3D Printable Rebar Free Concrete Members
(Technical Topic)

Additive Manufacturing, Supply Chains and Disaster Response
(STS Topic)

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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I. Introduction

Additive manufacturing (AM) refers to a processing technique, by which a part is fabricated in an automated layer-wise manner using input from a digital 3D model. This technology is gaining popularity in a number of fields, like medical and aerospace, where personalized and complex products are especially advantageous (Berman, 2012; Holmström et al., 2010). As more techniques are being developed, additive manufacturing is increasingly being applied in the structural engineering and architectural worlds, with several companies beginning to create full scale structures using cement-based AM processes (O'Neal, 2016; Starr, 2016).

Concrete is printed by an extrusion-based process, during which a cementitious mixture is pushed through a nozzle and deposited in a pattern dictated by a computer model. The nozzle is then raised and the next layer is printed, repeating until the structure is complete. This form of fabrication provides many distinct benefits over traditional cast-in-place concrete constructions. 3D printing does not require formwork, which results the elimination of construction costs as formwork currently accounts for 40-60% of the cost of concrete casting (Lab, 2007). Additionally, AM processes improve construction safety by allowing for the automation of dangerous jobs typically performed by concrete workers (Bhardwaj et al., 2019). Finally, 3D printing allows for higher geometrical freedom, which opens the door for designing and optimizing beams for specific applications. However, despite these notable benefits, there are still several challenges that complicate the 3D printing of full-scale structures; one such challenge is reinforcement. Concrete is by nature a very brittle material with little strength in tension, which necessitates the inclusion of reinforcement inside concrete structures to accommodate tensile loading. Steel rebar is traditionally used as reinforcement; however, rebar is not easily incorporated into layer-wise additive manufacturing methods, as its placement involves the pouring of wet concrete around pre-placed rebar.

This thesis project aims to solve the technical problem of reinforcement in cement-based AM by coupling a new fiber-reinforced 3D printable concrete mixture with an optimized beam geometry. The goal of this project will be to design, print and mechanically test a rebar-free beam that has significant flexural strength. The STS portion will study the disruptive nature of AM to supply chains and how it relates to a society's ability to quickly and effectively respond to natural disasters. The paper will examine this topic through the lens of the Actor Network Theory and discuss how the introduction of additive manufacturing actors will alter the crisis response network.

II. Technical Topic

As previously discussed, the complication of reinforcement is a common problem encountered when 3D printing concrete structures. Although AM structures have already been constructed, the methods of reinforcement have varied widely with several companies failing to fully report what types of reinforcement, if any, were used (Bos et al., 2016). The lack of a standard reinforcement method for AM makes it difficult to ensure structural safety. However, several potential methods for 3D printed reinforcement have been proposed. 3D printed concrete can be reinforced by leaving gaps in the structure during deposition, so that rebar can be placed after the printing process is complete (Lu et al., 2019). However, this method limits both the possible complexity of the final geometry and the automation of the process, as additional post-printing work is needed (Soltan & Li, 2018). Another proposed solution is simultaneously reinforcing the concrete during printing by utilizing a mixture with dispersed fibers that are capable of carrying tensile loads. These mixtures, known as fiber-reinforced cementitious composites, have been shown to have increased tensile and flexural strength, while still allowing for full automation and freedom of design (Figueiredo et al., 2019; Hambach & Volkmer, 2017; Soltan & Li, 2018; Zhu et al., 2019). For this project, fiber reinforcement was selected for study, as it imposes less restrictions on the design of the beam.

The technical work of this thesis explores the use of fiber-reinforced cementitious composites to create structurally optimized beams with complex geometries. The project is split into two main tasks, the design of a new 3D printable fiber-reinforced cementitious composite and the computational modelling and optimization of beam geometries. In order to be printable, a cementitious composite must have a low enough viscosity to be extruded through a nozzle, yet be firm enough to retain its shape under stress after exiting the nozzle. This complexity motivated a systematic study into the rheological (flow) properties of different candidate concrete mixtures with dispersed Polyvinyl Alcohol (PVA) fibers. Rheology tests will be performed to determine the characteristics of the concrete right after mixing, also known as the fresh properties. Once the fresh properties are determined, select mixtures will put into the 3D printer to test their ability to be extruded through the nozzle without clogging and assess the quality of the printed specimen. Finally, both cast-in-place and 3D printed standard mechanical testing specimens will be produced and tested to determine the flexural, compression and tensile properties of the mixtures.

The second task focuses on the design and optimization of unique beam geometries. Since 3D printing allows for more freedom and complexity in the fabricated shape, it is possible to design a beam for a specific loading situation. This project aims to create a geometry that can reduce the tensile stresses on the beam and distribute the material to best accommodate the loading. Different beam geometries will be modelled under different loads to determine where the maximum stress will be located in the beam cross-section. Using this information, the beam will be optimized, fabricated and tested using the fiber-reinforced cementitious composite created in the first task.

III. STS Topic

A potential application of 3D printed concrete structures is in the construction of temporary shelters for victims of natural disasters (Gregory et al., 2017). However, AM's use in the disaster response sphere is not limited to cement-based constructions, as many other types of AM are being considered for or are currently used as part of disaster response plans. These technologies are specifically suited to relief applications, due their supply chain affects. The STS portion of the thesis will build on the current body of knowledge, by examining AM's role in disaster response through the lens of the Actor Network Theory. The ability to plan ahead helps to minimize losses of life and property and understanding the role of AM in disaster relief will better allow for its incorporation into pre-disaster planning.

AM is promising technology that has already been shown to have an impact on the ability of a country to respond to natural disasters, through its alteration of supply chains. One such alteration relevant to disaster response is the decentralization of manufacturing (Holmström et al., 2010; Petrick & Simpson, 2013). Attaran (2017) predicts that AM "could transform the global supply chain to a globally connected, but totally local supply chain" (p. 196). Decentralization or local manufacturing has already been proven to be beneficial in disaster relief efforts, by allowing for onsite manufacturing during a crisis. Several companies, including Oxfam, American Red Cross and Field Ready, are currently employing AM techniques for humanitarian aid (Saripalle et al., 2016). James (2017) has discussed in great detail the successful deployment of AM techniques by Field Ready in remote crisis situations by creating "3D designs for basic medical items so they can be 3D printed in the field" (p. 3). The onsite manufacturing and subsequential redesigns of supplies for medical procedures allowed for fast supply procurement time, whereas traditional supply chains could take over 4 months. While the onsite manufacturing of goods in difficult locations has shown promise, there are still several challenges that need to be addressed. One such challenge is apparent by the difficulty in selecting the correct materials and printers for a given application. To address this challenge, Meisel et al. (2016) details formal considerations that need to be addressed when selecting an appropriate AM technology class, equipment model, or material in remote areas. The most salient consideration categories were found to be “process, machine, part, material, environmental, and logistical constraints and objectives” (Meisel et al., 2016, p. 912). Each of these categories has numerous subcategories associated with them and present a spectrum of different considerations manufacturing faces in remote or disaster struck areas.

Additionally, AM allows for an increase in process flexibility when compared to traditional manufacturing. Muthukumarasamy et al. (2018) notes that “AM incorporates flexibility in the supply chain specially to meet and manage disruptions and disasters” (p. 517). Flexibility in the manufacturing process is a widely studied aspect of AM that has the potential to be instrumental in disaster response. Traditional means of manufacturing need large amounts of time to alter production runs, while AM technologies only require raw materials and a new design file. The potential of flexible manufacturing has been recently demonstrated by AM’s role in filling the holes in traditional supply chains and supplying medical equipment during the COVID-19 pandemic. During the pandemic, global supply chains were disrupted resulting in a shortage of ventilators and PPE (Ranney et al., 2020). Sinha et al. (2020) observes that the pandemic gave rise to an “informal supply chain” that was made “feasible because of the rapid expansion of inexpensive additive manufacturing capabilities (3D printing) by small business and maker communities, wide availability of computer aided design software, and public design repositories" (p. 1162). The authors argue that the community should play a significant role in natural disaster relief and should be supported by governmental regulations. The study by Manero et al. (2020) expands on this idea, by identifying factors that are needed to coordinate an effective and rapid change of AM production lines to produce essential equipment. The roles of government regulations, coalitions with both physical and social networks, additive manufacturing of different products and file sharing are discussed.

The disruptive nature of AM to supply chains and how it relates to disaster scenarios is widely studied and the benefits and challenges are well documented. The STS paper will build on the body of knowledge, by using the Actor Network Theory to identify relationships between actors and discuss how the incorporation of additive manufacturing technologies will alter the crisis response network. The Actor Network Theory (ANT) is a theory originally developed by Michel Callon, Bruno Latour and John Law, which "represents technoscience as the creation of larger and stronger networks" with both human and non-human entities represented as actors in them (Sismondo, 2010, p. 81). In order to apply ANT in the STS report, current literature was leveraged to identify several major actors in the disaster response network; the disaster, the communities affected, AM machines, supply chains (global and local), governmental regulations, the surge demand, companies (both non-profits and for-profits), environmental constraints and available resources. ANT is well suited to answer the posed question, because disaster relief can be easily visualized as a fast-acting network, in which each actor needs to exactly understand their role to ensure a timely response.

IV. Timeline and expected outcomes

The final expected goal of the technical project is to fabricate a 3D printed fiber-reinforced cementitious composite beam with an optimized geometry and mechanically test the structural properties. The mechanical testing of the concrete mixture with standard printed specimens and the optimized beam model should be completed by December 2020. The mechanical testing of the designed geometry printed with the experimental mixture should take place early next year, February 2021. The anticipated outcome of this project is the publishing of a conference paper. The STS portion of the project is expected to result in a paper that concisely analyzes how the structure of the disaster response network will change with the addition of AM. This will hopefully help current actors, such as companies, communities and governments, understand the implications of deploying AM in their disaster response plans.

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