Print Tilt Lift_Concrete 3D Printing for Precast Assemblies
Project Final Report

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Proposed Project

Additive manufacturing (AM), more commonly referred to as 3D printing, is poised to revolutionize the building construction industry. It has attracted significant commercial interest due to its potential to reduce time, labor, and material use, while improving safety and overall building performance through computational optimization. The most promising application for the construction industry centers on concrete, where a significant portion of the construction cost is attributed to formwork production, which in the case of complex surface geometries or topologies can often be cost prohibitive. 3D printing concrete holds the promise of partially or completely eliminating the need for molds. Simultaneously, the design of advanced materials such as engineered cementitious composite (ECC), can be calibrated to optimize performance requirements of strength, ductility, and multi-functional characteristics such as self-healing/cleaning, air-washing, and carbon sequestration. This research focuses on the development of novel approaches for concrete 3DP with ECC to radically rethink the design and fabrication of building envelope systems. Through an integrated approach to matrix/reinforcement design, process control, tooling, and computationally driven fabrication systems, high performance building envelopes will be prototyped, tested, and assessed at full-scale to explore design constraints and priorities in terms of structural capacity/durability, greenness, and experiential conditions. Moving away from rectilinear formworks for flat panels, this project investigates precast units that have variable sectional qualities and complex surface geometries. Rather than printing vertically as is typical with most 3D printing processes, the orientation is horizontal, with the finished panel tilted and lifted after hardening. This technique reconsiders typical processes for prefabrication by using advanced concrete printing technology to create panel systems whose geometries respond to specific localized performance requirements.

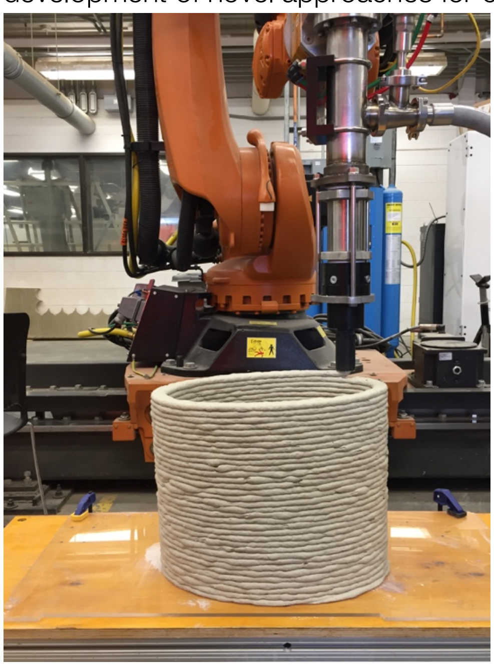

Fig. 1 Early test printing with ECC

Project Assessment

This project is part of a nexus of research being conducted on 3D printing (3DP) of concrete at the University of Michigan. This research includes the development of novel materials, hardware, and software. A significant portion of the research period was dedicated to the development of robust equipment to support 3DP research, based on existing industrial robotic tools in the Taubman College Fabrication Lab. While the basic technology for 3DP of concrete is well known, this project revolved around the use of engineered cementitious composites (ECC), which are a special class of materials developed at UM which possess tensile capacities which far exceed normal concrete. **Fig. 1** These same properties make them significantly more challenging to extrude and therefore 3DP. Developing the tooling necessary to 3DP ECC required several ground-up redesigns of the equipment, now in its 4th version. This tooling development has been fueled by promising results and additional funding sources, including a *Prototyping Tomorrow Grant* ($20,000 with Wes McGee and Victor Li) from Taubman College of Architecture and Urban Planning. Through this grant, we were able to leverage additional funds to not only support both tool and component prototyping, but to also develop long term collaborations with the College of Engineering.

The prototyping process proved beneficial toward fine-tuning in terms of matrix design, geometric complexity, and design parameters for printing. We were able to hone a level of crafting that begins to address component details in relation to tool-specific limitations such as turning radius and material ‘smashing’ with previously lay beads. The latter part is most helpful for panel ribs that are printed upside down on a mold, which enables the surface to have connected ribs rather than

(left) Fig. 2 View of ribs behind panel, showing turning radius of the tool as well as geometries of the ribs, connecting at the turn. (right) Fig. 3 Panel that’s printed face down, showing smoother surface from contact with mold. Note side edge has variable thickness where the back edge is flat to meet other building stock materials.

Fig. 4 Three columns showing progression of geometric complexity (from far right to left) and surface finish through bead shaping.

single bead extrusions (to build vertically). **Fig. 2** The devised system enable us to now control variable thickness to a panel where the smoother surface on the mold could be complex geometries while the back of the panel can be flat to meet other building materials. **Fig. 3** Thus the front can be envisioned as façade surfacing while the back can connect with stock materials. While the project's main focus was to 3DP panels that were to be tilted up after printing, to further understand and expand the developed 3DP process, columns were printed to specifically address questions of buildability using the engineered matrix. **Fig. 4**

Outcomes

The proof-of-concept results of the *Print Tilt Lift* project were exhibited in the *Lab to Site: Innovation in Concrete* exhibition in Fall 2019, which accompanied a symposium of the same name (organized by the PIs of this grant). This consisted of three prototypical columns approximately 2 m high and a 1 m x 1 m panel. **Fig. 5** More importantly, several innovations in tooling were developed which are contributing to ongoing research. The hardware development was accompanied by the development of software tools which allow the simulation of the printing process accurately in three-dimension. **Fig. 6** The research has led to several publications, including a pending conference paper (*Digital Concrete 2019 Conference*, currently in review) and a journal article (in *Cement and Concrete Research*, in review).

The research is currently in a phase of scaling up, as the current print tooling imposes limitations on the material that we would like to push further. This is also part of the development of a dedicated robotic lab in the University of Michigan Civil and Environmental Engineering department for 3DP ECC, which is being led by the project team. The underlying goal is to continue to explore the range of geometric possibilities afforded by the technology as well as to advance the boundaries for structural performance of the printed specimens.

Fig. 5 Display at exhibition showing panel (rib side) and video at Liberty Research Annex Gallery.

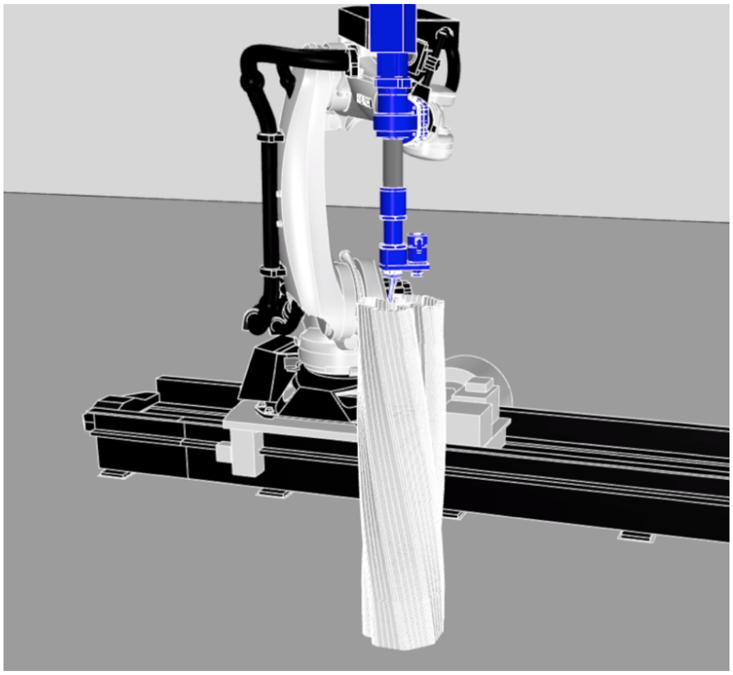

Fig. 6 Screen capture of simulation for printing.