TRANSPORTATION RESEARCH

CIRCULAR

Number E-C304 September 2025

TRB Conference on Advancing Additive Manufacturing and Construction in Transportation

November 7–8, 2024
Irvine, CA

NATIONAL ACADEMIES Sciences Engineering Medicine

TRB TRANSPORTATION RESEARCH BOARD

TRANSPORTATION RESEARCH CIRCULAR E-C304

TRB Conference on Advancing Additive Manufacturing and Construction in Transportation

November 7–8, 2024
Irvine, CA

Rapporteur
Victoria V. Deguzman
Institute of Transportation Studies
University of California, Irvine

Transportation Research Board
500 Fifth Street, NW
Washington, D.C.
www.trb.org

TRANSPORTATION RESEARCH CIRCULAR E-C304
ISSN 0097-8515

The **Transportation Research Board** is one of seven major program divisions of the National Academies of Sciences, Engineering, and Medicine. The mission of the Transportation Research Board is to mobilize expertise, experience, and knowledge to anticipate and solve complex transportation-related challenges.

The **Transportation Research Board** is distributing this E-Circular to make the information contained herein available for use by individual practitioners in state and local transportation agencies, researchers in academic institutions, and other members of the transportation research community. The information in this E-Circular was taken directly from the submission of the authors. This document is not a report of the National Academies of Sciences, Engineering, and Medicine.

Conference Planning Committee

Randy Iwasaki, *Iwasaki Consulting Services, Inc. (Co-Chair)*
Zofia Rybkowski, *Texas A & M University, (Co-Chair)*
William Anker, *Transportation Solutions*
Patricia S. Hu, *Bureau of Transportation Statistics*
Caitlin G. Hughes, *Federal Highway Administration*
Megan A. Kreiger, *U.S. Army Engineer Research and Development Center*

TRB Staff

Nancy Whiting, *Senior Program Officer*
Joanice L. Johnson, *Operations Coordinator*
Karissa Bingham, Director, *TRB Meetings and Conferences*
Bruce Millar, Deputy Director, *TRB Meetings Department*
Emily Gribbin, Senior *Meeting Assistant*

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. Tsu-Jae Liu is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The National Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at **www.nationalacademies.org**.

The **Transportation Research Board** is one of seven major program divisions of the National Academies of Sciences, Engineering, and Medicine. The mission of the Transportation Research Board is to mobilize expertise, experience, and knowledge to anticipate and solve complex transportation-related challenges. The Board's varied activities annually engage about 8,500 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state departments of transportation, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

Learn more about the Transportation Research Board at **www.TRB.org**.

Preface

The TRB Conference on Advancing Additive Manufacturing and Construction in Transportation was held November 7–8, 2024, at the Arnold and Mabel Beckman Center in Irvine, CA. The Additive Manufacturing (AM) process and Additive Construction (AC) applications are linked by 3D printing technical concepts. This global forum identified future transportation research needs by providing an idea of what is possible based on how the technology is being used now.

Speakers and panelists were organized into several tracks, each focusing on overarching issues to help decision makers and transportation officials prepare for expanded AC and AM adoption. The conference began with an opening plenary session (Session 1), moderated by Zofia Rybkowski, Texas A&M University. In this plenary, Creg Blue, Oakridge National Laboratory addressed Building a Future-Ready Manufacturing Innovation Ecosystem, followed by an Industry Update by Mark Burnham, Additive Manufacturing Coalition.

This was followed by two sets of breakout sessions, a plenary session and a site tour.

Session 2 was divided into two concurrent breakouts. Session 2A focused on the U.S. National Science Foundation (NSF) and Civil, Mechanical, and Manufacturing Innovation Program in Additive Manufacturing and Transportation, and was moderated by Daniel Linzell, U.S. National Science Foundation. Presentations began with an Overview of NSF Built Environment Research Efforts, by Daan Liang, NSF; followed by NSF Sponsored Built Environment Research Efforts and Their Impact on Transportation Infrastructure, by Kenichi Soga, University of California, Berkeley; an Overview of NSF Additive Manufacturing Research Efforts, by Linkan Bian, NSF; and NSF Sponsored Additive Manufacturing Research Efforts and Their Impact on Transportation Infrastructure, by Mania Aghaei Meibodi, University of Michigan, and Mo Li, University of California, Irvine.

Session 2B, titled Concrete Materials in Additive Manufacturing and Construction, was moderated by Maryam Hojati, University of New Mexico. It began with 3D Printing Using Ultra-High-Performance Concrete (UHPC) in Bridge Applications, by Atorod Azizinamini, Florida International University; followed by Additive Construction of a New Seismic Protective Bridge

System by Anthony Mackin, Jenna Migliorino, Hamdy Farhoud, and Islam Mantawy from Rowan University; Mix Design Concepts for Printing Concrete in 3DPC Applications by Ben Manaugh and Jeffrey Raphael Roesler, University of Illinois at Urbana-Champaign; and Development of a Slicer for Additive Construction of Concrete by Charith Nanayakkara Ratnayake, and Wenchao Zhou, University of Arkansas; Jim Mantes, Applied Research Associates, Inc; and Carl Jaggers and Zachary Hyden, AMBOTS, Inc.

Session 3 was also divided into two breakout sessions. Session 3A, titled Robotics, Automation, and Additive Construction in Building New Transportation Infrastructure, was moderated by Chris Atkinson, Office of the Secretary, U.S. Department of Transportation, and was a Panel Discussion by Xiaopeng Li, GE Vernova; Iris Rivero, University of Florida; and William Vavrik, Applied Research Associates, Inc.

Session 3B was composed of four presentations on Steel Construction in Additive Manufacturing, and was moderated by Atorod Azizinamini, Florida International University. These presentations were A Bridge to the Future of Steel Additive Manufacturing, by Ryan J. Sherman, Georgia Tech; Cold-Spray Additive Repair of Corroded Steel Bridge Beams, by Brian Schagen, UMass Amherst/MIT; Wire Arc Additive Manufacturing in Highway Bridge Infrastructure, by Ryan Slein, Federal Highway Administration (FHWA); and Evaluating the Material and Fatigue Performance of Wire Arc Additively Manufactured Steels for Transportation Applications by Hannah Kessler, Georgia Institute of Technology.

Session 4, Standard and Policy Session, moderated by Islam Mantawy, Rowan University, was a Panel Discussion by Eric Kreiger, U.S. Army Engineer Research and Development Center; Shawn Platt, National Institute of Standard and Technology; and Julie Ann Hartell, Texas A&M University.

The day ended with an optional site tour, 3D Printing at the University of California, Irvine–A Laboratory Tour.

The second day of the conference began with two plenary sessions, followed by a set of concurrent, breakout sessions, a final plenary session and closing remarks. The planning committee also met in a closed session following the closing remarks.

Session 5 (the first session of this day), titled Freight and Supply Chain, was moderated by Caitlin Hughes, FHWA. It began with a presentation on the Hawaii Department of Transportation (HDOT) by Edwin Sniffen, HDOT; followed by a presentation on the U.S. Department of Transportation (USDOT) by Allison Dane Camden, USDOT; and Neighborhood 91: How the First Additive Manufacturing Production Campus Shortened Supply Chains by Eric Versluys, The Barnes Global Advisors.

Session 6 addressed Culverts, Pipes, and Other Structures and was moderated by Pranay Singh, University at Buffalo. Presentations included Investigating the Seam Effect on Structural Failure of Additively Constructed Pipe Culverts by Alireza Hasani, Boshra Besharatian, and Sattar Dorafshan, University of North Dakota, and Marc Maguire, University of Nebraska-Lincoln; Design and Evaluation of a 3D-Printed Concrete Box Culvert, by Jim Mantes, Jon Mikhael Erekson, and Jaden Bennett, Applied Research Associates, Michelle L. Bernhardt-Barry and Tim Nunez, University of Arkansas, and Casey Roberts and Matt Friedell, Robotic Construction Technologies; Performance of Cast Grout and Foam Infilled Additive Construction Concrete Composites by Michelle L. Bernhardt-Barry, University of Arkansas; and Driving Transportation Innovation: 1Print's Strategic Research and Partnerships in 3D Concrete Printing Technology by Ian Arthur, Adam Friedman, and Fredrik Wannius, 1Print LLC; and Prannoy Suraneni, and Landolf Rhode-Barbarigos, University of Miami.

Session 7 was divided into two concurrent sessions. Session 7A, Constructing with In Situ Materials, was moderated by Alireza Hasani, University of North Dakota. Presentations included Additive Construction Material Processing by Jim Mantes, Aaron Pullen, and Sungho Kim, Applied Research Associates, and Michelle L. Bernhardt-Barry and Javier Lozano Casas, University of Arkansas; Additive Construction with Custom Concrete Mixes for Expeditionary Applications by Benjamin D. Nelson, Eric Faierson, and Patrick A. Johnson, Iowa State University, Jim Mantes, Applied Research Associates Inc., and Michelle L. Bernhardt-Barry, University of Arkansas; The Use of Indigenous Soils in Additive Construction: Material Characterization, Mix Design, and Performance by Michelle L. Bernhardt-Barry, Bailey Downing and Jesus Serrano Espinoza, University of Arkansas, Jim Mantes, Applied Research Associates; and Eric Faierson and Benjamin Nelson, Iowa State University; and the Impact of Geometry on Performance in the Built Environment and Its Potential for 3D Printing by Zofia Rybkowski, Texas A&M University; Mehdi Farahbaksh, University of Texas, and Negar Kalantar, California College of the Arts.

Session 7B focused on Geopolymers and Cementitious Composites, and was moderated by Brian Schagen, University of Massachusetts, Amherst. Presentations included Fostering Resilient Transportation Infrastructure: Exploring the Fresh and Hardened Properties of 3D-Printed Ultra Ductile Engineered Cementitious Composites by Maryam Hojati, University of New Mexico; Additive Construction of Low Embodied Carbon Geopolymer Concrete by Aly Ahmed and Islam Mantawy, Rowan University; and Development of 3D Printable Strain Hardening Cementitious Composites for Bridge-Related Applications by Pranay Singh, Venkateswara Swamy Gadde, Chi Zhou, Pinar Okumus, and Ravi Ranade, University at Buffalo.

The final session of the day and conference was a plenary session titled Wrap-up and Mapping a Research Agenda, moderated by Patricia Hu, Bureau of Transportation Statistics. Results of a Mentimeter poll are included in Appendix B.

The conference ended with Closing Remarks and Adjournment from Randy Iwasaki, Iwasaki Consulting Services, Inc. by pre-recorded video message, and Nancy Whiting, TRB, in-person, followed by a closed meeting of the Conference Planning Committee.

Conference participants left with a better understanding of how increased use of AM can affect logistics, supply chains, movement of goods, and related fields, and explored research into AC that is used in large-scale mobile AM (i.e., gantries, extruded structures, forms, molds and systems). Attendees included researchers from federal and state public governmental agencies, universities and colleges, non-governmental organizations, as well as private contractors and consultants.

In 2019, an earlier conference on the same theme held in Washington, DC, examined the state-of-the-art and explored some of the first connections between the technology and transportation.

This conference summary, prepared by Victoria Deguzman, is a compilation of the presentations and a factual summary of the ensuing discussions at the event. The planning committee was responsible for organizing the event. The views contained in this summary are those of individual participants and do not necessarily represent the views of all participants, the project panel, TRB, or the National Academies of Sciences, Engineering, and Medicine.

Presentations and key topics are summarized throughout this report. These summaries should not be construed as reflecting a consensus of the planning committee, the event participants, TRB, or the National Academies.

Contents

PUBLISHER'S NOTE

The views expressed in this publication are those of the committee and do not necessarily reflect the views of the Transportation Research Board or the National Academies of Sciences, Engineering, and Medicine. This publication has not been subjected to the formal Transportation Research Board (TRB) review process.

Committee Co-Chairs' Welcome

ZOFIA RYBKOWSKI
Texas A&M University
RANDY IWASAKI
Iwasaki Consulting Services, Inc.

Welcome to the Transportation Research Board (TRB) Conference on Advancing Additive Manufacturing and Construction in Transportation, held at the Arnold and Mabel Beckman Center in beautiful Irvine, California. TRB is part of the National Academy of Sciences, Engineering, and Medicine. TRB's mission is to harness a wealth of expertise and experience to address complex transportation challenges and identify research gaps.

As one of the seven principal branches of the National Academies, TRB explores research topics and implementation with impartiality by convening experts that span multiple disciplines and sectors. TRB's committees, volunteers, and staff all work together to enhance infrastructure resilience, explore groundbreaking technologies, and ensure public health, safety, and welfare in transportation. TRB then disseminates research through convening activities, cooperative programs, and consensus studies, which assists in informing Congress and the nation.

This is actually the second international conference on 3D printing and transportation. The first was held from November 20–21, 2019, at the Keck Center at the National Academies in downtown Washington, DC, and included an array of topics ranging from an introduction to the history and background of 3D printing and transportation to freight movements and defense applications, from the microscale of chemical engineering and material science, to the macroscale of 3D printing of structures in space.

While the focus of the first conference was primarily vertical, as a large percentage of large-scale 3D printing research at that time was building-oriented, the organizers of this year's TRB conference have chosen to emphasize horizontal applications that tend to reside within the domain of transportation.

We will hear some of the latest innovations in novel material developments and their applications to bridges, culverts, pipes, and other structures. Plenary speakers will discuss recent innovations emerging from Oakridge National Laboratory and industry. Panelists from the National Institute of Standard and Technology and the American Society for Testing and Materials will address developments in standards and policies. We will also hear from speakers from the U.S. National Science Foundation (NSF) and the Federal Highway Administration (FHWA). Finally, we will be addressing some of the latest innovations from robotics, automation and additive construction in new transportation infrastructure.

Zofia Rybkowski, PhD
Professor
Texas A&M University

Randy Iwasaki
President and CEO
Iwasaki Consulting Services, Inc.
(Did not attend)

OPENING PLENARY SESSION

Building a Future-Ready Manufacturing Innovation Ecosystem

ZOFIA RYBKOWSKI

Texas A&M University

Moderator

PRESENTATION SUMMARY

Additive manufacturing (AM) has been around for more than four decades and has seen a surge of innovation and investment over the last decade due to the rapid advancements in materials, machines, sensors and controls, and the digital thread. This presentation explored the advancements in polymer, metal, and concrete printing as well as their potential uses and effects on the transportation industry. Large-scale printing of components which was unimaginable a decade ago is happening today enabling tools, molds, and parts at infrastructure scale. Advances in artificial intelligence and the digital thread impact how and where we make products and therefore is drastically changing materials and parts flow throughout the United States and the world. It's important to understand the state of the art in AM technology and the pace at which today's innovations are rapidly evolving for a future-ready, smart, integrated transportation infrastructure.

BUILDING A FUTURE-READY MANUFACTURING INNOVATION ECOSYSTEM

CRAIG BLUE

Oakridge National Laboratory

Craig Blue

Speaker Biography

Craig Blue, PhD, is the Chief Manufacturing Officer for Oak Ridge National Laboratory (ORNL) and Defense Manufacturing Program Director for the National Security

Sciences Directorate. In this capacity, he leads a $130M research portfolio with more than 280 industry partners that delivers scientific discoveries and technical breakthroughs in energy and national security.

ORNL's Manufacturing Demonstration Facility (MDF) demonstrates an innovative interface between the public and private spaces of manufacturing. Launched in 2012, the MDF's program allows technology to flourish, taking science from low- to mid-tech readiness. Even after industry's adoption of MDF technologies, the MDF works with industry to re-evaluate its work with the Department of Energy. MDF involves over 50 universities across the country and involves active workforce development from the middle-school-age group up. Despite its lofty goals, ORNL's MDF still works at the speed of U.S. manufacturing and acts as a "trusted broker" and "impartial center of expertise" by respecting intellectual property and working agreements in its industry collaborations.

Large-Scale Technology

ORNL's large-scale thermoplastic technology includes a gantry system for open air processes and a commercial-scale system for Big Area Additive Manufacturing (BAAM). To enable BAAM, ORNL is working toward improving print rates for efficient and high-quality prints. In addition, ORNL considers improvement of both processing and the development of new materials. For example, in a collaboration with Lockheed Martin and Stratasys, ORNL is developing a pelletized feedstock reinforced with fibers. Material considerations include opting for a low coefficient of thermal expansion and higher strength. To improve deposition, their development of pellets with carbon fiber involves aligning the direction of the fibers with the direction of printing extrusion. To account for the fiber direction and scale of production, ORNL developed their own slicer software. In addition, BAAM is further enabled by reducing steps in autoclave processing through methods like tooling, unmanned aerial vehicles, and robotics.

To show a commercial-scale implementation of BAAM, ORNL and Cincinnati Incorporated collaborated to develop large-scale AM through targeted tooling. In another collaboration, ORNL and Thermwood developed a large-scale AM system with both additive and subtractive methods on the same machine. Further still, the University of Maine developed a large-scale, large-volume, agile, additive, and hybrid manufacturing (LAAHM) system. The largest LAAHM, as of 2024, can print 9.9 to 500 pounds per hour with a total system that is 100 ft by 32 ft by 18 ft, 4 times that of the world's largest polymer 3D printer in 2019.

Sustainable Manufacturing Through Materials and Additive Manufacturing

From a sustainability perspective, AM can make rapid manufacturing more economically feasible through single, continuous print patterns. The world's first 3D-printed bio-based house demonstrates durability over 2 years as well as energy efficiency. Such materials may further be applied to infrastructure and the boating industry's manufacturing needs. The design of parts for printing can also improve product lifetime, as with a 3D printed culvert diffuser. The University of Maine demonstrated a printed culvert diffuser that increased culvert flow by 40%, improving culvert life through fine-tuned geometry for hydraulics enabled by AM.

In addition to using bio-based materials and developing stronger products, advances in sustainable manufacturing emphasize the recyclability of molds and scaffolding for construction. Gate Precast rehabilitated Domino Sugar Building, a 42-story building, with the MDF-developed polymer material, CF-ABS. The company used CF-ABS for molds that were used up to 200 times, nearly 50 times that of traditional wooden molds. In addition, the mold geometry allows use of more than 100 material combinations and a high deposition rate. Similarly, recyclable printed formwork is used in railroad bridges.

Additional Technology for Advanced Additive Manufacturing

The configurable holonomic additive manufacturing platform (CHAMP) is a vehicle that can withstand a payload of up to 10,000 pounds for configuring deposition. Control is made precise through a robotics operating system architecture and laser tracking, with accuracy of prints within 0.01 inches over 275 feet of printing. Deposition methods compatible with CHAMP include composite thermoplastics, composite thermosets, metal wire arc printing, and metal electroslag AM in development. For wire arc additive manufacturing, a 5-foot-long hot stamping die, that was printed and machined in only 8 days, reduces the cost of cross-hold drilling and plugging. The hot stamping die also improves the uniform temperature distribution and reduces the cooling rate by 20% for more efficient part development. Through direct energy deposition, large-scale components with specific shapes, such as a 900 lb hydro impeller, were printed of stainless steel in just 46 hours. Compared with the more traditional manufacturing methods, such as powder production, feedstock costs may decrease by 50% and reduce waste streams. ORNL's technologies show a range of AM applications such as robotics, automobiles, bio-based housing, construction machinery, submarines, turbine blades, and locally enabled infrastructure during the COVID-19 pandemic.

Manufacturing Needs for the Immediate Future

According to a McKinsey & Company study from 2017, modern day manufacturing needs better analytics to identify areas of improvement, techniques such as computer vision to identify defects in real time, closed loop controls, robotics, and convergent manufacturing. 98% of manufacturers operate at a small scale in the United States, and they especially require a convergent approach, in which a company can manufacture from a computer aided design drawing, build a product, heat and treat, and develop a final product. Additive manufacturing will likely be especially crucial for the future of transportation, in which smarter infrastructure can be embedded with sensing technology at each layer. Such manufacturing can be better "democratized" through additive manufacturing from a local supply chain.

INDUSTRY UPDATE

MARK BURNHAM
Additive Manufacturing Coalition

Speaker Biography

Mark Burnham is the Director of Policy for the Additive Manufacturing Coalition. He has more than 20 years of experience advocating for universities, large research facilities, and associations in Washington and has represented universities including the California Institute of Technology, Michigan State University and the University of Michigan. He helped establish the Additive Manufacturing Coalition in 2019 in order to advocate for the use of AM. Mark is a graduate of the University of Michigan and Boston College Law School.

Mark Burnham

Presentation Summary

This presentation centered on the issues and opportunities that AM—both for construction and for manufacturing of goods—will have on U.S. transportation infrastructure needs.

Impacts of AM on Transportation

Additive manufacturing will have both direct and indirect impacts on the transportation industry. Directly, AM will likely improve construction of components, change the face of the workforce, and increase demand for new materials. Indirectly, AM will increase local development of parts, leading to a “re-shoring” of manufacturing. AM applications include 3D-printed houses that are built in just a few days, barracks for the Department of Defense (DOD), and bases for wind turbines. Benefits such as rapid manufacturing and customizable designs can motivate use of AM for bridges, ports, and more infrastructure. For hypersonics in transportation, improved alloys are needed, and their composition is affected by the extrusion of 3D printing.

Considering When to Use AM for Transportation

Additive Manufacturing, though a powerful and flexible solution, is most relevant in cases where a design is too complex for traditional manufacturing methods, there is a tight time frame, an application needs significant customization, and speed is a major criterion. However, there are cases where traditional manufacturing may be more cost-effective. It is important to reference ASTM and ISO standards such as ASTM 52939-23, which details processing and post-processing for AM methods in construction.

The Importance of Onshore Manufacturing

DOD is prioritizing onshore manufacturing as a major national economic need, since the supply chain is vulnerable to global tensions. Increasing production of raw materials domestically can reduce the import of manufacturing. In local production, printing can occur at the site of a product need, and this will potentially reduce interstate shipping. Transportation technology itself can benefit from the local printing and repair of parts for the aerospace and automotive industries.

Present State of Industrial Use

With rising interest rates, smaller manufacturing companies are faced with a decision to move to more accessible, efficient, and affordable methods of construction. More small companies need to connect with AM. However, AM is still viewed as a risky direction. Standards for AM are slowly developing. In the case of tariffs, domestic printing is important, but more investments must be made to establish local production.

SESSION 2A

National Science Foundation and Civil, Mechanical, and Manufacturing Innovation Program in Additive Manufacturing and Transportation

DANIEL LINZELL

U.S. National Science Foundation

Moderator

MODERATOR BIOGRAPHY

Daniel Linzell

Daniel Linzell is the Associate Dean for Graduate and International Programs and the Leslie D. Martin Professor of Civil and Environmental Engineering at the University of Nebraska, Lincoln College of Engineering. He holds a PhD in Civil Engineering from Georgia Institute of Technology and a BS in Civil Engineering from The Ohio State University. His areas of research and professional interest include Structural Health Monitoring, Laboratory and Field-Testing of Structures Force Protection, Curved and skewed concrete and steel bridges; Advanced Materials for Structural Engineering, and Advanced Finite Element Modeling.

This session served as an introduction to NSF and their goals and research objectives for built environments, followed by some projects conducted by researchers from the University of California and University of Michigan.

OVERVIEW OF NSF BUILT ENVIRONMENT RESEARCH EFFORTS

DAAN LIANG

U.S. National Science Foundation

Speaker Biography

Daan Liang is Program Director at NSF, Humans, Disasters, and the Built Environment; Smart and Connected Communities (SandCC); Civic Innovation Challenge (CIVIC); Sustainable Regional Systems Research Networks.

Daan Liang

Presentation Summary

This presentation highlighted the structure of the NSF and the scope of their work. The NSF is divided into eight divisions (called "colleges"), which focus on fields from geoscience to social and economic science. The newest college, the Technology, Innovation, and Partnerships (TIPS), has the goal of progressing basic research and translating it into something useful for the general public. The TIPS funds projects in transportation infrastructure and supply chains and also conducts workshops and information sessions to raise awareness about NSF's mission.

The presentation then transitioned to the division's three main programs. The ECI (Engineering for Civil Infrastructure) supports fundamental research related to the materials and design of infrastructure. The second program, the CIS (Civil Infrastructure Systems), similarly focuses on infrastructure systems, like power and wastewater, and transportation. The CIS looks at these systems as a whole, rather than individual components, with the goal of making them more sustainable and resilient overall. Finally, the Human Disaster and Building Environment division focuses on civil infrastructure projects specifically with natural disasters in mind. In addition, they also support research focusing on recovery efforts for communities.

NSF SPONSORED BUILT ENVIRONMENT RESEARCH EFFORTS AND THEIR IMPACT ON TRANSPORTATION INFRASTRUCTURE

KENICHI SOGA
University of California, Berkeley

Speaker Biography

Kenichi Soga is the Donald H. McLaughlin Professor in Mineral Engineering and a Distinguished Professor of Civil and Environmental Engineering at University of California, Berkeley. Soga is also the Director of the Berkeley Center for Smart Infrastructure, a faculty scientist at Lawrence Berkeley National Laboratory, and serves as a Special Advisor to the Dean of the College of Engineering for Resilient and Sustainable Systems. Soga's research focuses on infrastructure sensing, performance-based design and maintenance of infrastructure, energy geotechnics, and geomechanics.


Kenichi Soga

Presentation Summary

Infrastructure is designed to last for 50 to 100 years or more, yet the world is continually changing due to natural hazards, pandemics, extreme weather, and evolving ways of working, living, and moving. To prolong the lifespan and enhance the adaptability of transportation infrastructure, we are rethinking every aspect—from demand prediction to design, construction, maintenance, and rehabilitation.

Infrastructure should be designed not only to meet immediate needs but also to adapt to future demands throughout its lifespan. Traditionally, design philosophy has focused on predicting foreseeable demand, which creates a significant risk of infrastructure becoming inadequate or obsolete before its intended lifespan is over. For instance, the COVID-19 pandemic has changed infrastructure demands as teleworking transforms residential and travel patterns. Additionally, the growing adoption of new mobility platforms, along with trends in automation and electrification, will further influence future infrastructure requirements.

Adaptation is essential for sustainable living. Infrastructure needs to address current changes and threats. There is an urgent need to improve the ability to predict, design, and manage the longevity of infrastructure. Soga's personal opinion is that this calls for "smart infrastructure" engineering that emphasizes sustainability, resilience, and equity for communities. How can we rehabilitate or create the built environment to ensure that future generations benefit from smart infrastructure?

Emerging technologies empower decision-makers to enhance infrastructure. Innovations in materials, sensing, communication, and computing can be leveraged for smart infrastructure applications. Recent advancements in science and technology enable us to collect and analyze data on how communities utilize infrastructure and the environment. By utilizing emerging technologies such as digital twins, net-zero or negative carbon materials, sensors, robotics, and new processes, smart infrastructure can effectively predict, design, and manage its lifespan. The presentation introduced several emerging technologies that could help us achieve this vision.

Soga began with an emphasis on the importance of adaptability in infrastructure systems—pipelines and roads that are built to last 100–200 years are often not responsive to changing demand and pose a problem to future generations who have to worry about the safety and efficacy of aging infrastructure. As a result, integrating sensors into infrastructure allows us to collect and analyze data, which can allow us to create more adaptable structures.

Soga then discussed several different applications of sensor-integrated infrastructure, specifically fiber optics. Fiber-optic cables have the ability to monitor a variety of metrics, including temperature, strain, and water leakage. A fiber-optic cable was installed along with a pipeline replacement along the Hayward Fault in Berkeley, which measures the seasonal shrinkage and expansion of the pipe. This information can be used to inform us when the pipe would need to be replaced or even be used to predict future earthquakes.

Soga's shared that his research also has applications in disaster modeling, such as seeing what parts of the population would lose access to water in the event of an earthquake or other natural disaster. In addition, wildfire modeling and traffic simulations were also considered. This data can be used to estimate recovery times and help inform decisions made on emergency response and preparation. These efforts can not only make transportation infrastructure become more responsive to current demands but also provide valuable information that allows us to be more adaptable to other conditions.

OVERVIEW OF NSF ADDITIVE MANUFACTURING RESEARCH EFFORTS

LINKAN BIAN
U.S. National Science Foundation

Speaker Biography

Linkan Bian

Since June 21, 2022, Linkan Bian has been on detail as a program director in the Advanced Manufacturing cluster of the Division of Civil, Mechanical, and Manufacturing Innovation (CMMI) of the NSF. Bian is a Thomas B. and Terri L. Nusz Endowed Professor in the Industrial and Systems Engineering Department at Mississippi State University. He received his PhD in Industrial and Systems Engineering from Georgia Institute of Technology, and BS in Applied Mathematics from Beijing University. Bian's research focus is on the process-structure-property relationships for advanced manufacturing, as well as the investigation of how AI/ML (artificial intelligence/machine learning) can transform the modeling and experimental approaches. His research has also been applied to other areas including a predictive maintenance,
cybersecurity, and human-machine interface.

Presentation Summary

Bian shared that the NSF's Additive Manufacturing program aims to provide support for more sustainable manufacturing initiatives and developing processing technologies and materials development. In addition, solicitation from researchers about core program ideas was encouraged, including AM and sustainable manufacturing. An emphasis was placed on university research and proposals as the breeding ground for potential future ideas.

NSF SPONSORED AM RESEARCH EFFORTS AND THEIR IMPACT ON TRANSPORTATION INFRASTRUCTURE

MANIA AGHAEI MEIBODI
University of Michigan

MO LI
University of California, Irvine

Speaker Biographies

Mania Aghaei Meibodi

Mania Aghaei Meibodi is an Assistant Professor of Architecture at the University of Michigan's Taubman College of Architecture and Urban Planning. She leads the DART (Digital Architecture Research and Technology) laboratory, where she and her team innovate integrative computational design methods with robotic construction and 3D printing to tackle real-world construction challenges. Their interdisciplinary research focuses on computational design, robotic construction, large-scale 3D printing, and novel building materials. She earned a PhD and Master of Architecture degree from the KTH Royal Institute of Technology.

Mo Li

Mo Li is a Professor of Civil and Environmental Engineering and a Professor (Joint Appointment) of Materials Science and Engineering at the Samueli School of Engineering, University of California, Irvine. She earned a PhD in Civil Engineering, an MSE in Industrial and Operations Engineering, and an MSE in Civil Engineering from the University of Michigan; and a BSE in Civil Engineering from Tongji University. Li's research focuses on unconventional infrastructure materials and their interfaces with structural engineering, damage sensing, and advanced manufacturing, with the goal of improving infrastructure service life, safety and resilience.

Presentation Summary

The talk, presented by both Meibodi and Li, covered DART Laboratory's research on Robotics and 3D Printing for Architecture and Construction, and focused on enabling sustainable construction and creating next-generation structural building components. It also shared ongoing research and preliminary results on data collection methods for machine-learning-based predictive control models in robotic 3D printing. The presentation focused on the inefficiencies associated with the construction industry, such as its labor- and time-intensive nature, high environmental impact and emissions, and the limited quantity of materials like concrete. 3D printing is presented as an alternative that can automate and replace labor while using sustainable materials to produce the same output.

Meibodi then discussed some of the challenges associated with 3D printing suitable alternative materials with robots, like the need to design the material so that it does not require external support when printing. Decentralized printing, where multiple robots are printing simultaneously, has the most potential upside, but is extremely complex and requires intensive computational power to effectively execute. For example, if the end effector is too slow or a single pump stops working, the material will likely fail, and the more complex the material, the more likely this would happen. In order to optimize this, sensors were integrated throughout parts during testing, which measured the layer thickness variation and temperature over time, among other metrics. Through these metrics, they were able to understand which features were most efficient. In the end, they were able to create materials with equivalent compressive strength using 40% less material.

The presentation concluded with tested applications. 3D printing was used to create molds that could be cast with recyclable aluminum, which was then used to help with collecting and redirecting stormwater. Another project involved additively manufacturing a lightweight cantilever, which ended up using 75% less material and used recyclable and green materials.

SESSION 2B

Concrete Materials in Additive Manufacturing and Construction

MARYAM HOJATI

University of New Mexico

Moderator

3D PRINTING USING ULTRA-HIGH-PERFORMANCE CONCRETE IN BRIDGE APPLICATIONS

ATOROD AZIZINAMINI

Florida International University

Speaker Biography

Atorod Azizinamini

Atorod Azizinamini is a Professor of Civil Engineering at Florida International University and Director of the Innovative Bridge Technology and Accelerated Bridge Construction University Transportation Center. A specialist in bridge engineering and expert in the field of accelerated bridge construction, he specializes in the use of advanced materials and technologies in bridges by educating professional engineers and conducting major research studies. Azizinamini holds a BS degree in Civil Engineering from the University of Oklahoma and a PhD from the University of South Carolina.

Presentation Summary

This session explored the latest developments in 3D-printed Ultra-High-Performance Concrete (UHPC) for bridge construction, emphasizing durability, efficiency, and cost challenges. The research, funded by the U.S. University Transportation Center program and the U.S. Army Corps of Engineers (USACE), aims to enhance construction methods without replacing human labor, pushing the boundaries of modern bridge engineering.

UHPC is a highly durable material with superior strength and resilience, making it ideal for construction applications. However, traditional 3D printing methods have limitations, and future advancements will focus on automation and new techniques beyond layer-by-layer printing. Despite its advantages, UHPC comes with significant cost considerations, particularly due to material expenses and fiber sourcing regulations.

Key properties of UHPC include strength and durability (UHPC is reinforced with steel fibers, which improve performance but also make processing more challenging); a steel fiber content (the United States typically uses 2% steel fibers, while Europe uses 3.84%, enhancing stability for applications like 3D printing); freeze-thaw resistance (UHPC can withstand 300+ freeze-thaw cycles with no degradation, significantly outperforming traditional concrete); and low permeability (with 100–150 coulombs, UHPC has extremely low water penetration, reducing long-term deterioration. In addition, UHPC is fire resistant, and heating UHPC to moderate temperatures (~300°C or lower) can temporarily increase strength (however, at higher temperatures structural integrity begins to decline).

UPHC does come with cost challenges including those of materials. Standard UHPC costs up to $4,000 per cubic yard, making it expensive for widespread use. One challenge is the steel fiber sourcing. A major cost driver is steel fibers, and in the United States, federal regulations require American-made fibers for bridge projects, further increasing expenses. However, cost reduction efforts and open-source alternatives have been developed, sometimes bringing costs down to $500 per cubic yard.

UHPC as a Permanent Framework

A major innovation in construction is the use of 3D-printed UHPC as a permanent formwork, replacing traditional wooden formwork. Unlike conventional formwork that must be removed after concrete sets, UHPC remains in place, enhancing structural integrity and reducing material waste. Even a thin UHPC shell significantly increases load capacity, allowing for smaller cross sections and more efficient material use.

Key benefits of UHPC as permanent framework include the fact that there is no need for formwork removal, which eliminates labor and material costs associated with dismantling traditional formwork; increased structural efficiency as UHPC's high strength allows for smaller, more efficient designs while maintaining performance; prefabrication and faster assembly as UHPC walls can be 3D-printed off-site, transported, and assembled on-site, and reinforced with a steel cage and filled with lightweight concrete for added stability, reducing on-site labor and minimizing traffic disruptions.

Advanced Printing Method Allows for Continuous Material Deposition.

Instead of a layer-by-layer approach, UHPC is printed in a continuous flow. It also allows for a smooth surface finish. This eliminates visible layer lines, resulting in a seamless and refined final structure.

Structural Performance of 3D-Printed UHPC Components

Testing has shown that 3D-printed UHPC components perform as well as cast-in-place concrete. Structural comparisons found that a UHPC-printed beam with reinforced concrete infill had similar deflection performance to a fully cast-in-place beam and that a 3D-printed reinforced column exhibited comparable axial and lateral load resistance to a traditional cast-in-place column.

To support these advancements, researchers have developed custom 3D printers that enable both precise material deposition, ensuring structural integrity, and reinforcement integration, making 3D-printed UHPC viable for bridge components. These innovations demonstrate that 3D-printed UHPC can be used for durable, structurally sound infrastructure, further proving its potential for large-scale construction applications.

Modular UHPC Formwork for Short-Span Bridges

A new modular UHPC formwork system has been introduced for short-span bridges up to 48 feet. Instead of traditional formwork, 3D-printed modular sections are used, which are assembled without mechanical fasteners. These sections rely on gravity and arch action for structural stability, eliminating the need for additional connectors or adhesives.

The process consists of several key steps. First, 3D-printing modular UHPC sections are tailored to the bridge design. Then the modules are positioned in place without mechanical fasteners. The next step is to insert a steel reinforcement cage to enhance structural strength. Finally, the last step is to fill the modules with concrete to complete the bridge structure. To enhance efficiency, the printing system features a customizable nozzle that allows for precise material placement and reinforcement integration. This makes the process highly automated and adaptable, improving both speed and accuracy in construction. Structural testing has demonstrated that UHPC experiences distributed cracking, meaning that instead of large fractures forming, embedded steel fibers control crack propagation, significantly enhancing durability. This innovative formwork approach reduces labor and material waste, while ensuring strong, long-lasting bridge structures.

Next-Generation 3D Printing: Combining UHPC and Shotcrete

Traditional 3D concrete printing faces layer bonding issues, which affect structural integrity. To address this, researchers developed a hybrid approach that integrates UHPC shotcrete application at the nozzle level, improving adhesion and performance. Over 1.5 years, the team refined a sprayable UHPC mix, overcoming challenges related to steel fiber dispersion and equipment limitations. This approach was successfully tested in August 2024, when UHPC shotcrete was used to repair two bridge abutments in Washington, DC, requiring only minimal equipment, proving its practicality in real-world applications.

Performance improvements are many. For example, a 1-inch UHPC shotcrete layer resulted in both reduced permeability (RCP values dropped from 1200 to 170) and a significant increase in structural strength and durability.

Future applications include wind tunnels, where enhanced strength and aerodynamics are critical; sea walls, with the potential to reduce structure size by 50% while maintaining strength; and field structures, where rapid construction and reinforcement are essential.

Long-Term Vision

Azizinamini envisions a future where infrastructure can be rapidly built and reinforced using UHPC spray technology. This hybrid approach has the potential to revolutionize the industry by making construction faster, more efficient, and more resilient, ultimately improving longevity and reducing maintenance costs.

ADDITIVE CONSTRUCTION OF A NEW SEISMIC PROTECTIVE BRIDGE SYSTEM

ANTHONY MACKIN, JENNA MIGLIORINO, HAMDY FARHOUD, AND ISLAM MANTAWY
Rowan University

Speaker Biography

Islam Mantawy

Islam Mantawy is a Professor of Civil and Environmental Engineering at Rowan University, specializing in additive construction and structural optimization. A registered Professional Engineer in Navajo Nation, Mantawy's expertise spans additive manufacturing for both concrete and metallic structures, with a focus on topology optimization, reinforcement techniques, and sustainable construction practices. His research explores innovative methods for improving seismic resilience in bridge structures, advancing the field of automated construction and structural engineering. He holds a PhD from the University of Nevada, Reno (2016), an MS from Ain Shams University (2013), and a BS, Ain Shams University, (2010).

Presentation Summary

This research, led by the ARC-LAB team at Rowan University, explored hybrid 3D printing techniques to improve seismic resilience, efficiency, and sustainability in construction. Their work focuses on low-carbon materials, optimized structural design, and external dissipation devices to create earthquake-resistant infrastructure.

The Need for Innovation in Construction

Traditional construction methods have remained largely unchanged since 1950, using the same materials and techniques. ARC-LAB is developing hybrid additive construction, integrating 3D printing with reinforcement and new material technologies, to transition from conventional construction (manual forming and reinforcement) to hybrid construction (additive techniques with reinforcement) and optimized construction (fully automated, continuous 3D printing).

Advancing 3D Printing for Seismic Resilience

ARC-LAB is optimizing 3D-printed concrete systems for earthquake-resistant structures by integrating rocking mechanisms, energy dissipation devices, and structural optimization techniques.

Seismic-Resistant Rocking Columns

These are self-centering columns which restore themselves after an earthquake. Yielding links at the base absorb seismic energy while keeping the structure intact. This approach reduces damage, prevents buckling, and allows structures to remain operational after a quake.

External Energy Dissipation Devices

These replace traditional internal yielding mechanisms with friction-based dampers for better seismic absorption, using double-concave surfaces to distribute stress, preventing localized damage. Lehigh University testing confirmed these devices effectively absorb seismic forces.

Printing Complex Structures on Steep Slopes

Accomplishments include successfully printing pyramidal structures on a 26-degree slope without internal supports and achieving 60-degree printability, expanding the range of possible architectural forms.

Material and Process Innovations

Low-carbon concrete printing is developing eco-friendly concrete mixtures using fly ash and industrial by-products to reduce the carbon footprint. There are two printing systems:

- A 1K System—Single-component material that solidifies upon deposition; and
- A 2K System—Dual-component mix with a solidifying agent for better flow control.

Current material strength is 9-10 ksi, with potential for fiber reinforcement.

Optimized 3D Printing for Structural Performance

The first prototype (half-inch nozzle) had defects due to too many layers and was later upgraded to a one-inch nozzle, reducing layers and improving print stability. Simulated printing parameters in G-code to optimize flow and material placement.

Seismic-Resilient Bridge Prototype

Real-world applications and testing include a 72-foot-long bridge designed to withstand earthquakes using prestressed strands and built as part of a 2014 NSF-funded project, showing practical feasibility. Unlike conventional bridges, this system recenters itself after deformation, preventing collapse.

Large-Scale Testing and Future Research

The research team has now successfully 3D-printed a fiber-less concrete structure and documented its progress from start to completion. The next step is to scale up the design and load-bearing testing using Abaqus modeling. Planned for summer 2025, large-scale testing will evaluate various design strategies for seismic performance as well as durability and material performance under earthquake conditions.

The Future of Additive Construction

ARC-LAB's research proves 3D printing can enhance seismic resilience, reduce environmental impact, and improve construction efficiency. The next phase will focus on automating hybrid construction methods, refining energy dissipation systems, and scaling up successful prototypes. With further testing and industry adoption, this technology could redefine how we build earthquake-resistant infrastructure worldwide.

Question and Answer Session

Question: What materials are used for the 3D-printed columns?

Response: The columns are made from concrete or a high-set mortar mix incorporating fly ash. The two-foot-high prototype is designed as a rigid body with a rocking motion, meaning it moves within its foundation instead of deforming under stress. Since the column is primarily under compression, tensile reinforcements are not heavily required, unlike traditional high-tension designs. This approach minimizes tensile stress, improving efficiency and durability.

MIX DESIGN CONCEPTS FOR PRINTING CONCRETE IN 3DPC APPLICATIONS

BEN MANAUGH AND JEFFREY RAPHAEL ROESLER
University of Illinois at Urbana-Champaign

Speaker Biography

Jeffrey Raphael Roesler

Jeffrey Raphael Roesler, Ernest Barenberg Professor at the University of Illinois at Urbana-Champaign specializes in concrete innovation and infrastructure. His expertise spans 3D concrete printing (3DPC), microscale urban infrastructure, and passive sensing for construction. His research focuses on mix design challenges in 3DPC, particularly the use of coarse aggregates instead of traditional mortar-based printing. He aims to optimize pumping efficiency, extrusion, and sustainability, addressing key barriers to industry adoption.

Presentation Summary

This research explored 3DPC with a focus on mix design challenges, material optimization, and industry adoption. Emphasizing the need for true concrete printing, it highlights the advantages of using coarse aggregates over traditional mortar-based mixes, which lack the strength for large-scale applications.

Key Observations in 3DPC

There are significant challenges in 3DPC with aggregates. Early 3D printing research relied on mortar-based mixes, which lack the necessary strength for large-scale construction. Using coarse aggregates presents pumping and extrusion issues, such as segregation and clogging. Current 3DPC mixes use excessive cement (1200-1500 lb/cu yd), conflicting with low-carbon construction goals. Optimizing particle gradation, paste content, and rheology is crucial for practical, sustainable mix designs.

Industry Engagement and Real-World Applications

LX Construction (a concrete contractor in Monticello, Illinois) is implementing large-scale 3D printing using coarse aggregate mixes and has successfully printed a 5,500 sq ft recreational building with 4-inch layer heights—no admixtures required. Volumetric mixing and on-site material control improve workability and efficiency.

Experimental Research and Mix Development

Research focuses on pumping efficiency, extrusion rheology, and material flow. Vibration along the pipeline significantly reduces pumping pressure and prevents material segregation. Current layer heights range from 2.75 to 4 inches, with ongoing research to improve buildability and reduce shrinkage cracking.

Reinforcement and Construction Process Challenges

Most 3D-printed structures lack traditional reinforcement, instead relying on masonry ladders or horizontal/longitudinal reinforcement and limited vertical reinforcement, making taller structures difficult to stabilize. Manual reinforcement placement is inefficient, contradicting the automation benefits of 3D printing.

Adoption Challenges and Industry Standardization

Regulatory issues include the need for DOT and public sector approvals, which may slow down adoption. Another challenge is the extent to which there is a trained workforce: Few workers have expertise in both concrete and 3D printing technology. Industry collaboration is essential to bring together contractors and researchers to share data and prevent industry stagnation.

Future Research and Industry Advancements

These include material optimization, investigating admixtures, optimized particle gradation, and improved mix designs; advanced applications, exploring underwater 3DPC for defense and infrastructure; and developing new reinforcement integration methods to eliminate manual rebar placement.

Future of 3DPC in Construction

Roesler's research is focused on 3D concrete printing by addressing material challenges, reinforcement limitations, and industry adoption barriers. His team's work in pumping optimization, low-carbon mix design, and large-scale construction applications is advancing 3DPC as a viable and sustainable construction method.

Question and Answer Session

Question 1: Is the 5% error target measured at the source or at the extrusion stage?

Answer: The 5% error is the target at extrusion, meaning that the material should be deposited with that level of accuracy. However, most testing is conducted in the lab, not in the field, so real-world accuracy may vary. Roesler does not have direct involvement in quality control for field applications and cannot confirm actual field error rates.

Question 2: Have fibers been used to prevent cracking, and if so, how effective are they?

Answer: Fibers have been tested and can be incorporated, particularly for reducing plastic shrinkage cracks. However, full-scale implementation has not been prioritized yet, as research has been focusing on other areas. The team has the capability to introduce fibers via volumetric mixing but has opted to delay further fiber testing for now. Macro fibers were tested in previous trials, and while beneficial, they are not currently a focus area.

Question 3: Are pump limitations a major issue in 3D concrete printing?

Answer: Yes, current pumps are not designed for 3D printing at scale. Traditional concrete pumps are built for moving large amounts of material quickly, whereas 3D printing requires slow, controlled extrusion of thick material over long distances. The industry lacks a dedicated 3DPC pump, but once manufacturers recognize market demand, specialized pumps will likely be developed. A new slicer machine in Florida claims six-inch lift heights, but its solid-wall construction method aligns with European standards, which are more difficult to implement in the United States due to different building codes.

Question 4: What are the challenges in underwater 3D concrete printing?

Answer: The biggest challenge is the binder-to-aggregate ratio. The proposed ratio of 90% aggregate to 10% binder is highly difficult to achieve underwater. Maintaining material stability and preventing dispersion in an underwater environment makes printing with such low binder content unlikely. The team has not yet conducted full-scale underwater printing tests.

Question 5: What is the bead width for printed layers, and does it cause material inefficiency?

Answer: The layer height is four inches, and the bead width is three to three-quarters inches. This means the layer is taller than it is wide, which raised concerns about excess material use and potential inefficiencies in reinforcement spacing. Roesler noted that the bead width was determined based on structural engineering recommendations, but there is limited flexibility due to system constraints. The current setup uses a two-inch pipe, meaning increasing the bead width would require a different pump system. Additionally, existing pumps deliver material too quickly, creating further challenges in controlling material flow.

DEVELOPMENT OF A SLICER FOR ADDITIVE CONSTRUCTION OF CONCRETE

CHARITH NANAYAKKARA RATNAYAKE AND WENCHAO ZHOU
University of Arkansas

JIM MANTES
Applied Research Associates, Inc.

CARL JAGGERS AND ZACHARY HYDEN
AMBOTS

Speaker Biographies

Charith Nanayakkara Ratnayake

Jim Mantes

Charith Nanayakkara Ratnayake and coauthor Jim Mantes research additive construction (AC), specializing in automation and software solutions for 3D concrete printing. Ratnayake, a graduate research assistant at the University of Arkansas, has a background in Mechatronic Engineering from General Sir John Defense University in Sri Lanka and is currently pursuing a PhD in Mechanical Engineering.

Jim Mantes, PE, Principal Program Manager at Applied Research Associates, Inc., is the lead presenter on the development of a slicer for additive concrete construction, focusing on optimizing toolpath generation and automation in 3D printing. He is an experienced project manager and operational leader with a demonstrated history of working in the construction industry. He is skilled in Managing Projects, Construction Engineering, Operational Planning, Sewer and Water, Transportation Infrastructure, Tunneling, Concrete Structures, Steel Fabrication, and Steel Erection and has strong program and project management professional experience. He holds a Master of Science focused on

Engineering Management, from University of Wisconsin-Platteville and is experienced in managing teams and subordinate leaders of teams in military and civilian environments.

Presentation Summary

The ACME Tech (Additive Construction of Maneuver Enabling Technology) team is performing research and development work to build a purpose-built slicer software which better handles the unique challenges associated with AC 3D printing concrete. The slicer reads in multiple formats of 3D models or point paths and converts them to G-CODE instructions for the AC printer. The ACME Tech is a research program funded by USACE Engineering Research and Development Center (ERDC) with a goal to advance AC technology. This research, funded by USACE ERDC, focused on automating and optimizing concrete 3D printing for austere environments. The project is a collaboration between Applied Research Associates, Inc., the University of Arkansas, Iowa State University, and Robotic Construction Technologies.

Key Project Components and Innovations

Research Goals were to develop an advanced slicer software for concrete 3D printing, overcoming limitations of plastic-based slicers; improve automation in additive manufacturing, particularly in challenging and remote environments; to integrate indigenous materials to enable construction in austere environments with limited access to high-quality concrete; and to replace UHPC with Ultra-Low-Performance Concrete (ULPC), a mix designed to tolerate contaminants and impurities while remaining viable for temporary construction in forward-operating locations.

Development of the ACC Slicer Software

Charith presented on the ACC Slicer, a custom-built software designed to generate continuous tool paths for concrete extrusion, unlike traditional slicers for plastic-based 3D printing.

Challenges with existing software were found. The team evaluated proprietary, open-source, and Rhino-based slicers, but none provided continuous tool path support for concrete printing. Existing options lacked the flexibility and control required for additive concrete construction. The solution was to develop a new slicing software from scratch, tailored for academic research in 3D concrete printing.

Structure of the ACC Slicer Software

The software was built with three major modules, each designed to improve model preparation, tool path generation, and printer execution. First is the Pre-Processor Module, which imports, scales, and manipulates 3D models, supporting multiple objects and custom positioning. Second is the Slicer Module, which generates continuous tool paths using Zigzag infill algorithm (to optimize path continuity and material deposition) and a wall slicer algorithm (to create inner and outer walls for robust component construction). Finally, a Post-Processor Module converts tool paths into G-code for printer execution, allowing for manual tool path modifications and replication of layers and predefined catalog items for standardization.

Custom Pump System and Equipment Integration

A new pump system is being developed for concrete additive manufacturing, specifically designed to handle varied materials, with results expected in future research. This includes integration of a complete equipment package, including printers, mixers, and pumps for use in remote and austere environments.

Standardization and Catalog for Printed Structures

Work is underway to develop an item catalog to define standardized printed components for field applications. Targeted applications include culverts, bridge components, and protective works as well as foam and concrete composites for structural efficiency.

Enhancing the ACC Slicer Software

Anticipated enhancements include developing support structures for more complex prints, refining wall slicing algorithms to improve structural integrity and compensating for bed leveling inaccuracies to ensure greater precision in printing.

Expanding Material Applications

There is ongoing research into local material mixes for sustainable and cost-effective 3D printing and exploration of foam-concrete composites for lightweight and insulated structures.

Practical Deployment and Military Applications

The research was presented across six different papers at this conference, covering: material mix development, integration of foam and concrete composites and use of local materials for in-field 3D printing applications. Potential military applications include rapid construction in forward-operating environments and bridge and protective structure manufacturing in disaster or conflict zones.

Future of 3D Concrete Printing in Remote Environments

This project demonstrates the potential of automation and software solutions in expanding AC to challenging environments. By developing a custom slicer, pump system, and standardized catalog for field structures, this research enhances efficiency, adaptability, and scalability in concrete 3D printing. With ongoing testing and industry collaboration, these advancements could revolutionize construction in remote locations, making it faster, more cost- effective, and more resilient.

Question and Answer Session

Question 1: Can the saw-tooth pattern be made into a radial or curved version instead of linear?

Answer: The team has developed both radial and saw-tooth patterns but is primarily focusing on the saw-tooth pattern for the current application. There was previous discussion regarding whether the corners of the saw-tooth pattern might be too tight, but they have implemented a sine wave-based approach that allows for curvature adjustments as a parameter. The wall spacing algorithm is still being refined, but for solid objects, the current wall algorithm provides a continuous toolpath that works effectively.

Question 2: What is the final intent for the slicer? Will it be proprietary or open source?

Answer: The slicer software is being developed in partnership with ERDC and is intended for government use across various printing applications. The details regarding licensing and accessibility are still being discussed. Some government partners are already considering where it might be housed, potentially behind secure firewalls. The intent is for the slicer to fill a gap in the industry by providing a usable tool for construction applications, but the level of availability to the public is yet to be determined. The software is being designed with flexibility to accommodate various equipment configurations, but making it fully equipment-agnostic remains a challenge due to differences in print systems, ramp-up and ramp-down controls, and hardware integration.

Question 3: Does the slicer have automatic object avoidance for toolpaths?

Answer: Yes, the slicer includes algorithms for automatic object avoidance, particularly when combining multiple objects in a single toolpath. These algorithms prevent intersections between toolpaths, ensuring that objects do not interfere with one another during printing. However, at the moment, the object avoidance does not account for scenarios where toolpaths extend beyond the print bed boundaries, and the team is currently working to refine this feature.

SESSION 3A

Robotics, Automation, and Additive Construction in Building New Transportation Infrastructure

CHRIS ATKINSON

Office of the Secretary, U.S. Department of Transportation

Moderator

PANEL DISCUSSION

The panel discussion included Xiaopeng Li, GE Vernova; Iris Rivero, University of Florida; and William Vavrik, Applied Research Associates, Inc.

ARPA-I'S ROLE IN FOSTERING INNOVATION AND ADVANCED TECHNOLOGIES

Presenter Biography

Chris Atkinson

Chris Atkinson is the Deputy Director of Technology for the Advanced Research Projects Agency-Infrastructure (ARPA-I), at the U.S. Department of Transportation (U.S. DOT). He is Director of Smart Mobility and Professor of Mechanical Engineering at Ohio State University. From 2014 to 2020 he was a program director at the Advanced Research Projects Agency-Energy (ARPA-E) in the U.S. Department of Energy. He is a Fellow of the Society of Automotive Engineers, and of the American Society of Mechanical Engineers (ASME). He has worked at the intersection of mobility and energy for over 30 years as a consultant, academic, and federal government program manager.

Presentation Summary

ARPA-I in the U.S. DOT was authorized by Congress in part to develop new materials and construction methods for transportation infrastructure. Mobility across all transportation modes is critically dependent on our nation's physical infrastructure—the roads, bridges, ports, airports, pipelines, and transit and rail systems that facilitate the safe, efficient and accessible movement of people, goods and services. The emerging combination of automation and robotic construction methods will transform infrastructure construction. The further addition of advanced AI techniques for infrastructure design, planning and siting will upend our current methods of infrastructure construction that are slow and increasingly costly, and not responsive to emerging threats like resilience to extreme weather. This session explored the combination of robotics, automation and AC in building new transportation infrastructure and shared new insights and perspectives into the current state of the art of these methods, their future opportunities and challenges, and what work needs to be done to overcome these challenges.

ARPA-I: Mission and Goals

ARPA-I is modeled after DARPA (Defense) and ARPA-E (Energy), focusing on transportation innovation. Its objectives are to solve persistent infrastructure and transportation challenges, create new R&D ecosystems for developers and innovators, ensure the United States leads in 21st-century infrastructure technology, support net-zero emissions by 2050, and to develop the safest, most efficient, climate-friendly, and resilient transportation system. Priority areas are safety (over emissions), building resiliency in transportation infrastructure, and developing advanced automation and robotics solutions.

Potential topics of interest for ARPA-I include Materials and Structures, such as zero or negative carbon materials for infrastructure, durable and resilient concrete for bridges, tunnels, high-speed rail, and seawalls and accelerated construction using 3D printing; Sensing and Computation for Mobility, such as 6G and edge computing for automated vehicles, Artificial Intelligence and Machine Learning (AI/ML) for vehicle safety and virtual Light Detection and Ranging (LIDAR), high-definition mapping for surface/sub-surface infrastructure, Ground Vehicles, Air, and Maritime such as vehicle connectivity (V2X) and logistics automation, infrastructure adaptations for Advanced Air Mobility (AAM), autonomous shipping and electrified transportation solutions; and Cross-cutting and Enabling Technologies such as advanced Positioning, Navigation, and Timing (PNT) for millimetric accuracy, cybersecurity for mobility infrastructure, digital twins for transportation systems.

Robotics, Automation, and Additive Construction in Transportation Infrastructure

Robotics Applications include surveying, earthmoving, piling, and concrete work automation. Automation in construction allows for rebar laying, installation, and tying using automated solutions.

Additive Construction (3D Printing) can be used for on-site manufacturing of forms, rebar, beams, trusses, bridge decks and also concrete pumping advancements to enhance infrastructure build times.

Key Takeaways and Final Thoughts

Marrying additive construction with automation and robotics is crucial for next-generation transportation infrastructure. Concrete pumping efficiency plays a critical role in infrastructure development. Automation can accelerate horizontal infrastructure development while addressing cost challenges. With U.S. transportation infrastructure devaluing at $600 billion annually—automation is needed to do more with less. ARPA-I is driving advanced development to transform transportation infrastructure through technology and automation.

ADDITIVE CONCRETE TOWER

XIAOPENG LI
GE Vernova

Speaker Biography

Xiaopeng Li, PhD, is a Senior Research Engineer at GE Vernova Advanced Research Center. Prior to his current role, he served as a technical leader at GE Renewable, where he focused on developing 3D concrete printing technology for wind turbine towers. Li earned his PhD from the University of California, Irvine, under the guidance of Mo Li, who is also presenting at this meeting. Li has specialized in advanced manufacturing of concrete and metal, manufacturing process simulation and optimization, and structural design and analysis.

Xiaopeng Li

Presentation Summary

This session focused on the development of large-scale 3D-printed concrete wind turbine towers, highlighting a project supported by the U.S. Department of Energy under Award DE-EE0009059 exploring technology development, cost reduction, rebar integration, and material advancements.

Project Background and Goals

The objective is to enable taller wind turbine towers through AM. But why taller towers? Taller turbines capture more energy from higher-altitude wind and unlock more land area for wind energy expansion. Traditional construction methods, on the other hand, area limited to 4.3m tower diameter. 3D printing is a potential option to achieve taller towers.

Technology Development Timeline

Initial concept design and feasibility studies were conducted from 2017 through 2019. In 2019, researchers made a comparison between casting vs. 3D printing concrete, focusing on cost-effectiveness. From 2020 through 2022 there were large-scale printing demonstrations and DNV D-level certification was achieved in March 2021. In 2022, a testing lab was set up in Bergen, New York, which was followed by significant advancements in rebar integration, pumping technology, and material development.

Key Achievements and Technical Innovations

Structural design and optimization progress has included the development of concrete and steel hybrid design for taller, more resilient towers; a post-tensioning system optimization for enhanced structural integrity; and overall tower system dynamics modeling to improve performance.

Rebar integration and automation includes rebar design optimized for additive manufacturing with segmented rebar placement allowing for easier on-site assembly. Automated rebar installation techniques are under development.

Material and process advancements include mixing and pumping technologies (for example, the integration of mixing systems with 3D printing hardware and extruder development for print head applications), quality control and monitoring (such as advanced scanning and sensing technologies and the application of Process Failure Mode and Effects Analysis). Concrete/steel transition piece development includes the testing of several configurations (L-flange, T-flange, and prefabricated hybrid connections) and establishing installation and grouting procedures. The primary focus of testing was to reduce construction costs and labor requirements. Challenges include the continued optimization of rebar automation and the need for faster and more reliable material delivery systems.

Key takeaways are that the TRL (Technology Readiness Level) 6 was achieved for major components, the MRL (Manufacturing Readiness Level) achieved 5 to 6 for quality control and process reliability, and that further improvements are needed for scalability and cost efficiency.

Conclusions and Future Applications

Findings are that additive construction enables cost-effective wind turbine towers with increased height potential; that rebar automation and material process refinement remain areas for further development; and that there are significant and numerous potential applications beyond wind energy such as large-scale civil engineering structures, tall infrastructure solutions for energy and transportation, and hybrid additive manufacturing for complex geometries.

INFRASTRUCTURE 5.0

IRIS V. RIVERO
University of Florida

Speaker Biography


Iris V. Rivero

Iris V. Rivero is the Paul and Heidi Brown Preeminent Chair and Department Chair of Industrial and Systems Engineering, University of Florida. She holds a BS, an MS, and a PhD in Industrial and Manufacturing Engineering from Penn State University and is the former Kate Gleason Professor and Department Head at Rochester Institute of Technology and Associate Chair at

Iowa State University. Rivero is a research leader in additive and hybrid manufacturing processes such as scalable hybrid manufacturing techniques for biopolymers, metal alloys, and concrete; biomanufacturing for aerospace and tissue engineering applications; and in situ nondestructive testing for additive manufacturing. Rivero is a NASA Fellow at Marshall Space Flight Center, a Fellow of the Institute of Industrial and Systems Engineers (IISE), has more than 90 peer-reviewed publications, and has given more than 100 invited talks.

Presentation Summary

This presentation focused on exploring 3D printing, fiber-reinforced concrete, AI-driven quality control, and smart manufacturing in infrastructure development as well as addressing structural soundness, cost, workforce development, and material innovations for roads, bridges, and sustainable construction.

Customizing Sustainable Infrastructure

Localized supply chains will enhance sustainability and efficiency. There are significant challenges in labor force development for additive construction. One case study is El Cosmico, a 3D-printed hotel and residential community in West Texas. This is a 64-unit hotel community project, which broke ground in 2024, and is expected to be opened in 2026. For this project, 3D printing efficiency reduced overall project timelines, but construction costs so far have remained high. The savings potential should be up to 80% of traditional construction costs with only 20% additional time needed for the setup and optimization phase.

Roads and Bridges: Challenges and Opportunities

For road infrastructure, there is a shift toward repairs instead of full replacement. How close are we to automated repairs? Needed technology and innovation includes automated scanning systems to assess road conditions and drones for infrastructure monitoring. One example of this is the UK's Self-Repairing Cities Project. We have 3D asphalt printers for autonomous crack repair, but they are limited in that they work on asphalt but not concrete.

There are considerable constraints (or "areas of opportunity"). These include the structural soundness of 3D-printed concrete (still a work in progress), ongoing challenges in material consistency and repeatability, limitations requiring ongoing research in concrete reinforcement, high initial costs and the level of standardized regulations, and the workforce needing training to integrate traditional construction labor with additive manufacturing skills.

Fiber-Reinforced Concrete and Nozzle Effects

3D-Printable Fiber-Reinforced Concrete is a mix of concrete, water, and fillers. Enhanced fiber alignment allows for structural integrity.

Nozzle Effects in Additive Manufacturing

The challenge is preventing clogging and misalignment of fibers in concrete printing. The objective, therefore, is to develop nozzles that optimize fiber alignment without additional manual adjustments. Current progress includes achieving general control over dimensions, but improving internal reinforcement strategies remains key. The research team is now testing fiber alignment within a 16-range nozzle.

Sensor System Management for Infrastructure Monitoring

The goal is to create and deploy smart networked sensor systems that detect anomalies and environmental shifts in prints and integrate with drone-based sensing technology for live monitoring, and adaptive sampling and anomaly detection to prevent cascading failures in large-scale 3D prints.

There are several key takeaways and future directions. Sustainable 3D-printed construction will require localized supply chains and workforce training. Also, road and bridge infrastructure must shift toward repair-based models rather than full replacement. AI integration and sensor-driven monitoring are key to ensuring quality and efficiency in large-scale additive construction. Ongoing research in nozzle design and fiber-reinforced concrete will improve structural integrity and automation potential. And important next steps include collaboration across academia, industry, and government to standardize 3D printing for infrastructure.

ACME TECH INTRODUCTION

William R. Vavrik

Applied Research Associates, Inc.

Speaker Biography

William R. Vavrik is Senior Vice President for Transportation and Infrastructure at Applied Research Associates, Inc. He is an active member of TRB with contributions to highway materials and construction committees, a trusted subject matter expert for U.S. DOT, DOD, and multiple state DOTs and has designed and contributed to infrastructure projects worth billions across North America. Vavrik is currently collaborating with the USACE ERDC with a focus on additive construction with local materials for military operations. He has a PhD in Civil Engineering from the University of Illinois and is a licensed professional engineer in multiple states.

William R. Vavrik

Presentation Summary

This session focused on advancing additive construction in military infrastructure and transportation, utilizing indigenous materials for rapid, on-site 3D printing of essential structures, and reducing logistical burdens and improving mobility support for military and defense applications.

Mission and Goals

The primary objective is to enable on-demand, in-field construction using local materials instead of shipping resources. The military challenge is that troops, trucks, and tanks need to navigate diverse terrains, but gaps (such as streams and ditches) hinder movement. The current process is to fly in the materials, creating high logistical costs and time constraints. A new strategy would be to bring manufacturing to the point of need instead of transporting pre-built structures.

Key Innovations

Key innovations include the utilization of indigenous materials (sand, silt, and other local sources) to 3D-print infrastructure components and new, deployable additive construction technology for rapid fabrication of culvert pipes (allowing vehicles to cross terrain gaps); mobile bridge blocks, jersey barriers and T-walls for protection, and semi-permanent structures (base operations, bunkers, and defense installations).

Development of AC Capabilities

One new and very useful resource would be an item catalog for AC. The goal is to create a standardized catalog of 3D-printable items for military infrastructure. The design approach is based on finite element analysis to ensure structural integrity, focuses on modular, easy-to-assemble components, and uses Lego-style interlocking designs to simplify construction. Current prototypes include culvert pipes and mobile bridge components, jersey barriers and defensive walls, and temporary and semi-permanent shelters.

Use of Local Materials in AM

A challenge in construction is that transporting traditional construction materials is costly and inefficient. One solution is to develop on-site material processing to scoop and process natural resources (riverbed rocks, sand, and silt), to create printable concrete mixtures with available resources, which could also result in minimizing the environmental footprint and reducing costs.

Converting Designs to Machine Instructions

It is important to ensure that AC is accessible to soldiers. Some strategies for this are the adoption of simplified training for military personnel (meaning there is no engineering degree needed), creating user-friendly interfaces for 3D printing operations, and providing deployable printers and mixing systems mounted on trucks. The future vision is of as many private sector applications possible, and there are ongoing discussions on how to make the technology widely available commercially. There is also hope for optimization of geometries to improve load-bearing capabilities in the near future

AC in Transportation and Military Mobility

Additive construction has many strategic advantages. First, it decreases the logistical burden by using locally available materials. Second, it reduces crew sizes, as robotics and automation minimize the need for manual labor. Third, it increases flexibility for on-demand construction, removing the need for stockpiled materials. And finally, it enables construction of shapes that would be nearly impossible with traditional methods.

There are practical deployments and field-testing now. For example, the Army Corps of Engineers is actively testing prototypes. And use cases include Forward-Operating Bases, expediting deployment of essential infrastructure, new bridging solutions for rapid troop movement, and the use of protective barriers and defensive structures.

Key Takeaways and Future Considerations

ACME Tech focuses on making additive construction practical, scalable, and deployable for military and emergency response operations. Leveraging local materials eliminates costly supply chain challenges. Field-ready 3D printing technology can empower troops to rapidly create mission-critical infrastructure. There is government-wide interest with potential for adoption beyond the military into civil transportation infrastructure. Next steps are to further optimization of machine learning for print instructions, rebar integration, and automated mixing solutions.

Question and Answer Session

Question 1: What are the critical technologies that still need to be developed? What compact research and development efforts could unleash the full potential of additive manufacturing?

Answers:

Rivero: Real-time computer vision and sensing for quality control are essential. Understanding the quality differences between a 5m and 20m print will be key in advancing AM.

Li: The use of native materials is a major area for development.

Vavrik: Optimizing shape and design flexibility is crucial. Current designs rely on standard culverts (oval, square, rectangular), but AM should allow us to customize shapes to meet performance needs. Similar to how 3D metal printing enabled complex military designs, concrete AM should push beyond traditional structures.

Atkinson: There needs to be a way to lay concrete differently rather than using the current "toothpaste-like" extrusion method. Research has found that a 41% strength increase can be achieved by integrating vertical and horizontal layering, utilizing a 6th-axis nozzle and periodic layer compression.

Question 2: What safety concerns should be addressed in AM?

Answer (Rivero): Toolpath planning should ensure that workers are aware of their locations in relation to active equipment, making the process fool-proof for safety.

Question 3: What are the key challenges regarding design codes?

Answers:

Vavrik: AM design should be performance-driven, with load-based standards rather than traditional prescriptive methods. Current mix designs rely heavily on cement and water, but real solutions need aggregates for durability.

Rivero: Collaboration across multiple engineering disciplines is needed to establish new standards.

Li: Unlike traditional structures, 3D-printed components can't rely on a single test to prove 100-year durability. AM requires a different validation approach.

Question 4: In a recent wind tower test in Minnesota, failure seemed to be related to fixturing issues. What happened?

Answer (Li): The failure was due to compression failure at the interface, rather than an overall structural failure.

Question 5: Were the wind tower durability tests conducted on printed samples or cast samples?

Answer (Li): Tests were performed with both vertically and horizontally printed samples, and results varied depending on layer orientation.

Question 6: Reinforcement remains a major challenge in 3D concrete printing. What are the future possibilities for rebar integration?

Answers:

Li: Steel fiber alone cannot fully replace rebar, but it does help with shrinkage and cracking control.

Rivero: Fiber reinforcement needs to be integrated with printing technology, but current challenges include clogging. For stiffer materials like steel, alternative reinforcement methods—not reliant on the nozzle—must be developed. A challenge is that long-span reinforced concrete structures remain difficult to achieve using current AM methods. Research in Germany is leading in this area.

Question 7: What are the cost barriers to scaling AM?

Answer (Vavrik): Materials are the biggest cost factor. Current AM relies heavily on fine aggregates (sand and mortar), but for sustainable large-scale adoption, rock-based concrete mixes will be necessary. The ACME Tech perspective is that military applications tend to focus on short-term solutions (2-year missions) rather than long-term durability. High-quality concrete for AM currently costs about $2,000 per cubic yard, but for broader adoption, costs need to be reduced to $250 per cubic yard. Also, local aggregates should eventually replace fine mortar-based mixes, but current printers struggle with coarser materials.

Question 8: How do we balance cost, efficiency, and safety in AM?

Answer (group discussion): Perspective matters. What is considered "better" depends on who is defining it. Some may prioritize speed, while others value longer-lasting infrastructure. And considering federal funding, may want to avoid framing AM as mostly a "labor-saving" technology when applying for government grants, as there may be understandable concerns about funding technology that simply eliminates jobs.

Question 9: What role will additive construction play in future infrastructure projects?

Answers:

Atkinson: AM will be particularly valuable for horizontal infrastructure, including bridges, pipelines, and seawalls.

Vavrik: AM is especially useful for retaining walls, where surface texture doesn’t matter, allowing for cost-effective, functional designs.

SESSION 3B

Steel Construction in Additive Manufacturing

ATOROD AZIZINAMINI,

Florida International University

Moderator

This session explored the process of considering additive steel manufacturing techniques to address repairs for bridges. The presenters covered the process of identifying and testing steel manufacturing processes to be comparable with current structural standards.

A BRIDGE TO THE FUTURE OF STEEL ADDITIVE MANUFACTURING

RYAN J. SHERMAN

Georgia Tech

Speaker Biography

Ryan J. Sherman is an Assistant Professor in the School of Civil and Environmental Engineering at Georgia Institute of Technology. He earned his BS in Civil Engineering from Michigan Technological University, followed by his MS and PhD in Civil Engineering from Purdue University. Sherman has conducted large-scale laboratory testing, as well as field monitoring and instrumentation projects on steel bridge and ancillary highway structures. He has had an active role in over 25 research projects, encompassing large-scale structural experimentation, structural health monitoring, sensor development, material characterization, fatigue and fracture, and analytical simulation.

Ryan J. Sherman

Presentation Summary

This first presentation began with an introduction to the various applications of steel manufacturing, such as optimizing key structural components and replacing traditionally complicated fabrications. The presentation also covered the importance of research and education in the additive manufacturing field as a whole. Additive manufacturing is a relatively new concept, and often the applications use materials like concrete rather than steel. Identifying use cases for steel manufacturing specifically, getting the industry excited about these potential applications, and promoting this technique to the public are the key goals moving forward.

The presentation then shifted to a demonstrational project and some of the various challenges associated with additive steel design and production. The project itself, (relating to Wire Arc Additively Manufactured Steel: https://www.fhwa.dot.gov/bridge/pubs/hif24008.pdf) focused on production speed while being limited to current production capabilities, which meant that modular components were preferred. In order to generate excitement for the project, another key focus was to make the design interactive and "instagrammable." With these considerations, the structural engineers began to design, considering the structural integrity and connections between components. The project also focused on integrating the structural components with fundamental architectural design, such as adding spiral trees and branches. Further limitations, such as the inability to print steel horizontally and the final design having to actually be buildable, influenced the use of castings in many of the architectural components.

COLD-SPRAY ADDITIVE REPAIR OF CORRODED STEEL BRIDGE BEAMS

BRIAN SCHAGEN
UMass Amherst/MIT

Speaker Biography

Brian Schagen

Brian Schagen is a structural engineering researcher currently pursuing a PhD at the University of Massachusetts-Amherst (UMass Amherst), specializing in Structural Engineering and Mechanics. He is a visiting PhD student at the Massachusetts Institute of Technology (MIT) and holds a master's degree in Structural Engineering from Delft University of Technology, where he graduated with distinction. His research focuses on the Cold-Spray Additive Repair of Corroded Steel Bridge Beams.

Presentation Summary

Currently, there are more than 620,000 bridges across the United States, out of which 7.5% are considered structurally deficient. When a bridge is given a rating of poor condition, it immediately closes to traffic due to safety protocols and will only open after repairs have been applied to it. However, current repairs are expensive, labor intensive and require many resources.

Bridge deterioration occurs due to a multitude of factors, including weather-related wear and tear, heavy vehicular loads, and insufficient maintenance. Deteriorated components often cannot be repaired and as a result a replacement is needed due to the lack of effective restoration methods. A possible new repair method for corroded steel bridge beams is cold spray additive manufacturing (CSAM), where the substrate is being treated by an oxide-free deposit without damaging the underlying substrate thermally. In this process, a high temperature compressed gas (nitrogen) is used to accelerate the metal powder feedstock, reaching all the way up to 300 m/s and beyond. With cold spray, it is possible for a bridge beam to retain its original capacity using targeted and limited added material. A so-called bond is created between the substrate and the powder ensuring the ability to retain capacity.

In recent years, the use of CSAM applications has grown significantly due to the low working temperature, less product size limitations, and one order of magnitude higher deposition rates compared to other established additive manufacturing techniques. The current study discusses a new state-of-the-art application where CSAM is introduced for additive repair of corroded steel bridge beams. Through a collaboration between Massachusetts DOT, UMass Amherst and MIT, the research team tested cold-spray repairs on naturally corroded substrates that have been obtained from deteriorated bridges in the New England region. Several types of tests with tensile coupons and compression pillars have been performed and research is currently expanded toward fatigue and bending strips. Furthermore, the focus will be on moving from a lab environment to the field using portable equipment. With that, process parameters are tested outdoors to deposit repair on steel corroded elements with CSAM.

The research results highlight that the beams repaired by CSAM can retain significant capacity in comparison to the volume of metal added. Furthermore, the repair is precise and could be performed directly in the field. This gives the opportunity to possibly prevent extensive repairs, that could lead to load and weight restrictions or even closure for a longer time.

Schagen's presentation addressed the issue of bridges needing urgent repair and becoming unsafe, and the importance of identifying and making these bridges safe. As a result, his joint project between UMass and MIT worked on testing bridge beams to obtain detailed information about the failure points and develop an additive manufacturing solution to efficiently repair bridges.

Schagen covered various scanning methods, including using lighter skinning, regal scanners, and Arctic radio devices. Lighter skinning is a scanning method that can capture both the overall scale of bridges and individual structural members. This method can also generate computer maps, which provide accurate length and weight metrics. A regal scanner is a lightweight device that is able to capture components with accuracy up to 5 millimeters. These data collection devices are able to provide rich data about failure points at a relatively low cost.

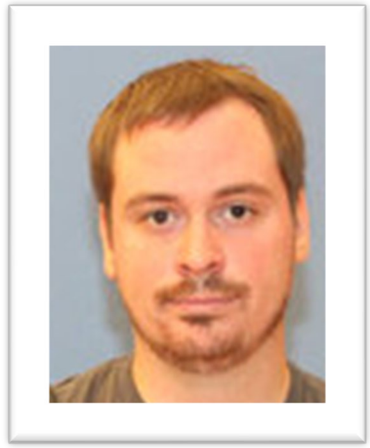
The primary repair method discussed involved using a stainless-steel powder, putting it under extremely high velocity to make it deform and stick-on impact. This method skips traditional processes where sandblasting is needed before repairing, making it a more cost-effective option. Using the data collected, the team is able to test the steel to obtain ideal mechanical properties. The repeatability and customizable nature of stainless-steel powder, and the ability to source materials locally make the materials cost competitive with traditional methods. Future research involves testing the new materials on corrosion and other durability factors.

WIRE ARC ADDITIVE MANUFACTURING IN HIGHWAY BRIDGE INFRASTRUCTURE

Ryan Slein
Federal Highway Administration

Speaker Biography

Ryan Slein's research focuses on identifying cost-effective and accessible materials to use for bridge repairs, and the process of working with state and federal agencies to implement and adopt these methods. This method uses direct energy deposition (DED) along with commercially available materials to fabricate materials for specific repair cases and has the potential to scale well into the heavy infrastructure sector.


Ryan Slein

Presentation Summary

This presentation highlighted Slein's research for bridge repair materials and working with agencies to implement and adopt these new materials and methods. Slein shared that the first step in the process was to identify current use cases and research gaps. Agencies like the Asheville DOT and ASME have adopted qualification standards, which include the bracketed qualification procedure. Due to the nature of DED, where heat is used to create the structure of the component, more complex areas will naturally take more time to fabricate and be more exposed to heat as a result. The goal is to make all parts of a component fit within the acceptable range of thicknesses, as too much heat will lead to mechanical property changes and not enough could lead to cracking and hydrogen issues. This research aimed to push the acceptable bounds of the bracketing procedure, by addressing parameters such as property variations within the same material, or consistency of the machine learning algorithm. When testing the performance, the focus was on analyzing fatigue results, as well as testing these components in unfavorable environments.

This research has been implemented in collaboration with Connecticut DOT, on a bridge repair project with severe corrosion. Since only a single part needed to be replaced and the scale fit within the printing capabilities, this project represented a potential application of future DED-manufactured components to be used in repair projects.

EVALUATING THE MATERIAL AND FATIGUE PERFORMANCE OF WIRE ARC ADDITIVELY MANUFACTURED STEELS FOR TRANSPORTATION APPLICATIONS

HANNAH KESSLER
Georgia Institute of Technology

Speaker Biography

Hannah Kessler

Hannah Kessler is a PhD candidate in civil engineering at Georgia Institute of Technology, with bachelor's and master's degrees in civil engineering from Clemson University. Her current research centers on characterization of the material, connection, and fatigue performance of wire arc additive manufacturing (WAAM) steels, aimed at advancing their integration into structures. She has expertise in experimental testing of novel structural materials, components, and systems made from a variety of materials.

Presentation Summary

Advances in large-format metallic additive manufacturing have demonstrated that WAAM is an ideal candidate for transportation structures. However, limited knowledge of the material and fatigue behaviors of wire arc additively manufactured steels hinders widespread adoption. The presenter's team studied two welding wire feedstocks, American Welding Society (AWS) ER70S-6 and ER80S-Ni1. The results of extensive material and fatigue tests indicate the promise of WAAM ER70S-6 and ER80S-Ni1 as structural materials.

This presentation builds on the previous discussion of wire arc manufacturing for bridges, specifically focusing on the mechanical properties of potentially viable wire feedstocks. The two main materials analyzed in this research were the ER70S-6 and the ER80S-Ni1. Both feedstocks are compatible with Grade 50 steel and other materials commonly used in bridge construction, and the ER80S is inherently corrosion-resistant. These materials were tested at various temperatures and orientations, producing Tension and Charpy V-notch (VCN) impact datasets that were then compared to current standards.

This study found that the inter-pass temperature had an impact on the overall properties of the material. Typically, at higher inter-pass temperatures, the material tended to have lower strength elongations, as well as lower yield and tensile strength. However, when the orientation was adjusted to be parallel to the build direction, the overall VCN turned out to be independent of temperature.

Summary metrics include tensile/impact testing, temperature evaluation, deposition direction, and build direction. Specific testing metrics include temperature (three inter-pass temperatures), build direction and/versus deposition direction, Tension and Charpy V-notch (VCN) impact datasets created.

The study found the following results. Yield/tensile strength increases and elongation decreases with decreasing temperature; CVN parallel to build direction is independent of temperature; CVN parallel to deposition direction equals higher temperature and temperature energy (exceeded AASHTO, but not AWS). The following were referenced:

https://ascelibrary.org/doi/full/10.1061/JMCEE7.MTENG-18732

https://www.sciencedirect.com/science/article/pii/S2352012424002868

SESSION 4

Standard and Policy Session

ISLAM MANTAWY, MODERATOR

Rowan University

PANEL DISCUSSION

This panel included Eric Kreiger, USACE ERDC; Shawn Platt, National Institute of Standard and Technology (NIST); and Julie Ann Hartell, Texas A&M University. The discussion focused on the standards and codes specific to additively manufactured materials to ensure safety and reliability as an alternative solution to traditional materials. The presenters shared the inadequacy of current materials standards for AM materials, the importance of good public perception about AM, and specific criteria to evaluate when creating these new sets of standards.

Speaker Biography

Eric Kreiger

Eric Kreiger has 15 years of experience in structural design, structural testing, construction materials research, deployable and expeditionary construction, engineering decision-making using GIS data, material degradation evaluation, and retrofit design, and building science. Kreiger is currently the Structural Lead for the Additive Construction Program at USACE ERDC where he ensures that the structures that are will be constructed by military personnel in an expeditionary environment.

Presentation Summary

Kreiger's presentation addressed the current status of AM as a viable technology, and the importance of communicating the benefits of AM to the public to increase adoption. Many innovative technologies or methods like AM have early adopters, but without good public perception and continued collaboration among public and private sectors and researchers, these technologies will eventually fall into the chasm of overhyped technologies. This presentation emphasizes the potential applications of AM through demonstrations, which simultaneously would produce valuable data that could contribute to the development of standardized codes for AM materials.

One such demonstration consists of constructing a building structure at Camp Atterbury, Indiana, where every component of the structure includes some form of additive construction. Blast loads conducted on the structure feed information to develop standards and codes and prove that this technology could eventually be viable for defense applications. Variables associated with the AM process are also measured, such as seeing whether the printing nozzle orientation had an impact on compressive strength, or whether printing straight versus a chevron pattern could improve structural performance.

Throughout this process, the research team found that many of the current codes were extremely conservative for additively manufactured materials. As a result, they conclude that pushing for newer standards specific to AM materials is a critical step for advancing this technology, so the barrier for manufacturing and testing can be lower for others. Although currently there is a high level of interest by the government and private sector, they conclude that without collaboration to develop these standards and codes, this technology is unlikely to be widely accepted as an alternative manufacturing method.

Speaker Biography

Shawn Platt

Shawn Platt is a Research Civil Engineer at NIST within the Infrastructure and Materials Group of the Materials and Structural Systems Division, the Project Lead for the Additive Manufacturing with Cement-based Materials project at NIST, and the lead investigator for the Reliability of Fiber-Reinforced Polymer (FRP) Composites in Resilient Infrastructure project.

Platt holds a PhD in Civil and Environmental Engineering in advanced infrastructure systems focusing on structural materials, and an MSc in Civil and Environmental Engineering with a concentration in structural engineering and mechanics.

Presentation Summary

Platt began by posing several questions.

- How do standards actually apply between the lab and in the field?
- If I come up with a way to measure the compression load, then what do I do?
- What's needed right now?

Platt explained that these questions are related to the need for standards—in all industries, not just manufacturing. Specifically, he addresses the lack of effective testing methods, which was the reason for his "Standardization Workshop" series. One problem contributing to the lack of standards is the competitive nature of some industries. Some companies will withhold data from potential partners rather than work together with them, when in reality the partnership could be mutually beneficial. Due to this competitive mindset, he concluded, there has been a lack of standardized testing methods for AM manufacturing.

Even those who realize the importance of testing don't always know what to do with test results. Each entity has its own methodology to conduct tests, and all of them usually end up being slightly different from actual field conditions. Even though organizations all collectively realize that a universal standard for testing is needed, nobody is willing to take that next step and establish the standard.

Platt's alternative is already being implemented. The Army Standardization Workshop Series was bringing different groups of people together, from researchers to suppliers to manufacturers. These workshops aimed to more accurately predict the performance of materials in the lab versus in the field and apply these to developing testing standards. Furthermore, it aims to educate others on what exactly to do with measuring material properties, and to start to approach testing materials in more similar ways.

Presentation Summary

Julie Ann Hartell's presentation focused on applying the currently available testing methods for additively manufactured materials. The presentation began with a discussion on the challenges associated with developing standards for additively manufactured materials, which included test replicability, highly variable material properties, and lack of data. As a result, any method designed to test the structural capabilities of AM materials must be sensitive enough to detect between material failure and other types of failure. Hartell's research focused on using

Julie Ann Hartell

the ASTM 666, a widely known testing method, to see its viability for detecting and quantifying damage, as well as its repeatability and reliability. Size, geometry, duration and cost were secondary considerations.

The study printed three samples that would be tested over 300 cycles, so nondestructive testing methods were used. The specimen samples were multilayered and were tested through various frequency and pulse tests, and humidity and air tests. Although there was minor surface degradation after the tests, the overall degradation was far above the ASTM standard. When testing resistivity, extra care was taken to ensure temperature was constant throughout the samples—there was some variation that was attributed to material performance. Hartell found that the resonant frequency of the materials varied between samples, which could possibly be due to the material changing during the tests. For future work, larger-scale testing is planned, including longer cycles and a larger variety of exposure conditions.

SESSION 5

Freight and Supply Chain

CAITLIN HUGHES

Federal Highway Administration

Moderator

MODERATOR BIOGRAPHY

Caitlin Hughes serves as the Director of the Office of Freight Management and Operations for the Federal Highway Administration where she directs FHWA's work on federal freight programs and input to freight policy, including the implementation of certain freight initiatives from the Fixing America's Surface Transportation (FAST) Act. Hughes is a graduate of the University of Vermont and received her Master of Public Administration degree from George Washington University.

Caitlin Hughes

SESSION SUMMARY

This session featured three panelists from U.S. DOT, Hawaii DOT (HDOT), and The Barnes Global Advisors. They provided their perspectives on the benefits of additive manufacturing and their potential impacts on increasing the efficiency of the supply chain. Specifically, using AM to produce materials that traditionally travel thousands of miles through the supply chain can decrease reliance on imports and strengthen America's supply chain resilience and drastically cut down on costs and delays.

Speaker Biography

EDWIN SNIFFEN

Hawaii Department of Transportation

Edwin Sniffen currently serves as the director of HDOT and is responsible for the state's transportation connections through the airport, commercial harbor, and highway systems. As Chief Executive of HDOT, he is focused on fulfilling the state's transportation needs, which are integral to advancing the administration goals of housing, economic development, energy, food security, education, climate resiliency, and emergency preparedness. Across all modes of transportation, his priorities are safety, preservation and improvement of transportation facilities, ensuring efficiency and transparency of HDOT operations, and creating and maintaining partnerships that will help improve the quality of life and the transportation experience for Hawaii residents and visitors.

Edwin Sniffen

Presentation Summary

Sniffen's presentation highlighted the unique circumstances of Hawaii, being an island-nation thousands of miles away from the nearest continent. Due to its isolation, Hawaii is inflexible when it comes to adapting to changes in the supply chain. Most things are imported via ship, which usually takes weeks or months, or flown in via plane, which is considerably more expensive compared to trucking or rail alternatives available in the mainland. Some of the issues highlighted with Hawaii's geography included severe delays in infrastructure projects and repairs. A tunnel was closed for over six months because the stainless-steel rods that needed to be replaced took that long to arrive. A TSA (Transportation Security Administration) line at an airport was closed down and caused delays of 45 minutes and longer for people because three hardware parts were broken, affecting the whole system. Infrastructure projects in Hawaii, like building emergency housing for the homeless or protecting the coastline, are often delayed from the start due to the delay in receiving the materials.

Hawaii stands to benefit on a large scale from 3D printing. Instead of waiting for 6 months for stainless-steel rods to be manufactured and shipped, they can be printed on-site. In the event of natural disasters, this technology could be used immediately for repairs and upgrades, providing a cost-effective way for the state to address these challenges. HDOT has already been talking with both public and private agencies to explore using this technology in protecting its coastlines from erosion. Even though 3D printing may be more expensive overall now, it saves weeks to months of shipping time. And once it can be adopted at scale, Hawaii could have a viable way to manage its own production needs.

Speaker Biography

ALLISON DANE CAMDEN

U.S. Department of Transportation

Allison Dane Camden serves as the first-ever Principal Deputy Assistant Secretary for Multimodal Freight Infrastructure and Policy. She was previously at the Washington State Department of Transportation, where she served in a variety of executive roles, including as Deputy Assistant Secretary for Multimodal Development and Delivery, where she helped lead a team of 800 professionals in eleven divisions that worked daily to drive sustainable, integrated, multimodal transportation solutions for all across Washington.

Allison Dane Camden

Presentation Summary

This presentation began with the importance of supply chains, highlighting the severe disruptions that occurred during the COVID-19 pandemic. Many Americans felt this impact as they started ordering more things online, and found they took longer to arrive than usual. The government has also recognized the importance of a robust supply chain and has implemented measures in the IIJA (a bipartisan infrastructure bill), and a new council dedicated to strengthening America's multimodal freight capacity.

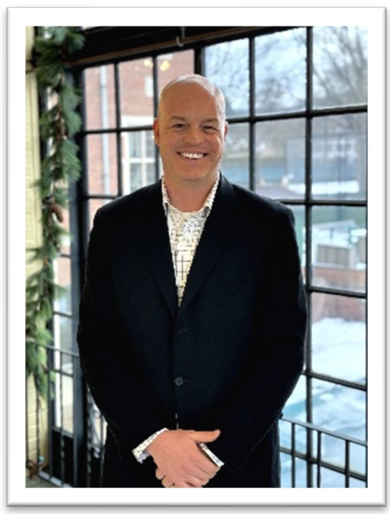
Additive manufacturing has the potential to improve the supply chain by reducing the amount of materials that are transported. AM can be used to create goods that traditionally may have required multiple different components. This reduces the need to have multiple suppliers and storage space for all the components, and overall diminishes the reliance on other countries for imports. Furthermore, with the reduced volume of components being carried through the supply chain, AM can indirectly reduce VMT (vehicle miles traveled). However, AM is currently limited to more complex, small parts, and is not yet cost-effective enough to be comparable to traditional manufacturing methods at a mass-production level. The higher up-front costs for materials required for AM, as well as the equipment itself, are the current obstacles that AM faces. Additive manufacturing is a potential solution that can increase the resilience of America's supply chain while decreasing reliance on other countries but is limited to specific niches by its current high costs.

NEIGHBORHOOD 91: HOW THE FIRST ADDITIVE MANUFACTURING PRODUCTION CAMPUS SHORTENED SUPPLY CHAINS

ERIC VERSLUYS
The Barnes Global Advisors

Speaker Biography

Eric Versluys is a program manager with a background spanning aerospace, automation, and manufacturing and currently leads technology and manufacturing ecosystem programs at The Barnes Global Advisors. At Lockheed Martin, Eric served as the ADP Platform Integration Lead and was recognized as an Associate Technical Fellow in AM of RF structures. Eric holds a bachelor's degree in mechanical engineering from Colorado State University.



Eric Versluys

Presentation Summary

The promise of AM to revolutionize supply chain resilience through on-demand part production has captured significant attention across industries. However, the common perception of AM as a simple "press print" solution overlooks the complex supply chain requirements inherent to metal additive manufacturing processes. These processes depend on specialized powder materials, post-processing equipment, testing facilities, and skilled labor—all of which can face their own supply chain disruptions and inefficiencies.

Neighborhood 91, located in Pittsburgh, Pennsylvania, presents an innovative solution to these challenges through its regional ecosystem approach specifically designed for AM. By co-locating key elements of the metal AM supply chain within a single campus strategically positioned at the intersection of major highway, air, and rail transportation networks, this initiative demonstrates how geographic clustering can significantly reduce transportation costs, lead times, and supply chain complexity. The ecosystem model enables agile response to market demands while maintaining the benefits of specialized expertise and shared infrastructure.

The success of Neighborhood 91 serves as a prototype for a broader Resilient Manufacturing Ecosystem (RME) model currently being expanded across the United States and internationally. This expansion represents a paradigm shift in how manufacturing networks can be organized to maximize efficiency while building in redundancy and flexibility. By examining the concept, implementation, and measurable successes of Neighborhood 91, we gain valuable insights into how similar regional manufacturing ecosystems can be developed to strengthen global supply chain resilience while maintaining the agility needed in modern manufacturing environments. The RME model suggests a future where manufacturing capability is both distributed for resilience and concentrated for efficiency.

Versluys's presentation focused on the novel concept of compressing the entire supply chain process into a single neighborhood. The presentation focused on a case study in Pittsburgh, called 'Neighborhood 91,' where this idea of bringing the entire manufacturing ecosystem within a single community was trialed.

These neighborhoods conceptually have large benefits, like reducing thousands of miles of rail and highway transportation to a couple of miles within the community. By bringing the materials supplier, manufacturer, inspector, and heat treater into the same area, lead times can also be reduced drastically, especially for things created Right on Time (or created when a good is demanded). In Neighborhood 91, the average lead time for some goods went from over 6 months of lead time to 15 days or less, over twelve times faster. Overall, these ecosystems like Neighborhood 91 can help reduce energy consumption and emissions from the traditional manufacturing process.

Additively manufactured components produced in Neighborhood 91 include various applications for the military, such as airplanes. One example was a brake key found on KC130 tankers and some Boeing aircraft. Although it is a simple component to manufacture, the production takes months via the traditional supply chain, and it is a part that airplanes cannot fly without. This is an example of the niche that AM is designed to address.

Due to the success of Neighborhood 91, Versluys mentioned the possibility of expansion to areas like Hawaii, which could benefit from this form of in-house efficient production. The importance of training a workforce to operate at the scale required was also raised, and making sure that all the manufacturing systems and digital files are secure. Overall, these types of communities excel at adapting quickly to current needs.

SESSION 6

Culverts, Pipes, and Other Structures

PRANAY SINGH

University at Buffalo

Moderator

INVESTIGATING THE SEAM EFFECT ON STRUCTURAL FAILURE OF ADDITIVELY CONSTRUCTED PIPE CULVERTS

ALIREZA HASANI, BOSHRA BESHARATIAN, AND SATTAR DORAFSHAN

University of North Dakota

MARC MAGUIRE

University of Nebraska-Lincoln

Speaker Biography

Alireza Hasani is a Research Associate at the University of North Dakota, holding an MS in Civil Engineering with a focus on structural performance of additively constructed structures. He specializes in structural design, analysis, material testing, and R&D. Alireza is dedicated to advancing construction technology and integrating digital models into additively constructed structures. Particularly, he designs buried concrete structures for the North Dakota Department of Transportation, ensuring compliance with design codes.

Alireza Hasani

Presentation Summary

Additive construction, specifically 3D concrete printing (3DPC), offers potential benefits for pipe culvert construction by reducing labor, material waste, and costs. However, concerns remain about the structural integrity of 3DPC pipes, particularly due to the seam effect stemming from layer-by-layer printing. This study tested six 3DPC pipes to assess how seam placement affects cracking patterns and load-bearing capacity. Pipes with seams aligned within 20 degrees of critical location failed at the seam while pipes situated further away failed at the typical region.

The Rise and Evolution of 3D Concrete Printing Projects Worldwide

The presentation emphasized a need for unreinforced printed structures in construction sectors across the world, with countries like the United States and China conducting 37 and 15 projects to date, respectively. Half of reported construction projects took place on-site, and printing is primarily conducted with a gantry, though use of mobile robotic arms is increasing. Primary applications are residential (42%), but projects are also being applied to infrastructure (18%), commercial (12%), and more applications. There are three primary concrete construction procedures: (1) load-bearing 3DPC structures, such as the Striatus Bridge in Venice, Italy; (2) printed and cast structures, based on unreinforced masonry design; and (3) non-load-bearing structures, used as permanent formwork for reinforced concrete. (Refer to presenter's paper: https://www.sciencedirect.com/science/article/abs/pii/S095006182402169X)

Interest in 3D Concrete Printing Pipes

Though 3DPC is a rising technology in the construction field, there is still difficulty in applying this method of construction to pipes. First, there is a lack of knowledge on load-bearing structural elements such as pipes, which 3DPC studies could improve. In addition, local needs require alternative methods to infrastructure such as culverts. If 3DPC is the solution, such pipes must be shown to comply with local standards and construction capabilities. Further, issues with production must be investigated and addressed.

Study on 3D Concrete Printing Pipes

Hasani presented a study on 3DPC Pipes. The group used a Kawasaki BX-130 6-axis robotic arm, a MAI Lyra3D progressive cavity pump, and a Collomix counter rotating mixer for printing the mixed concrete. After using computer aided design for a pipe pattern, the group's design was converted to a print pattern through a slicing 3D printing program. The printed pipe then underwent structural testing for evaluation of mechanical properties.

Preliminary Results of 3D Concrete Printing

For an initial large-scale structural test, Hasani's group conducted a three-edge bearing test on a 3DPC pipe in accordance with the standards ASTM C497 / AASHTO T280 on Standard Test

Methods for Concrete Pipes (astm.org/c0497-20e01.html). Results on two samples showed strength differences 23 and 42% higher than the strength requirements from the standards. However, the testing revealed potential weakness through crack propagation at the pipe's spring line. To mitigate the effect of the print seams, the research group considered the effect of seam alignment on the mechanical strength of the 3DPC.

3D Concrete Printing Seam Section Study

For an extended study on the seam section, the presenter's group manufactured six pipes of Quickrete and tested the pipe's performance on three-edge bearing tests. The group found a dependence of load capacity on the angle of the printing seams relative to the angle of seam alignment. Pipes with 20° misalignment had the highest strength and less bending stiffness. These results can inform construction procedures for maximizing the strength of 3DPC for culverts and more infrastructure.

Question and Answer Session

Questions raised by attendees included the possibility of offsetting the seams on each printed ring of the culvert as well as the importance of 3DPC for culverts. Due to the great demand for culverts in construction, water management, and transportation needs, 3DPC for culverts offers a way to better cast high strength culverts in a time frame suited to project timelines.

DESIGN AND EVALUATION OF A 3D-PRINTED CONCRETE BOX CULVERT

JIM MANTES, JON MIKHAEL EREKSON, AND JADEN BENNETT
Applied Research Associates, Inc.

MICHELLE L. BERNHARDT-BARRY AND TIM NUNEZ
University of Arkansas

CASEY ROBERTS
MATT FRIEDELL
Robotic Construction Technologies

Speaker Biography

Jon Mikhael Erekson, PE, has over 20 years of experience in analysis and design of structures, components, and systems for extreme loads including blast, progressive collapse, and natural hazards. Projects have included Anti-terrorism/Force Protection (AT/FP) and blast design and analysis support for federal office buildings, airport terminals, courthouses, underground mines, embassy compounds, hospitals, clinics, museums, monuments, power companies, laboratories, bridges, as well as various commercial products and systems.

Jon Mikhael Erekson

Presentation Summary

U.S. military combat engineers are routinely faced with missions involving construction of structures that enhance or deter mobility. Construction of these items in a combat zone is very difficult due to limited material options available. Further complicating construction in a combat zone is the large logistical footprint of traditional construction solutions. Additive construction is a potential revolutionary method to change the way battlefield mobility and counter mobility construction missions are accomplished. The ACME Tech is a research program funded by the USACE ERDC with a goal to advance AC technology by developing structural designs for mobility and counter mobility items, developing material mixtures using indigenous materials, developing AC slicer software solutions, and developing a mobile AC equipment package for military construction. The research program is supported by researchers from Applied Research Associates, Inc., University of Arkansas, Iowa State University, and Robotic Construction Technologies.

A common need for mobility on the battlefield is the placement of concrete box culverts for vehicle and soldier crossings. Precast concrete box culverts are a common choice for this application because they can be installed rapidly and require little maintenance. Precast concrete offers the advantage of high-quality materials as well as control and consistency during fabrication. However, typical precast box culverts can range in weight from 1,500 kg/m (approximately 1,000 lb/ft) to over 12,000 kg/m (approximately 8,000 lb/ft). Shipping such large and heavy structures is costly and provides logistical challenges in successful delivery and placement at a desired location. As a result, AC is seen as an ideal solution whereby indigenous materials can be used to produce AC mixes, which can then be employed to print box culverts and subsequently place them in the field with significantly reduced resources for production since only the printing equipment and limited materials would need to be transported to the desired location.

One notable challenge with utilizing AC for producing box culverts is that structural performance of the printed concrete is not well understood beyond compressive behavior. At the present time, printed concrete is not typically relied on for significant shear, flexural, or composite response. Culvert geometry does not lend itself well to designs or printing patterns that are predominantly loaded in compression only. Loads from surrounding soil, water, and surcharges from foot or vehicle traffic result in notable shear and flexural loads that must be resisted by the box culvert design. A combination of structural design, finite element analysis, and physical testing have been leveraged to better understand the ability of AC to handle these kinds of load combinations and a preliminary design approach for printed box culvert sections. The developed approach allows for modifications based on varying material properties and potential bonding and composite action of the AC box culvert concept.

Importance of 3D Printed Concrete Box Culvert

Erekson's group at Applied Research Associates, Inc. partnered with Dream Research and the USACE for Additive Construction from Maneuver Enabling Technology (ACME Tech). This is especially crucial for "horizontal entry missions" for military operations. A box culvert improves mobility for both soldiers on foot and vehicles carrying heavy loads in crossing unfamiliar terrain. Such boxes would be printed on-site with the ability to change patterns and work with local materials for mission requirements.

Most additive manufacturing research for construction focuses on vertical construction for compressive strength. However, these are focused on the mechanism of a part and require complex manufacturing techniques. A key battlefield need is to reduce the material and manpower for producing a part. The culvert infrastructure must improve safety and accommodate military vehicles carrying heavy loads, often 1,500-5,000 psi (pounds per square inch). A box culvert design can accommodate a larger range of loadings.

Evaluation and Tuning of Box Culvert's Mechanical Properties

Erekson discussed the importance of reinforcing the culvert bed. The required internal shear moment was calculated based on standards from Asheville and the Federal Highway Administration, important transportation references. Based on the load requirements, the team designed and tested several prints for preliminary results. These enabled the development of finite element methods to understand the range of the box culvert's capabilities. It is important to note that mechanical properties are high with a precast concrete technique.

In addition, the team evaluated multiple printing patterns. Erekson especially took note of the bonding between 3D-printed layers and potential weaknesses based on voids in unbonded printed components. In particular, the team's collaborators want to reduce or eliminate the need for inserting grout into culvert parts due to the intensive labor. Using a compressive strength test up to 4000 psi, Erekson's group evaluated the culvert's performance. These tests were further qualified by models of concrete damage under compression testing in collaboration with the University of Arkansas.

Question and Answer Session

The audience expressed interest in the geometry of the box culverts and the location of seams, especially given the discussion in the previous presentation. In the box culvert, the seam is shifted for each layer to reduce stress concentrations. Further discussion concerned the printing considerations. An audience member asked about using a plate to smoothen areas of stress concentration when concrete is extruded from the printer nozzle. However, for military applications, a key goal is using simple printers that are easy to transport, so design considerations must avoid parts that require additional mechanical elements.

Erekson also discussed the greatest concentration forced being at the top and bottom of the culvert, especially for flexible moment connections. In addition, the inner faces of the culvert experience tension, but this was clarified to be independent of the inner layer printed boundary for reinforcement.

Printing patterns such as triangulation, rectangular grids, and honeycomb shapes from the University of Arkansas were discussed as future avenues to test designs. Ultimately, Erekson is interested in employing a sinusoid pattern to incorporate both structural performance and permeability of the culvert structure. Though the box culvert is intended for short-term but strong military applications, the designs could be improved for permanent structural features in the long term.

PERFORMANCE OF CAST GROUT AND FOAM INFILLED ADDITIVE CONSTRUCTION CONCRETE COMPOSITES

MICHELLE L. BERNHARDT-BARRY
University of Arkansas

Speaker Biography

Michelle L. Bernhardt-Barry is an Associate Professor within the Department of Civil Engineering at the University of Arkansas. She received her BS, MS, and PhD in Civil Engineering from Texas A&M University. Her research interests include the multi-scale characterization of particulate materials, with a specific focus on the use of traditional and advanced laboratory testing, discrete element method modeling, and statistical methods to link fundamental material properties to the global observed behavior.

Michelle L. Bernhardt-Barry

Presentation Summary

Additive Concrete Composites for Military Mobilization

Bernhardt-Barry shared that she works on additive concrete composites with the ACME Tech research program, like the speaker from Applied Research Associates, Inc. Bernhardt-Barry's research group aims to relate fundamental questions of material properties to a composite's performance, especially for transportation applications for the military. Additive concrete composites can combine structural designs with a broader range of indigenous materials, which is especially important for military construction on-site.

Performance of Additive Concrete Composite Cylinders

Bernhardt-Barry's research group verified the mechanical performance of additive concrete composites through a series of mechanical tests and modeling. Using a commercially available concrete mixture and a robotic arm setup, the group printed cylindrical shells that were 6 inches in diameter and 12 inches tall. Three types of cylindrical shells were tested: a concrete shell with no infill, a concrete shell with an infill cast in the same concrete material, and a concrete shell with expansive foam at different densities. Special care was taken to specimen preparation, since the cylinders' surfaces must be parallel for valid compression strength results.

The group conducted compression testing and measured the distribution of stresses across the composite components with thin-film pressure mapping sensors. The mechanical tests also qualified discrete element method models. Qualitatively, the group observed that the concrete shell from 3D printing carries the majority of a load. Another important consideration of the cylinders is the nature of the bonding, or lack thereof, to the infill, which the group will further explore.

Question and Answer Session Summary

The presenter and the audience discussed the nature of composite formation and potential reduction in stresses with a larger cylinder and more core material. Bernhardt-Barry also emphasized considerations for the thin-film pressure mapping sensors, especially since friction was a concern with the concrete shells undergoing compression testing.

DRIVING TRANSPORTATION INNOVATION: 1PRINT'S STRATEGIC RESEARCH AND PARTNERSHIPS IN 3D CONCRETE PRINTING TECHNOLOGY

IAN ARTHUR, ADAM FRIEDMAN, AND FREDRIK WANNIUS
1Print LLC

PRANNOY SURANENI AND LANDOLF RHODE-BARBARIGOS
University of Miami

Presentation Summary

3D Printing SEAHIVEs for Shoreline Infrastructure


Ian Arthur

Arthur's industry team emphasized the importance of simplifying a construction process, especially in a blending of green and grey infrastructure. Through 3D printing technology, the team has deployed a technology known as SEAHIVEs in collaboration with the University of Miami. The team is especially interested in breaking down a system into constituent parts and refining design for a simpler system. SEAHIVES incorporate sustainable materials, such as Tyson America's and Carbon Limit's carbon dioxide absorbent technologies.

3D Printing from First Principles

One of 1Print's biggest aims is to reduce the complexity of a print job. There are limitations to casting concrete in unique shapes and scaling up. Arthur discussed how a recent 1Print approach involved printing octagons and stacking them for larger-scale deployment projects, such as the SEAHIVEs. This method involved developing a print path that aligned the job with grout holes, such that fiber-reinforced polymer reinforcement, which is non-corrosive and beneficial for underwater applications, could be added. After focusing on design, Arthur emphasized how 1Print also sought optimization from a material standpoint. 1Print began with the ASTM-approved concrete mix and partnered with Titan America to develop a printable mix with aggregates.

Testing of the structures shows an ability to dissipate wave energy, and Arthur mentioned models that can generate wave energy for greener infrastructure. The development of SEAHIVEs, in particular, allows growth of coral and species habitation.

Applications of 3D Printing Offer Cost Reductions

1Print has also partnered with the military for the deployment of SEAHIVEs and seen a cost reduction of 50%, compared to similar infrastructure. The printing production allows scalability and adaptability to location-specific requirements for conservation, such as developing planters for mangroves. Such applications must account for the wave energy of specific regions. Overall, Arthur emphasized that 1Print's approach offers optimization and scalability of a range of designs. Such designs offer field deployment.

Question and Answer Session

A member of the audience expressed a concern about how, for coastal conservation, creating "fish eyes" (unwanted tiny holes or gaps that appear in the printed object's walls or surface) is still a challenge. Arthur acknowledged that gaps in 3D prints (where the layers or lines do not fully connect) are common issues, and can be caused by under-extrusion, improper bed adhesion, or incorrect slicer settings. To address this, he noted that 1Print developed a technique called "gap print," in which excess extrusion is squeezed off. Whereas more traditional print jobs require programming the printer head to lift and move between printed lines, gap print allows 1Print to maintain print speed. A member of the audience recommended the 1Print team to investigate the effect of sand on the stability of a print job over time due to the weight of the sand.

The audience also praised 1Print's speed in deployment, taking just two years for the printing technology, design, infrastructure, and creation of the initial 3D-printed SEAHIVE. Arthur attributed this to the combination of entrepreneurship and engineering of their team, as well as collaboration with the University of Miami. Through connection with the private sector, 1Print hopes for commercialization within half a year.

Arthur clarified that their coastal infrastructure could mitigate hurricanes. The technology's projected lifespan is more than 50 years, and this is anticipated due to the FRP. However, 1Print is currently working with the military to certify ocean-ready underwater concrete for deployment. Arthur also clarified that 1Print uses a glass fiber reinforcement certified by the U.S. DOT.

SESSION 7A

Constructing With In Situ Materials

ALIREZA HASANI

University of North Dakota

Moderator

ADDITIVE CONSTRUCTION MATERIAL PROCESSING

JIM MANTES, AARON PULLEN, AND SUNGHO KIM

Applied Research Associates, Inc.

MICHELLE L. BERNHARDT-BARRY AND JAVIER LOZANO CASAS

University of Arkansas

Speaker Biography

Sungho Kim has a PhD focused on analog and RF IC design for sensors from Arizona State University. He is an experienced analog and mixed-signal IC designer with a demonstrated history of working in higher education and industry, skilled in analog and mixed-signal integrated circuit design, hardware development using Verilog HDL and FPGA, machine learning computing hardware and neuromorphic computing hardware design, skilled in Python (programming) and Matlab, PCB schematic and artwork for IC characterization, and demo platform.

Sungho Kim

Presentation Summary

The Expedient AC for Horizontal Construction Missions

Kim's research program is part of ACME Tech and works toward AC for horizontal engineering missions in battle. AC in contingent environments has multiple stages: the development of mobile AC equipment, the development of software controls for design in AC, the development of indigenous materials for AC mixtures, and the development of a catalog of AC printable items. Kim also emphasized the need for software to support AC in a range of environments, though his talk focused on the processing of local materials.

Testing AC Material Processing Methods

Kim emphasized his team's goals of maximizing use of in situ materials through efficient processing within limits of equipment capabilities. The team's study used two crushing buckets and two screening buckets to test the extraction of three different sized stones. The team studied Gabion Limestone, with a maximum size larger than 4 inches; AL Granite, with a maximum size between 0.5 and 2 inches; and local sand, with a maximum size smaller than 0.5 inches. A high-flow MB-L140 crushing bucket was selected for production of particulates. A Flip Screen bucket was chosen for the Screening Bucket to prevent a gap between the rotating screen and screen body frame.

For each material, the team scooped the stones, measured the initial weight, conducted a 60-second screening, and measured the retained weight. From these values, the team calculated production rates and found that the large stones had a production rate of 1.78 ton/hr, the medium stones had a rate of 1.37 ton/hr, and the small stones had a rate of 34.73 ton/hr.

Important Considerations for In Situ Material Processing

Kim emphasized the importance of material characteristics, such as size and hardness, equipment availability, and maneuvering time, which includes the time to scoop and transport materials for screening. Production rate also increased by about 3 ton/hr with a second crushing step for the medium stones. Kim recommends including additional crushing to reduce production time and material use for medium sized stones. However, smaller stones do not require crushing but only screening to remove contaminants. Kim aims to test these processing methods on a larger range of materials.

ADDITIVE CONSTRUCTION WITH CUSTOM CONCRETE MIXES FOR EXPEDITIONARY APPLICATIONS

BENJAMIN D. NELSON, ERIC FAIERSON, AND PATRICK A. JOHNSON
Iowa State University

JIM MANTES
Applied Research Associates, Inc.

MICHELLE L. BERNHARDT-BARRY
University of Arkansas

Speaker Biography

Benjamin D. Nelson is a PhD student in mechanical engineering and a graduate research assistant in the Laser Materials Processing Lab, Iowa Technology Institute, Iowa State University.

Benjamin D. Nelson

Presentation Summary

Evaluation of Constraints on 3DPC

Nelson is involved with AC for expeditionary applications with indigenous materials in the same research program, Expedient AC for Horizontal Construction Missions. He focused on the constraints of the 3DPC, such as acceptable indigenous materials, the design strength of concrete in casting versus 3DPC, extrudability, and buildability of concrete. Nelson evaluated cast concrete and 3DPC with different extruding robotic arms and pumps.

Fabrication of Concrete Mixtures from In Situ Materials

For testing, Nelson used general concrete mix materials, including limestone cement, mason sand, silt, pea gravel, clay, and soil. Concrete additives included super plasticizer, graphene, and fibers. For cast concrete fabrication, Nelson's team mixed small batches in buckets and cured them in molds for compressive and split-beam tests. For the 3DPC samples, preliminary tests showed that extrudable mixes with initially used pumps may not be ideal for buildability.

However, with the Kuka Robotic Concrete 3D Printing System, the team found that bentonite clay and super-p improved both extrudability and buildability. In addition, shorter fibers were chosen as more compatible with pumps for concrete mixes. Based on preliminary tests, the research team aims to evaluate and demonstrate an increase in strength for the 3DPC samples versus the cast concrete samples. Nelson also expressed an interest in the effect of curing conditions on the samples' strengths.

THE USE OF INDIGENOUS SOILS IN ADDITIVE CONSTRUCTION: MATERIAL CHARACTERIZATION, MIX DESIGN, AND PERFORMANCE

MICHELLE L. BERNHARDT-BARRY, BAILEY DOWNING AND JESUS SERRANO ESPINOZA
University of Arkansas

JIM MANTES
Applied Research Associates, Inc.

ERIC FAIERSON AND BENJAMIN NELSON
Iowa State University

Presentation Summary

Sourcing of Indigenous Soils

Nelson emphasized the need for using sustainable materials that allow for both printability and extrudability. Nelson's research group studies the processing of raw materials such as limestone, gravel, and supplemental materials such as sand through material characterization techniques. From a research standpoint, lab-obtained properties such as hardness can indicate how processing changes the material, but industry can also value such investigations for cost-benefit analysis.

Synthesis of Indigenous-Based AC Mixes

In addition, the lab group experimented with multiple compositions of indigenous soil mixtures and compared them to commercial mixes for structural concerns and printability. Nelson emphasized that studies of the print method are very dependent on the equipment used, such as the Potter Bot Auger 3D printer. The equipment can produce air voids and defects, so

Nelson's research group accounts for these defects through deposition methods. The research group is also interested in optimizing weight, having decreased the amount of cement from 800 to 675 lbs/yd^3.

IMPACT OF GEOMETRY ON PERFORMANCE IN THE BUILT ENVIRONMENT AND ITS POTENTIAL FOR 3D PRINTING

ZOFIA K. RYBKOWSKI
Texas A&M University

MEHDI FARAHBAKSH
University of Texas

NEGAR KALANTAR
California College of the Arts

Speaker Biography

Zofia K. Rybkowski

Zofia K. Rybkowski, PhD, is the Endowed Harold L. Adams Interdisciplinary Professor and Associate Professor, Department of Construction Science, College of Architecture. Her areas of research interest include Innovations in Architecture and Construction Management, Lean-Integrated Project Delivery, Large-Scale 3D-Printing for Architecture and Construction, Lean Simulations, Target Value Design, Life Cycle Cost Analysis, Environmentally Sustainable Architecture and Construction, Line-of-Balance Scheduling, Evidence-Based Design for Healthcare Facilities, Self-Regulating Building Skins, and Automation in Architecture and Construction. Rybkowski holds a PhD, Civil and Environmental Engineering, University of California, Berkeley; an MS, Civil and Environmental Engineering, University of California, Berkeley; MPhil, Civil Engineering, Hong Kong University of Science and Technology; MArch, Architecture, Harvard University Graduate School of Design; MS, Biology, Brown University; and a BS, Biology, Stanford University.

Presentation Summary

Sustainable Building Environments Through Geometric Design

Amid a push for a carbon-free future, Rybkowski said that an estimated 39% of all carbon dioxide emissions stem from construction, and quoted a United Nations estimate that over 80% of the environmental aspect of a production is determined at the design stage. To develop sustainable solutions at the design stage, Rybkowski examined the benefits and opportunities with large-scale 3D printing. Additive manufacturing allows placement of material where needed and reduces unnecessary material deposition or loss. Diving deeper into materials, optimizing the geometry significantly affects performance. At the molecular level, the bond structure of carbon atoms can yield sheets of soft graphite or a chair formation of diamond. This inspired Rybkowski to examine performance of print jobs with different print pattern geometries.

Optimizing Geometry for 3D-Printed Layers

To examine geometry, Rybkowski's research involved tuning the toolpath geometry and distance of the nozzle from the substrate to increase the interlayer bond strength of a printed structure. The research group tested 47 different specimens of concrete structures with flexural tests in accordance with ASTM standards for mortar and concrete testing.

Rybkowski emphasized the effect of the load orientation on the layers in the testing conditions. The tests showed that varying the height of the nozzle from the substrate improved bond strength by 41.2% on average, which she attributed to interlayer adhesion. Rybkowski encouraged the use of robots for multi-axis printing to achieve unique geometries and improved flexural strength. Ultimately, she envisions a paradigm shift in the prevailing approach to infrastructure design, citing case studies such as the Greenville Pedestrian Bridge project, which can achieve a 55% reduction in weight for 3D printing.

SESSION 7B

Geopolymers and Other Cementitious Composites

BRIAN SCHAGEN

University of Massachusetts, Amherst

Moderator

FOSTERING RESILIENT TRANSPORTATION INFRASTRUCTURE: EXPLORING THE FRESH AND HARDENED PROPERTIES OF 3D-PRINTED ULTRA DUCTILE ENGINEERED CEMENTITIOUS COMPOSITES

MARYAM HOJATI

University of New Mexico

Speaker Biography

Maryam Hojati

Maryam Hojati is an assistant professor in Civil, Construction, and Environmental Engineering at the University of New Mexico. She received her PhD from Pennsylvania State University.

Her research interests include Sustainable and Resilient Infrastructure and Building Materials; Green Building Integration; Materials for Space Projects; and Automation and Human-Machine Collaboration.

Presentation Summary

Digitization of Construction Through 3D Printing

Hojati emphasized the role of digitization in ushering in the fourth industrial revolution in the era of construction. Digitization can reduce construction cost and time as well as offer novel design capabilities for structures. Additive manufacturing, in particular, has shown advancement in residential applications in the past 5 years. However, Hojati noted that transportation has been slow to adopt 3D printing for production needs. In addition, she discussed recent proposals of 3D printing bridges.

Improving Sustainability of Concrete as a 3D Printing Material Through Engineered Cementitious Composites

Hojati emphasized the source-ability of concrete, which can incorporate local resources such as soil. However, there are concerns about the carbon footprint of concrete and how to reinforce concrete for transportation applications, in particular. Her research group wanted an alternative to rebar and sought reinforcements that could be in-process. Hojati promoted engineered cementitious composites (ECC) as a material solution to address the brittleness and susceptibility to cracking of traditional concrete.

In their research, Hojati's group aimed to minimize cement in a printing mixture by incorporating more cementitious materials. Key considerations included printability, short fibers (the group tested 8-millimeter-long fibers), and composite engineering properties. The team designed ECC mixes with different binders and polyvinyl alcohol (PVA) versus polyethylene (PE) fibers of only 38 and 15-micron diameters, respectively. The ECC samples with PVA showed a tensile strength of 1600 MPa and PE showed a tensile strength of 3000 MPa, both of which were much stronger than Grade 60 steel bars in a similar test.

The group also tested mixtures of 50% fly ash and 50% cement, 50% slag and 50% cement, 50% silica fume and 50% cement, and 50% metakaolin and 50% cement with the PVA and PE fibers. The research group also limited their sand to 25% for printability concerns. For dispersion of fibers, the group incorporated 1% of a viscosity modifying material.

Importance of Fiber Quality in ECCs

The group found that the fiber quality affects the formation of voids and can increase compressive strength of a concrete composite. Hojati's research showed how PVA and PE microfibers offer ductility that can reduce failure by blocking crack propagation, especially over sand pits in the mixture. Though the microfibers can crack, the neighboring microfibers are shown to close cracks in videos of samples undergoing deformation in compression tests and shearing. In direct tension tests, some ECCs show strength hardening. Comparing the fibers, PVA shows more rupture failure due to less ductility, but the PE shows pullout failure and fewer cracks. Altogether, Hojati's research demonstrates the improvement of concrete buildability for

3D printing through fiber inclusion and altering cement mixes for sustainability through local material usage.

ADDITIVE CONSTRUCTION OF LOW EMBODIED CARBON GEOPOLYMER CONCRETE

ALY AHMED AND ISLAM MANTAWY
Rowan University

Speaker Biography

Aly Ahmed

Aly Ahmed is an Egyptian Structural Engineer with an interest in advanced sustainable materials research and Building Information Modeling (BIM) technologies. He graduated with a bachelor's degree and a master's degree in civil engineering from Ain Shams University. During his master's studies, he focused on creating sustainable materials that can be produced using waste and by-products.

Ahmed is a PhD student and research assistant at Rowan University in New Jersey. His research group focuses on sustainable solutions for construction, additive construction and manufacturing (Concrete 3D printing), accelerated construction and repair, and low embodied carbon concrete and infrastructure (low to zero carbon negative).

Presentation Summary

Potential of Concrete Manufacturing for Seismic Systems

The speaker's construction lab is focused on non-metal manufacturing techniques, especially for hazard prevention applications such as seismic systems. The group uses locally sourced materials from New Jersey such as steel fibers for reinforcement of concrete print mixtures. The focus is compressive strength, which was noted to relate to another project presented on the first day of the conference regarding a seismic column by the same research group.

The speakers are also interested in multifunctional materials for residential applications, such as the use of a honeycomb structure for a shelter's wall. Such materials can incorporate fuses in a frame for dissipating seismic energy and improve a building's overall resilience with efficient material use. For example, a 0.5-gram concrete wall sample of 1 millimeter thickness and 2.5-inch height withstood 4,500 pounds (roughly 81,000 times the sample's weight) in a buckling test.

Improving Sustainability of Concrete Through Geopolymers

The research group emphasized a need to reduce concrete's carbon footprint. The second speaker noted that processing 1 ton of Portland cement leads to 1 ton of carbon dioxide emissions. Through the lab's geopolymer concrete, the research group can reduce emissions by up to 70%. The in-house lab mixture included varying composition of slag, fly ash, and silica fume.

DEVELOPMENT OF 3D PRINTABLE STRAIN HARDENING CEMENTITIOUS COMPOSITES FOR BRIDGE-RELATED APPLICATIONS

PRANAY SINGH, VENKATESWARA SWAMY GADDE, CHI ZHOU, PINAR OKUMUS, AND RAVI RANADE
University at Buffalo

Speaker Biography

Pranay Singh is a PhD candidate in the Department of Civil Structural and Environment Engineering at the University at Buffalo, with a background in structural engineering and advanced concrete materials. Singh's research project focuses on the application and development of 3D-printable advanced concrete materials for durability enhancement in precast bridges.

Pranay Singh

Presentation Summary

Importance of Durability in Concrete Casting for Bridge Infrastructure

Though 3DPC has great promise for transportation infrastructure, the pre-stresses introduced by a print job can cause cracking. Singh emphasized the risk of end-zone cracking in precast-prestressed concrete bridge girders, which was attributed to the girders experiencing a large prestressing force over a short distance. In addition, conventional concrete has a low tensile strain capacity. Singh proposes a 3D-printed ductile concrete shell to reduce cracking. The shell acts as form work to be integrated to a pre-caster workload on a bridge.

Strain Hardening Cementitious Composites for a Concrete Shell

To improve ductility of the concrete shell, Singh's research focused on Strain Hardening Cementitious Composites (SHCC) by incorporating mixtures with sand, cement, fly ash, PVA fibers, viscosity modifying admixture (VMA), and high range water reducing admixture (HRWRA). The average crack width in a SHCC specimen undergoing mechanical testing was found to be less than 0.1 millimeters, as expected by the strain hardening mechanism highlighted in their name. Singh began by developing a numerical model of a concrete girder with an SHCC cover and rebars. He simulated the print job's prestressing force to find the resulting temperature strain on the girder. Simulated tensile strains showed a strain capacity greater than 0.4%.

3D-Printing Considerations for SHCC

To improve printability, Singh calibrated the amounts of VMA and HRWRA to meet multiple rheological requirements for the mix. The process of mixing requires an optimal level of viscosity for fiber dispersion, pumping, preventing blockages in the printing pipe and nozzle, and layer buildability. To eliminate unsuitable mixes, Singh tested for fiber dispersion, water segregation, extrudability, and buildability. The resulting flowability factor achieved more than a 15% reduction per hour, which improves control in printing. To print with an optimum feed rate, Singh set up an extrusion system, modified a computer numerically controlled frame, and optimized control code.

CLOSING PLENARY SESSION

Wrap-Up and Mapping a Research Agenda

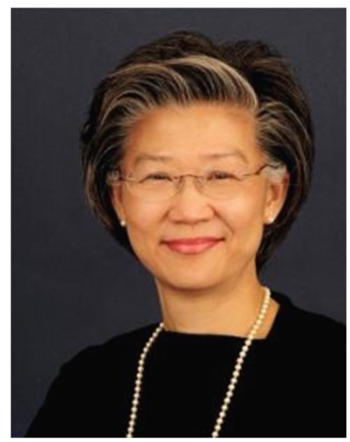
PATRICIA HU

Bureau of Transportation Statistics

Moderator

MODERATOR BIOGRAPHY

Patricia (Pat) Hu is the Director of the U.S. Department of Transportation's Bureau of Transportation Statistics (BTS). Prior to that appointment, she was the Director of the Center for Transportation Analysis at Oak Ridge National Laboratory. As BTS Director, she is focusing on enhancing the quality, timeliness, accessibility, and availability of transportation statistics to inform transportation decisions. Hu has led numerous research projects in the areas of travel behavior, traffic operations, transportation safety and security, data models, and visualization. Hu received her BS in Statistics from the Chengchi University in Taiwan, and an MS in Statistics from the University of Guelph at Canada.



Patricia Hu

SESSION SUMMARY

The conference concluded with an interactive, collaborative session in which participants highlighted key areas of pursuit and questions for academia and industry in the advancement of additive manufacturing for transportation. One group raised the question of open-sourcing designs and intellectual property, especially relating to optimal designs of print jobs. A participant mentioned the importance of cybersecurity with the digitization of construction processes and the sharing of U.S.-made versus foreign designs for 3DPC.

Participants shared that from an engineering perspective, it is crucial to consider the effect of seismic loads and traffic on bridges and other structures. With such new manufacturing techniques, there is a need for new standards, especially related to specific materials for structural concerns. One participant recommended the development of databases for local materials to help people determine easily derived mixes based on accessible materials. To improve confidence in steel for the construction industry, participants recommended a qualification process to guarantee performance, especially critical for bridge connections. In addition, extreme environments require locally sourced materials with properties such as high temperature performance. Many audience questions were specific to additive manufacturing. Additional concerns include optimizing the topology of a design, especially for printing at multiple scales. In addition, 3D printing for retrofitting old construction is a good direction to consider. Alongside a material-specific investigation, industry and academia can consider a decentralized approach to additive manufacturing that is material agnostic. Overall, there are multiple areas academia, industry, and local governments can collaborate on incorporating additive manufacturing in transportation technologies.

3D Printing at the University of California, Irvine

A Laboratory Tour

Approximately 40 conference attendees participated in a tour of the 3D printing laboratories at the University of California, Irvine. Below are tour highlights.

WARPSPEE3D

Overview of WarpSPEE3D and Cold Spray Additive Manufacturing Tour

During the laboratory tour, Daniel Mumm, Professor, University of California, Irvine (UCI) introduced the WarpSPEE3D, a state-of-the-art metal 3D printer that utilizes Cold Spray Additive Manufacturing (CSAM) (Figure 1). This machine was acquired through grant support from the Air Force Office of Scientific Research (AFOSR) and enhances UCI's additive manufacturing and materials characterization capabilities. It plays a crucial role in workforce development and research in advanced materials systems.

Figure 1

CSAM Technology

Unlike traditional heat-based 3D printing, the WarpSPEE3D accelerates metal powder particles to supersonic speeds using compressed air, bonding them onto a surface without melting (Figure 2). This solid-state deposition process enables:

- Rapid production of high-density metal parts
- High deposition rates (up to 100 grams per minute)
- The ability to combine dissimilar materials
- Lower energy consumption than traditional additive manufacturing

Figure 2

MELTING AND CASTING FACILITY

The Melting and Casting Laboratory at UCI's Advanced Casting Research Center is equipped for metal casting and alloy development (Figure 3). It features two Inductotherm 35 kW induction furnaces, enabling the melting and casting of iron, copper alloys, and aluminum.

Metallographic Imaging and Microstructure Analysis

UCI's Metallographic Imaging Lab uses advanced microscopy to analyze metal microstructures, defects, and surface characteristics.

- Olympus GX53 Metallurgical Microscope – Captures high-resolution images of metal grain structures and casting defects.
- Olympus LEXT OLS5100 3D Laser Scanning Microscope – Provides detailed 3D surface analysis, measuring roughness and micro-defects.

Figure 3

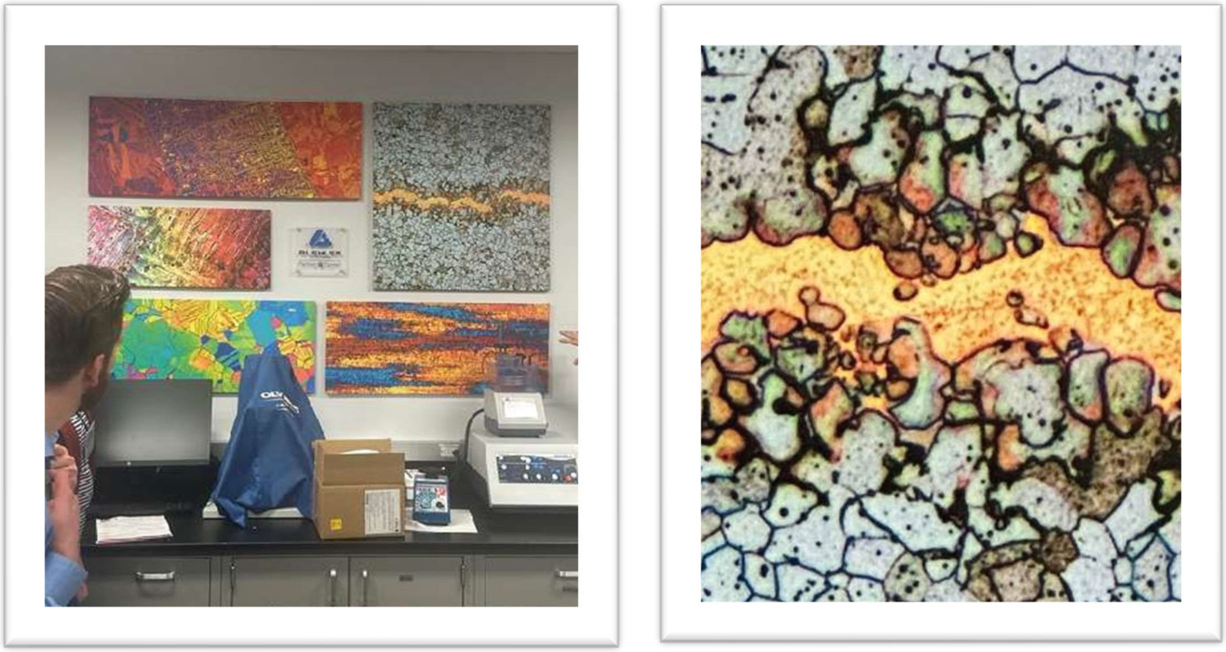


Figure 4

The lab displays metallographic art, where microscopic metal structures are enhanced with artificial colors for visualization and artistic effect (Figure 4). These images highlight variations in metal composition, grain boundaries, and structural patterns, blending scientific analysis with creative presentation.

VJ Technologies Veda CT Scanner

The VJ Technologies Veda CT 450 is an x-ray CT scanner used for nondestructive 3D imaging of objects (Figure 5).

- The 450 kV setting captures larger structures (macroCT).
- The 250 kV setting provides detailed scans of small features (microCT).

Figure 5

It allows researchers to see inside objects without cutting them open (Figure 6). During the tour, it was used to scan a grapefruit, showing its internal structure on a computer screen. This technology helps analyze materials, detect defects, and inspect metal parts in casting and additive manufacturing.

Figure 6

APPENDIX A

CONFERENCE SCHEDULE AT-A-GLANCE

Thursday, November 7	
Time	Session / Event
7:30–5:00 PM	Registration
7:30–8:45 AM	Continental Breakfast
8:45–9:00 AM	Welcome
9:00–10:00 AM	OPENING PLENARY SESSION
10:00–10:30 AM	Break
10:30 AM–NOON Concurrent Sessions	SESSION 2A: National Science Foundation and Civil, Mechanical, and Manufacturing Innovation Program in Additive Manufacturing and Transportation
	SESSION 2B: Concrete Materials in Additive Manufacturing and Construction
12:00 –1:30 PM	Lunch
1:30–3:00 PM	SESSION 3A: Robotics, Automation, and Additive Construction in Building New Transportation Infrastructure
	SESSION 3B: Steel Construction in Additive Manufacturing
3:00–3:30 PM	Break
3:30–5:00 PM	SESSION 4: Standard and Policy Session
5:30–7:00 PM	3D Printing at UC Irvine – A Laboratory Tour

Friday, November 8	
Time	Session / Event
7:00–1:00 PM	Registration
7:00–8:00 AM	Continental Breakfast
8:00–9:30 AM	SESSION 5: Freight and Supply Chain
9:30–10:00 AM	Break
10:00–11:30 AM	SESSION 6: Culverts, Pipes, Other Structures
11:45–1:15 PM	Lunch
1:30–3:00 PM	SESSION 7A: Constructing With In Situ Materials
	SESSION 7B: Geopolymers and Other Cementitious Composites
3:00–3:30 PM	Break
3:30–4:50 PM	PLENARY SESSION: Wrap-Up and Mapping a Research Agenda
4:50–5:00 PM	Closing Remarks and Adjournment
5:30–7:00 PM	Planning Committee Meeting (Closed Meeting)

APPENDIX B
MENTIMETER RESULTS

For Mentimeter polling, "3D printing" will be synonymous with Advancing Additive Manufacturing (AM)

What are some **existing applications** (examples) of 3D printing in transportation**?**

Buildings, culverts	Pedestrian bridges in Europe and china	Pipes, piers, culverts, manhole caps, sound walls	Transportation also involves rail systems as well. Research on AM for rail would be a potential idea. But rail systems rarely have customization, hence a need for AM
Bridge components , side walks, electric vehicle charging stations and many	Decks	Side walks and bridge components	Bridges

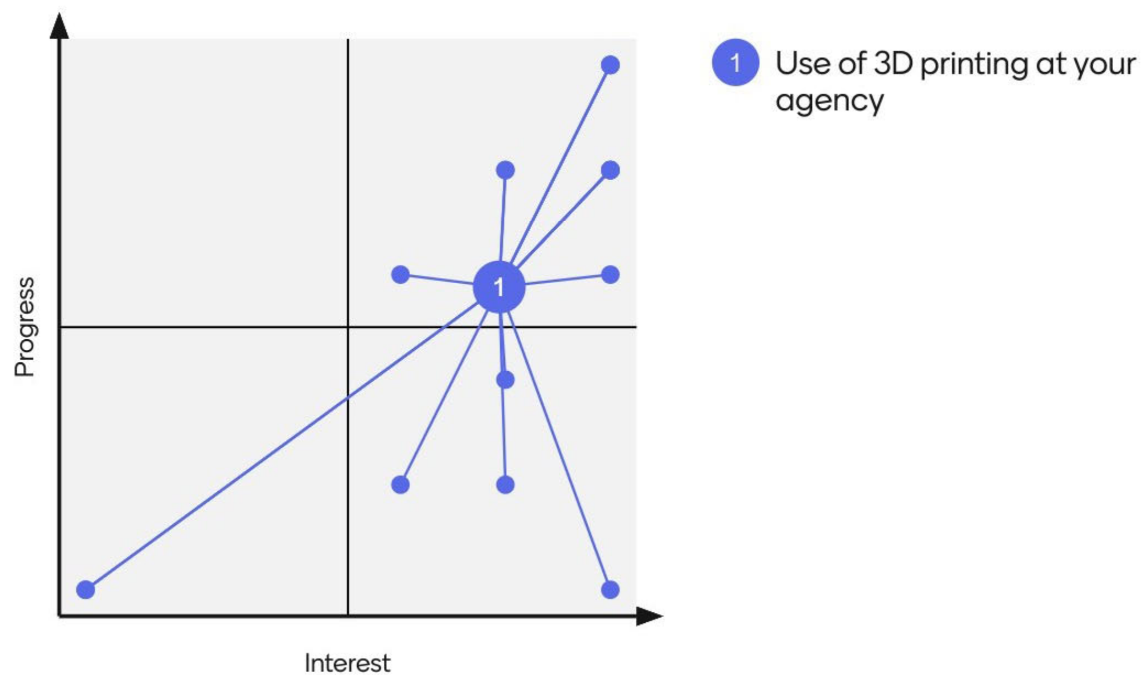
What are some **existing applications** (examples) of 3D printing in transportation**?**

Bridges	Culverts and retaining walls, some pedestrians bridges	Culverts, retaining walls, abutments for brushes	Bridge, houses etc
Not many	prototyping, research samples	Vehicles	Buildings, Culverts, retaining walls

What are some **existing applications** (examples) of 3D printing in transportation**?**

Cold spray additive manufacturing	Walls	Parts for older model vehicles	Bridges elements

What is your agency's **interest and progress** in using 3D printing for transportation purposes?



What **impediments** do you see to expanding adoption of 3D printing in the transportation world?

26 responses

What **research topics** are needed to support 3D printing in transportation?

Standardization	Reinforcement	Large scale testing	Standards
Training	Cooperative 3D printing.	Cooperative 3D Printing	Tools assembly, mix design , pilot projects with lessons learned

What **research topics** are needed to support 3D printing in transportation?

Materials development and testing,	Test methodologies, Field testing/property correlations, material characterization, physical structural testing	Advanced designs Materials - Need more aggregate in mixes	Innovative additive shapes.
Myriad	Join ASTM F42.	Templates for local building codes	AASHTO Codes

What **research topics** are needed to support 3D printing in transportation?

Data on public sector benefits	Definitions	....

Where do you see the greatest potential for **future use or expansion** of 3D printing?

20 responses

What are some **existing applications** of 3D printing in transportation that have not been covered in this conference?

NA	Cooperative 3D printing. Which is using multiple 3D printers to print 1 object. Faster.	None that I know if	Novel binders
None	None	Viscoelastic materials	Replication of outdated parts (ex. locks and damns).

What are some **existing applications** of 3D printing in transportation that have not been covered in this conference?

Disaster.recovery

What **next steps** are needed for expanding adoption of 3D printing in transportation?

Standardization	Qualification procedures	Confidence in performance and actually printing load bearing objects not just formwork	Standards
Codes	Testing data	More fundamental research	Need a TRB annual meeting session for 2026, also peer.to peer and brochure on best practices/EveryDayCounts initiatives

What **incentives** could help the private and public sectors advance implementation of 3D printing?

- Federal fundings
- Case studies showing cost, speed, unique use cases that make the business case clearer
- Partnership
- Funding
- Tax credits