UTC Project Information	
Project Title	Development of 3D Printed Materials for Rapid Fabrication of Pedestrian and Bicycle Infrastructure to Increase Mobility
University	University of Washington
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PI Contact Information	delehman@uw.edu
Funding Source(s) and Amounts Provided (by each agency or organization)	University of Washington PacTrans $45,000 University of Washington $45,000
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Agency ID or Contract Number	69A3551747110
Start and End Dates	September 1, 2018-August 31, 2020
Brief Description of Research Project	The long-term goal of this project is to develop a new construction methodology and materials for infrastructure to enhance mobility using fiber-reinforced cementitious materials (FRCMs) and 3D printing. The project will develop design and analysis methods for new, engineered fiber reinforced concrete for 3D printed structures, with a focus on pedestrian and bicycle infrastructure. This technology has several advantages over traditional construction methods and materials such as formed, cast-in-place concrete construction that requires substantial formwork and precast components that are expensive to construct and transport. In urban regions, pedestrian and bicycle brides are needed over busy streets with very little laydown space; therefore, printing in place will minimize equipment and space requirements. In isolated communities, printing in place reduces costs for transportation of precast components and cast-in-place formwork. New, cost-effective pedestrian and bicycle bridges have been a relatively low in priority for transportation infrastructure. In the Pacific Northwest, these bridges must meet the needs of urban and remote communities and be able to sustain seismic (extreme) demands with a negligible risk for significant structural damage or collapse. If successful, this project will provide new construction methods and structural systems for multi-modal transportation infrastructure.

Describe Implementation of Research Outcomes (or why not implemented)

Place Any Photos Here

Figure 1 Printer Operating with Research Team Observing.

Figure 2 Final Mix Design

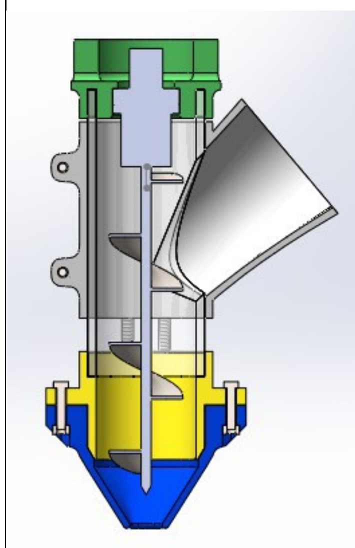

Figure 3 Auger Design

The research program will investigate the construction of fiber reinforced cementitious material (FRCM) components using extrusion-based 3D printing. Where conventionally formed concrete structures rely on the formwork for strength and stability during the hardening process, components constructed using 3D printing must rely on their green strength (i.e., strength during the time when the concrete has set but not appreciably hardened) and stiffness to resist instability, such as buckling and creep, during construction. As such, this proposal will investigate 3D printing from the point of view of materials and structural engineering, rather than construction. This study will result in engineered, 3D printed cementitious materials (CMs) meeting required quality control and engineering properties (from fresh to fully hardened) to simulate the response of the materials during construction (printing) and in their hardened state. The study is separated into the following research tasks to meet these specific objectives, as follows:

1. Design and fabricate material extrusion-based 3D printer for construction of CM components. (Task 1)
2. Investigate fresh-state properties of FRCMs fabricated using 3D printing (Task 2)
3. Disseminate research findings to the construction and structural engineering communities through partnerships. (Tech Transfer)

Impacts/Benefits of Implementation (actual, or anticipated)	The following summarizes the findings of each aspect of the research project **Literature review:** The research team investigated prior work conducted on printing concrete. The primary findings were as follows: 1. Most research conducted on 3D printing of concrete has been conducted in Europe 2. Most 3D printing of concrete has focused on architectural form or other non-engineered components 3. Fine aggregate (sand) is almost never included in the mix designs; most printing is of a cementitious mortar not concrete. 4. Although there are publications discussing the fresh state materials of 3D printed mixes, they do not provide the mix design. 5. Most printers are designed and fabricated by companies and therefore the printer design is proprietary. The end analysis is that although the literature review was useful, it left the team with very little information about prior work since most was proprietary and therefore, did not provide much guidance. This proved to be a distinct disadvantage especially for such a short timeline. **Printer Design**: 1. The research team included Mark Ganter, a professor of mechanical engineering. Mark has been involved in 3D printing since 2009. He has built a series of printers with different build scales. The printer uses a 3-axis gantry (called an MPCNC). 2. The printer built has a print area of 24 x 24 in area. This would allow printing of cylinders, prisms, and panels/slabs 3. The team spent most of their resources on the extruder design. 3D printing uses either extrusion or powder printing. Most cementitious materials (including clay) uses extrusion-based printing. The team investigate size of the extruded region as well as shape of the extruded region. The extruder was fabricated using a 3D printer in the ME 3D printing laboratory that is directed by Professor Ganter. The research was conducted by Professor Ganter's ME research student, Jacob Roth. In the end, the team utilized a rectangular extruded shape which provided benefit for layer stability and printing rectangular components (most concrete components are rectangular).

	4. There were several issues with the mechanical engineering of the printer that were explored including: (1) pump pressure, (2) motor properties, (3) rotating vs sliding extrusion piston, (4) bearing design, and (5) stiffness of the gantry. 5. In the end, the printer did print concrete but not until after the project was completed and the concrete that was printed did not have fine aggregate (sand). The team has realized that designing a large-scale 3D printer was outside of the research budget. The team plans to write an STF proposal to buy a 3D printer from a company. **Mix Design** The mix design was overseen by Professor Lehman and her colleague Professor Kuder. Professor Kuder has expertise in concrete materials complementing Professor Lehman's expertise in structural engineering. Professor Kuder and Lehman have collaborated successfully on other research projects. The mix design research was conducted by an undergraduate female research student in CEE, Hailey Stenslie; she presented the results at the Mary Gates Undergraduate Research Symposium (link provided below). There are complexities with a mix design for 3D printing that are unique to this construction method. Most importantly, the mix must be extrudable, but be able to hold its own shape after printing and the weight of layers that will be above the printed layer. To achieve this, the team using methylcellulose admixture in the mix design. Using hand-extruded layers, the team was able to extrude the mix and meet these requirements. This was a successful aspect of the project. A comparison was made for different water-to-cement ratio and different amounts of methylcellulose The second complexity was the addition of sand. As noted in the literature review section, sand has not been included in the vast majority of mix designs for 3D printing. The team very much wanted to explore the addition of sand, as this is a necessary component for concrete. The sand decreased the extrudability of the mix substantially. There was significant phase migration with the sand; this was somewhat mitigated with the methylcellulose. The team was unable to test any hardened specimens, so the focus was solely on the mix design and fresh state properties.
Web Links • Reports • Project Website	https://www.youtube.com/watch?v=g3Arud2MBhQ (please link to Pactrans report) U/G research presentation https://expo.uw.edu/expo/apply/534/proceedings/result?student_major=Civil+Engineering