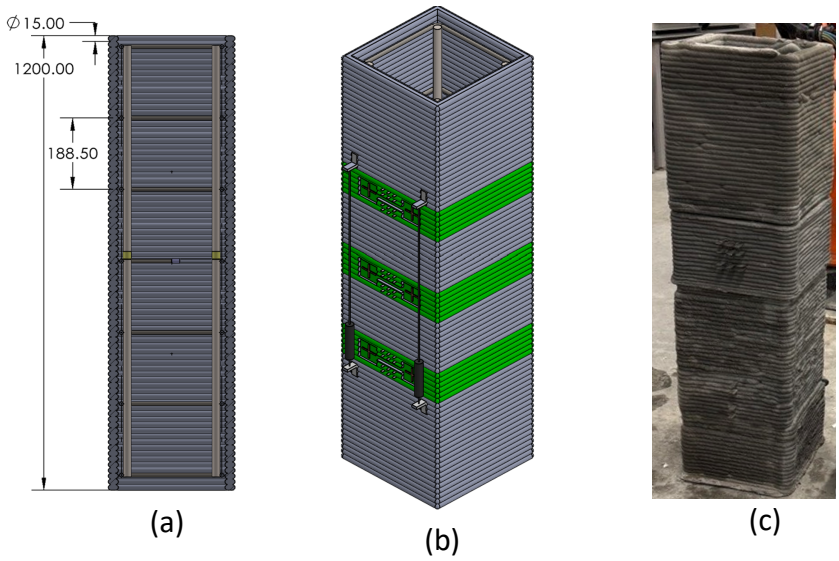


Figure 3. Cross-sectional (a) and isometric view (b) of the self-sensing column permanent mold and the 3D printed real column permanent mold (c)

The printing parameters are listed in Table 1. They were selected based on the pumpability, extrudability, and buildability of the concrete. A circular nozzle with a 16 mm (0.63 in.) diameter was used to print layers 30 mm (1.18 in.) wide and 15 mm (0.59 in.) high. The full-height column consisted of 80 layers, for a total height of 1,200 mm (47.2 in.). Buildability is the main limiting factor when printing tall structures, so the process was tuned to maximize it. The workability of the concrete was reduced to increase buildability without compromising extrusion quality. A vibrating hopper was also added to the pump to keep the concrete flowing continuously and prevent air gaps. This improved both print quality and buildability. As a result, walls 30 mm (1.18 in.) wide could be printed to a height of 200 mm (7.87 in.) before a pause was needed. To reach the full column height, printing was paused for 30 minutes after each such segment. Each pause let the printed concrete reach initial set, gaining enough stiffness to support the layers above, while it was still fresh enough to bond with the next layer. This allowed the full-height column to be printed as one continuous element.

Table 1. Printing parameters chosen for 3D printing the self-sensing column.

Printing Parameter	Setting
Nozzle Shape	Circular
Nozzle Size (mm)	16
Printing Speed (m/s)	0.2
Pump Speed (RPM)	12
Layer width (mm)	30
Layer height (mm)	15

Task 3: Load Testing [20% completed to date]
Mechanical testing was initially planned using a *servohydraulic Instron* actuator and an *MTS* load cell, each with a capacity of 110 kips (489 kN). The test program has since been expanded to include monotonic loading to failure in addition to cyclic loading at lower load thresholds (10% and 20% of capacity). The expected failure load of the 3D-printed columns is approximately 375 kips (1,668 kN), which is well beyond the capacity of the original setup. The testing will therefore use a 500-kip (2,224 kN) actuator accompanied by a 500-kip (2,224 kN) load cell. With this setup, the specimens can be loaded until failure while the peak load stays at about 75% of the device's rated capacity. To apply an axial load at an eccentricity of 100 mm (3.94 in.), a custom knife-edge hinge and loading plate were designed. The knife-edge hinge allows for the column end to rotate freely about a single axis, so it behaves close to a pinned boundary condition. The loading plate places the line of action of the applied load 100 mm (3.94 in.) from the column's centroid. An identical assembly is installed at both the top and bottom of each column, so the eccentricity is the same at both ends and the column bends in a single curvature. As a result, the column carries combined axial compression and uniaxial bending, with an end moment equal to the axial load times the eccentricity (M = P·e). The dimensions of the knife-edge hinge and loading plate are shown in Figure 4.

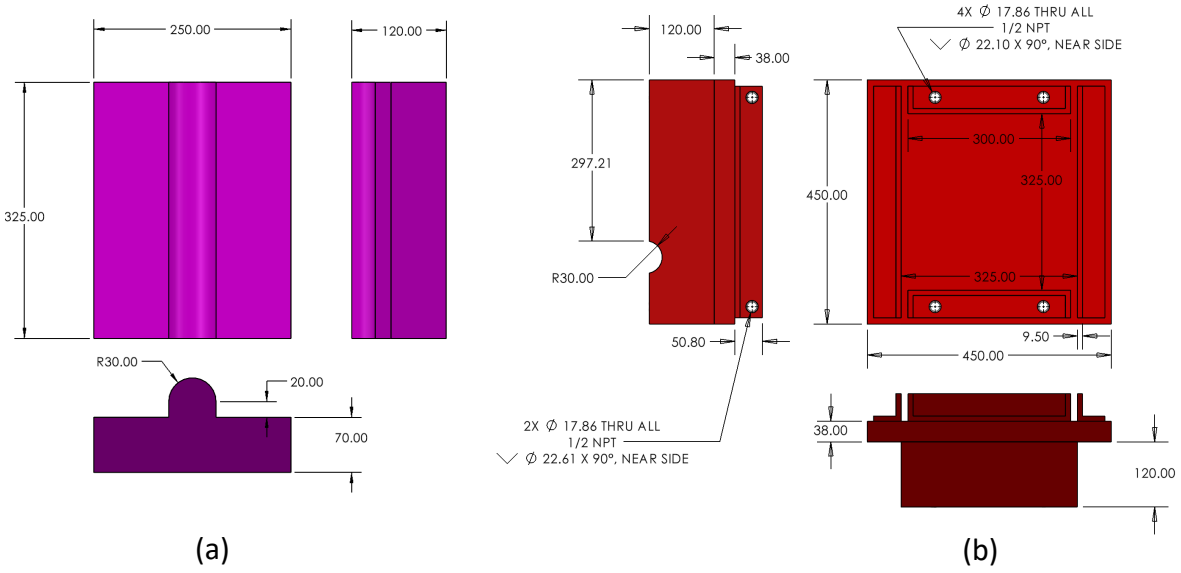


Figure 4. Custom knife-edge hinge (a) and loading plate (b) for the application of eccentric axial load

Task 4: Data Analysis and Multiphysics Modeling [80% completed to date]
A coupled thermo-electro-mechanical model is developed in COMSOL Multiphysics to reproduce the strain- and temperature-dependent electrical response of the self-sensing cementitious composite (SSCC). The piezoresistive component is adapted from Xu et al. [1], who reduced the combined ohmic and tunneling resistance to an exponential strain-dependent form. Temperature dependence is incorporated using the Arrhenius relationship reported by Chang et al.[8] for carbon-fiber-enhanced concrete. The resulting conductivity implemented in COMSOL is

$$\sigma(\varepsilon, T) = \sigma_0 \frac{1+g}{1+ge^{\kappa\varepsilon}} \exp\left[\frac{-E_a}{k_B}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] \quad (1)$$

where σ_0 is the baseline conductivity at reference temperature T_0, g is the relative tunneling contribution, κ is the piezoresistive strain-sensitivity parameter, E_a is the activation energy, and k_B is the Boltzmann constant.

Calibration follows the four experimental conditions. The no-load, constant-temperature (NL) test establishes σ_0 and T_0. Cyclic-load, constant-temperature (CL) data are used to obtain Young's modulus E

and Poisson's ratio v, while strain-dependent electrical responses are pooled to determine a single specimen-specific κ; with κ fixed, g is calibrated from the CL response. The no-load temperature-varying (NL-T) data isolate the thermal effect and determine a single specimen-specific E_a. Finally, the cyclic-load temperature-varying (CL-T) dataset is reserved for independent validation of the fully coupled model. Representative outputs from the coupled COMSOL analysis and the comparison between simulated and experimental FCR responses are presented in Figure 4.

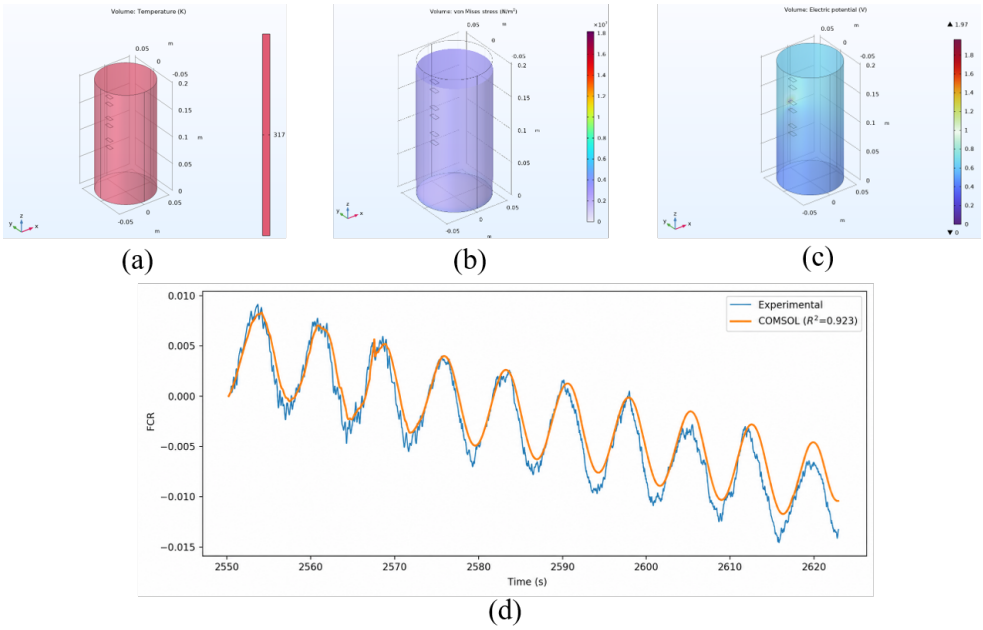
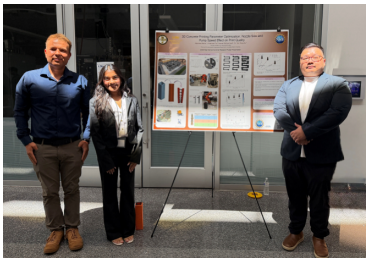


Figure 6. Representative results from the coupled thermo-electro-mechanical COMSOL model showing (a) temperature, (b) von Mises stress, and (c) electric potential fields, together with (d) the experimental and simulated FCR responses used to assess model performance

4. Percent of research project completed
   Task 1: Literature Review and Test Matrix Design [100%]
   Task 2: Specimen Fabrication [80%]
   Task 3: Load Testing [20%]
   Task 4: Data Analysis and Multiphysics Modeling [80%]

5. Expected progress for next quarter
   In the upcoming quarter, our goal is to finish fabricating all specimens and test them under both symmetric and asymmetric loads at upper thresholds. The dataset will be collected and analyzed for final report.

6. Educational outreach and workforce development
   (1) Mentoring one high school student – Adishree Mehta on the LSU High School Summer Research Internship, focusing on 3D printing of concrete columns.



7. Technology Transfer
   None

Research Contribution:

8. Papers that include TRANS-IPIC UTC in the acknowledgments section:
   (*G: Graduate Student, UG: Undergraduate Student*)
   (1) **Masoud Pasbani[G] , Khalilullah Taj[G], Ayman Okeil,** Xueying Wang, and **Yen-Fang Su***. 2026 "Sustainable Self-Sensing Ultra-High Performance Concrete with Portland Limestone Cement and Steel Carbon Hybrid Fibers: Multi-Objective Optimization of Mechanical, Durability, and Piezoresistive Performance" *Construction and Building Materials* (Revision under review)
   (2) **Khalilullah Taj[G], Shezan Mahmud[G], Mohammed Alnaggar,** and **Yen-Fang Su***. 2026. "Calibration and Standardization of Self-Sensing Cementitious Sensors through Polarization–Piezoresistivity Decoupling: Effects of Testing Configuration." *Structural Health Monitoring*, (In preparation)
   (3) **Khalilullah Taj[G]**, **Masoud Pasbani[G]**, and **Yen-Fang Su***. 2026. "Review of Structural Performance in 3D Printed Reinforced Concrete Members" *Engineering Structures*, (In preparation)

9. Presentations and Posters of TRANS-IPIC funded research:
   (1) **Khalilullah Taj[G]**, **Shezan Mahmud[G]**, Mohammed Alnaggar, **Yen-Fang Su***, "Temperature Compensation for Resistivity and Piezoresistivity in Self-Sensing Cementitious Composites", TRB Annual Meeting 2027, DC, (accepted)
   (2) **Khalilullah Taj[G], Shezan Mahmud[G], Mohammad Alnaggar, Yen-Fang Su*,** "Temperature Compensation in Piezoresistive Modeling of Self-Sensing Cementitious Composite Sensors for Critical Infrastructure", SMiRT 2027 Conference, Lyon, France (submitted).
   (3) **Khalilullah Taj[G], Yen-Fang Su*,** "Performance of Self-Sensing Cementitious Composite Sensors Embedded in Eccentrically Loaded 3D-Printed Reinforced Concrete Columns", SPIE Smart Structure + NDE, Vancouver, Canada (Submitted).
   (4) **Nasser Mohammed[G], Khalilullah Taj[G], Yen-Fang Su*,** "Pressure-Dynamics-Based Virtual Flow Sensing for Extrusion-Based 3D Concrete Printing", IEEE ONCON 2026 Conference (in preparation).
   (5) **Khalilullah Taj[G], Ayman Okeil, Yen-Fang Su*,** "Self-Sensing Performance of Structural-Scale 3D-Printed Reinforced Concrete Columns Under Eccentric Compression", ASCE 2027 Infrastructure and Engineering Experience Conference, Philadelphia, Pennsylvania (Submitted).

10. Please list any other events or activities that highlight the work of TRANS-IPIC occurring at your university

None

Appendix 1: Research Activities, leadership, and awards (cumulative, since the start of the project)

A. Number of presentations at academic and industry conferences and workshops of UTC findings
   - No. = 5

B. Number of peer-reviewed publications submitted based on outcomes of UTC funded projects
   - No. = 3

C. Number of peer-reviewed journal articles published by faculty.
   - No. = 1

D. Number of peer-reviewed conference papers published by faculty.
   - No. = 2

E. Number of TRANS-IPIC sponsored thesis or dissertations at the MS and PhD levels.
   - No. MS thesis = 0
   - No. PhD dissertations = 0
   - No. citations of each of the above = 0

F. Number of research tools (lab equipment, models, software, test processes, etc.) developed as part of TRANS-IPIC sponsored research
   - Research Tool #1 (Name, description, and link to tool) = 0
   - Research Tool #2 (Name, description, and link to tool) = 0
   - Research Tool #3 (Name, description, and link to tool) = 0

G. Number of transportation-related professional and service organization committees that TRANS-IPIC faculty researchers participate in or lead.
   - Professional societies
     - No. participated in = 1
     - No. lead = 0
   - Advisory committees (No. participated in & No. led)
     - No. participated in = 0
     - No. lead = 0
   - Conference Organizing Committees (No. participated in & No. led)
     - No. participated in = 0
     - No. lead = 0
   - Editorial board of journals (No. participated in & No. led)
     - No. participated in = 0
     - No. lead = 0
   - TRB committees (No. participated in & No. led)
     - No. participated in = 1
     - No. lead = 0

H. Number of relevant awards received during the grant year
   - No. awards received = 0

I. Number of transportation related classes developed or modified as a result of TRANS-IPIC funding.
   - No. Undergraduate = 0
   - No. Graduate = 0

J. Number of internships and full-time positions secured in the industry and government during the grant year.
   - No. of internships = 2

- No. of full-time positions = 0

References:

Xu, J., W. Zhong, and W. Yao, Modeling of conductivity in carbon fiber-reinforced cement-26 based composite. J. Mater. Sci., Vol. 45, No. 13, 2010, pp. 3538-3546