Exploratory Review of Reinforcing Solutions for Precast Concrete 3-D Printing

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ABSTRACT

There is a lack of knowledge for reinforcing methods in the cutting-edge technology of Precast Concrete 3-D Printing (PCP). This study explores reinforcing solutions and their implementations in PCP members. Two solutions are proposed to be applied in PCP: 1) Post-tensioning tendons & 2) Steel-fiber orienting method. A literature review of the relevant technologies and the implementation procedures of the reinforced 3-D printed precast concrete concept is presented in this research. The literature topics investigated in this study include precast concrete 3-D printing, mix design of concrete 3-D printing, types of fibers used in concrete and methods for orienting fibers, and post-tensioning method. Traditionally, Fiber-Reinforced Concrete (FRC) contains discrete fibers that are uniformly distributed and randomly oriented. Previous research has shown that the manipulation of the fiber dispersion and orientation to match the stress field pattern is significantly influential on the mechanical behaviors of FRC. Implementation of this concept leads to print the fibers in the stress trajectory of precast concrete members. This concept is explored in this study. Furthermore, the implementation procedure of post-tensioning tendons in PCP members is investigated. The theoretical framework provided in this study paves the way for the industrialization and applicability of PCP in the precast industry.

Keywords: Additive manufacturing; Buildability; Extrudability; Fiber-induced flow; Intentionally oriented fibers; Post-tensioning method

INTRODUCTION

Up until the last decade, additive manufacturing has been exclusively used in high-tech technologies such as aerospace and biomedical engineering. In recent years, there has been a significant increase in the application of large-scale 3-D printing, specifically with different materials such as metals[1], polymers[2], and concrete and cementitious materials[3,4,5]. Traditionally, concrete is cast into a formwork - typically containing a reinforcement cage - and then consolidated to be used in structural components such as beams, slabs, columns, etc. The 3-D printing of cementitious material facilitates the geometry of cast concrete (Fig. 1) and also the shape of the formwork. Irregular formworks can be printed to help casting ordinary concrete and producing any unconventional or aesthetic shapes (Fig. 2). This technology improves construction projects in different ways such as accelerate the construction process, implement where there is not enough manpower, and implement where a delicate/irregular surface is needed.

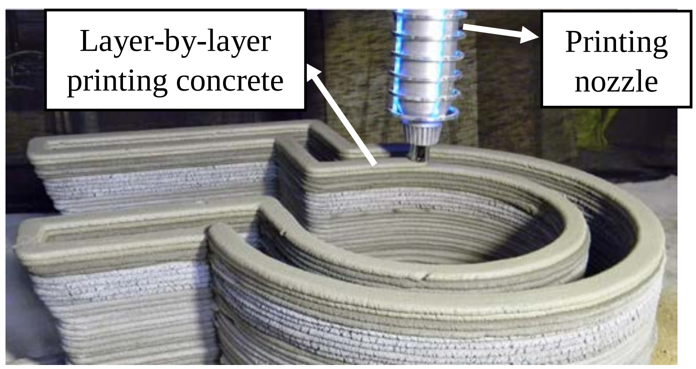


Fig. 1- Layer-by-layer concrete printing to a desired geometry (photo courtesy of 3D Concrete House Printer[6], used with permission)

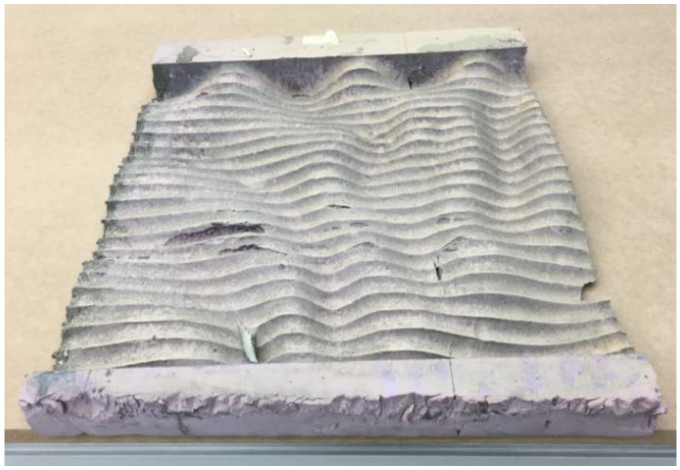


Fig. 2- A sample of printed formwork to make an aesthetic concrete surface

There is a lack of knowledge about the reinforcing methods of concrete 3-D printing. The bond between printed concrete and reinforcement must be present to reach the desired strength of the concrete components. This is particularly difficult to perform due to the nature of the layer-by-layer filament casting in concrete 3-D printing (Fig. 1). Considering the properties of Precast Concrete 3-D Printing (hereafter referred to as "PCP"), the post-tensioning method can be applied to resolve the concrete-to-reinforcement bonding problem. This is plausible due to the characteristics of the bonded, post-tensioning method (in which grouting is used to bond between concrete and post-tensioned tendons).

Additionally, structural behaviors of printed concrete can be improved by adding supplementary materials to obviate the need for other reinforcement. One example of these supplementary materials is the Fiber-Reinforcement Concrete (hereafter referred to as "FRC"). FRC is a concrete mix that contains fibrous materials, which improve the concrete's structural integrity. Traditionally, FRC contains discrete fibers that are uniformly distributed and randomly oriented[7]. This arbitrary dispersion of fibers leads to inefficient structural integrity and strength. There exists a method for specifically orienting the fibers in concrete, which is comprehensively discussed in the section "BACKGROUND".

The objective of this study is to explain and explore two methods, post-tensioning and steel-fiber orienting methods, that obviate the need for reinforcement in the cutting-edge precast concrete 3-D printing (PCP) technology. The first method involves the application of post-tensioning tendons in PCP members at the stressed locations and directions; this leads to a stronger structure that compensates for the lack of reinforcement. In contrast, the method for the intentional orientation of fibers in Fiber-Reinforced Concrete leads to a stronger material that requires no additional reinforcement. The "casting-flow induced" method is proposed in this study to orient the fibers in PCP members[7].

BACKGROUND

PRECAST CONCRETE 3-D PRINTING

3-D printing is an additive and automated procedure for constructing 3-D solid objects from a simulated model in the control unit. Conceptually, a series of 2-D layers is printed on top of each other to build the three-dimensional simulated model[8] (Fig. 3). Pegna initially suggested and explored the concept of cementitious material 3-D printing[9]. Concrete 3-D printing was initially employed to construct complex geometrical shapes without the use of formwork[10,11]. This is a significant advantage compared to conventional construction methods. Lim et al. used twenty-three post-tensioning tendons on a printed concrete member only for vertical reinforcement (i.e. transverse reinforcement against shear forces) as shown in Fig. 4 [5]. The current study explores the possibility of longitudinal (flexure) reinforcement in addition to transverse (shear) reinforcement in PCP members.

Fig. 3- 3-D printing of concrete (photo courtesy of 3D Concrete House Printer[6], used with permission)

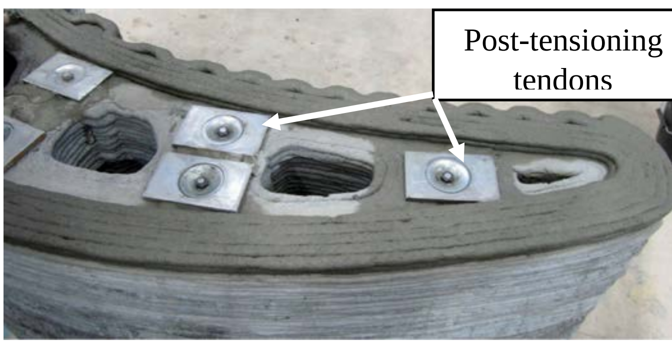


Fig. 4- Vertical post-tensioning tendons (photo courtesy of Lim et al. (2012)[5], used with permission)

MIX DESIGN OF CONCRETE 3-D PRINTING

There are two main fresh properties of concrete that facilitate the PCP procedure: extrudability and buildability. These two properties are closely related to workability and the open time of fresh concrete. The mix design proportion and the presence of supplementary cementing materials (such as superplasticiser, retarder, accelerator and polypropylene fibers) affect those mentioned properties[3]. Extrudability is the ability to transport the printing concrete from the pumping system to the nozzle where it becomes a layer of filament[12]. The open time is the period in which cementitious materials have not yet settled and the workability of the fresh concrete stays at a level that makes extrudability possible[3]; the open time is usually tested with a Vicat apparatus. In PCP, the buildability of fresh concrete is defined as the number of printing filament layers that can be built up without undesired deformation[3,13]. Previous research[3] has proposed that the optimum mix design for concrete 3-D printing fulfil all the mentioned requirements as shown in Table 1.

Table 1- Optimum mix design of printing concrete

Property		Quantity
Maximum aggregate size		2mm
Sand to binder ratio		3 to 2
Binder components	Cement	70%
	Fly ash	20%
	Silica fume	10%
	Polypropylene fibers	1.2 kg/m^3 of 12/0.18 mm (length/diameter)
Water to binder ratio		0.26

Notes:
1. A 9mm diameter nozzle is deemed appropriate for printing with the mix design.
2. In one session, this system can build 61 layers in one session without significant deformation of bottom layers.
3. The open time of fresh concrete can be up to 100min.
4. The compressive strength of concrete can be obtained as much as 110 MPa (16 ksi) at 28 days.

POST-TENSIONING METHOD IN PRECAST MEMBERS

Post-tensioned concrete is a type of precast concrete member (along with prestressed concrete) in which surrounding concrete elements are initially cast and the tendons are tensioned afterwards[14]. However, the concrete is not placed in direct contact with tendons. The tendons are encapsulated through a protective duct or sleeve, that is either cast inside the concrete element or placed adjunct to it. Tendons at each end are then firmly fixed to the surrounding concrete. Once the concrete is fully cast and settled the tendons are stretched (tensioned) at each end and the encapsulated concrete undergoes a resultant compressive force. By grouting the duct after tensioning, the tendon is bonded to the surrounding concrete; this is called "bonded post-tensioning" (Fig. 5).

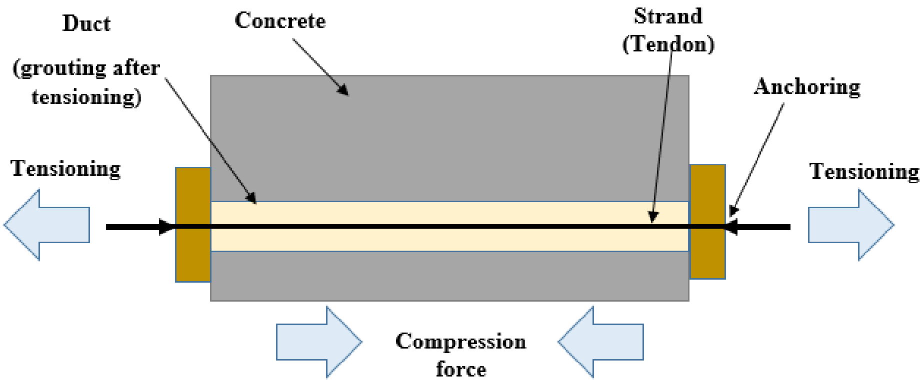


Fig. 5- Post-tensioning mechanism

FIBER-REINFORCED CONCRETE AND FIBER-ORIENTING METHOD

The concept of composite materials was initially considered in 1950s and FRC was one of the topics of interest in this category[15,16]. Fiber-Reinforced Concrete (FRC) contains discrete fibers that are uniformly distributed and randomly oriented. Previous research has shown that the manipulation of the fiber dispersion and orientation to match the stress field pattern is significantly influential on the mechanical behaviors of FRC[7]. In order to orient the fibers in concrete, the "casting-flow induced" method can be used[7]. Ferrara et al. showed that by virtue of a specific concrete mix design and an appropriate casting procedure, steel-fibers can be efficiently tailored along the direction of tensile stresses. The mix design proportion of concrete that leads to "casting-flow induced" concrete is shown in Table 2. It should be noted that the magnetic method proposed by Ferrara et al. is a nondestructive technique to monitor the direction and dispersion of fibers within a structural element[17,18].

Table 2- Mix design for constructing cast-flow induced FRC

Property		Quantity
Maximum aggregate size		2mm
Sand to binder ratio		1.5 to 2
Binder components*	Cement type I 52.5	50%
	Slag	42%
	Straight steel fibers**	8%
Water to binder ratio		0.17

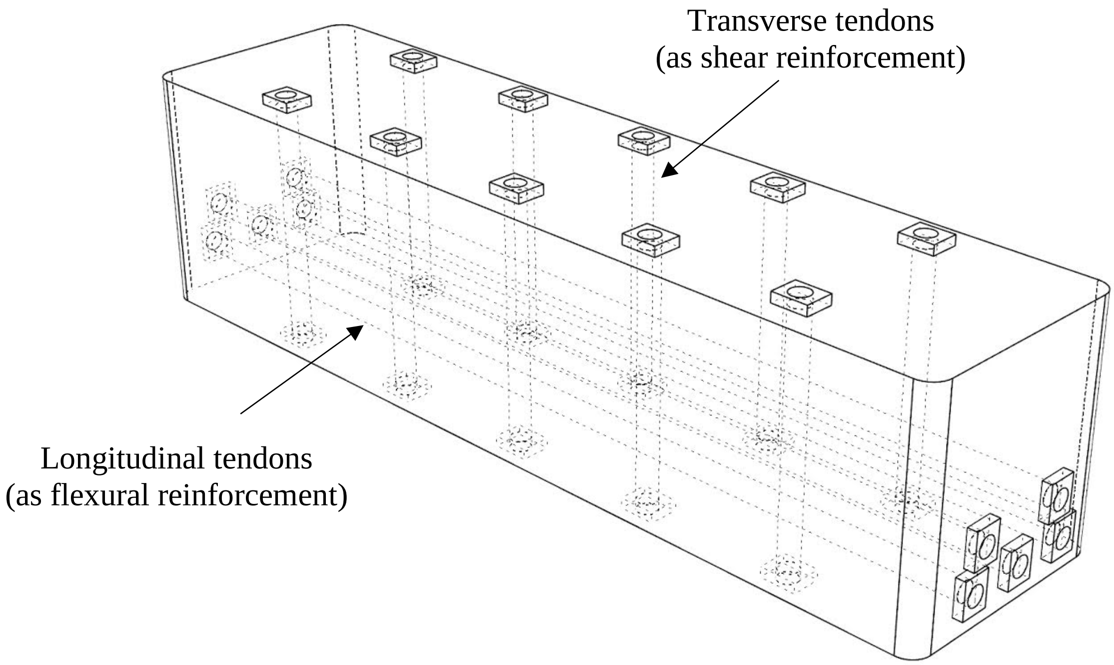
Notes:
* Superplasticizer used in the mix design is 33 $^{l}/_{m^3}$.
* Length (l_f) and diameter (d_f) of fibers are 13mm and 0.16mm, respectively.

PROPOSED REINFORCING METHODS FOR PRECAST CONCRETE 3-D PRINTING

In this study, two methods are proposed and explored to reinforce PCP elements, including 1) post-tensioning tendon method and 2) fiber-orienting method.

1) Post-Tensioning Method

As mentioned in the section "BACKGROUND", Lim et al.[5] showed that the possibility of transverse reinforcement in PCP members through the post-tensioning method. However, the current study suggests not only the transverse post-tensioning reinforcement (against shear forces) in PCP members, but also the longitudinal post-tensioning reinforcement (against flexural forces), as shown in Fig. 6. In general, the bond between concrete and reinforcement in PCP is difficult to achieve. The application of post-tensioning tendons could reduce (if not eliminate) this difficulty by grouting the ducts after stressing (tensioning) the tendons. In addition, the use of duck sleeve could be avoided by designing voids in the simulated program that can be printed in layers (Fig. 6).



a) Post-tensioning tendons

b) PCP member

Fig. 6- Configuration of post-tensioning method to reinforce PCP members

A future study is recommended as the follow-up research to conduct an experimental program where different variables (such as the post-tensioning tendon size, PCP cross-section and length, and printing nozzle diameter) are investigated. This study would further identify the variables affecting PCP shear and flexural capacities (Fig. 6).

2) Fiber-Orienting Method

In this method, it is proposed that the concrete mix design is manipulated such that to orient fibers along with the direction of the tensile trajectory of PCP members. The optimum mix design needed for printing concrete layers (using a 9mm-diameter nozzle) is shown in Table 1. In addition, Table 2 shows the optimum mix design for the implementation of reinforcing fibers. The current study proposes to combine these two mix designs through a concrete delivery system that uses two concrete containers and two pumps. Fig. 7 shows the schematic for the proposed delivery system.

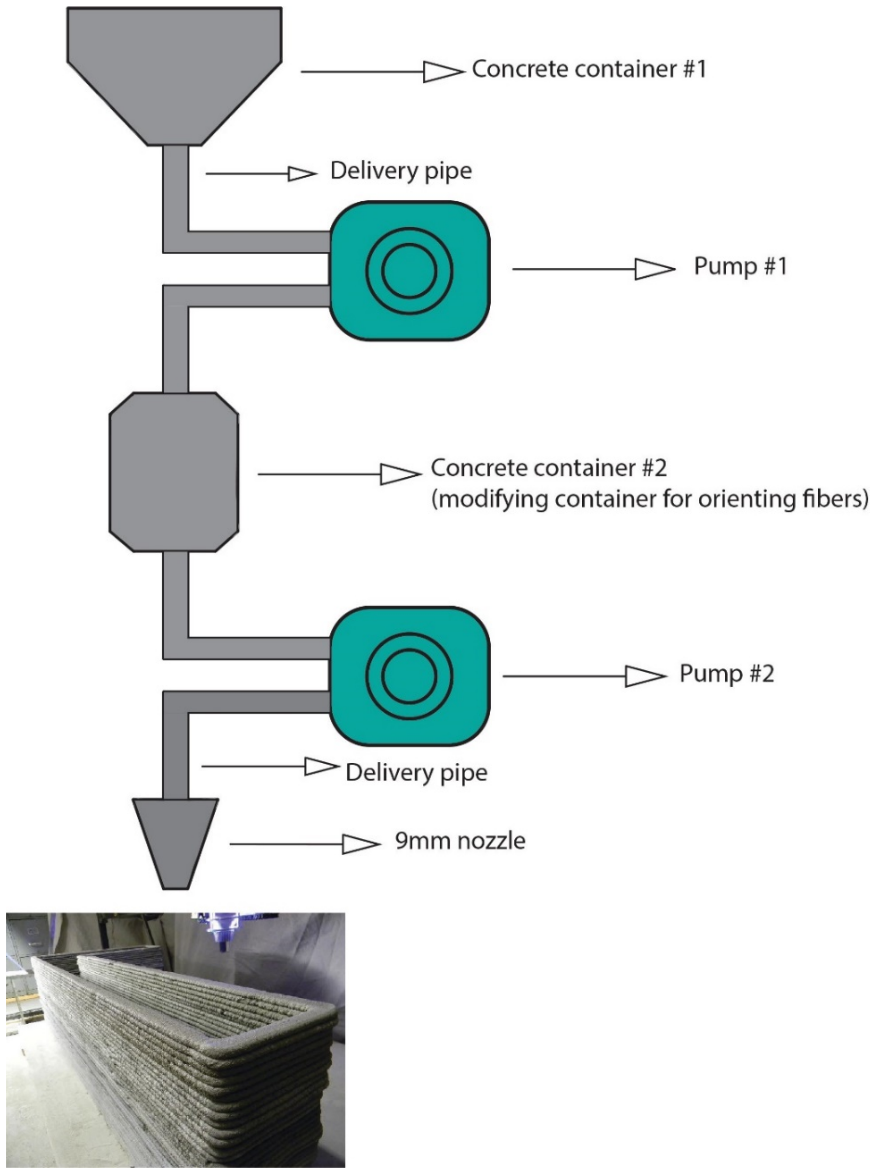


Fig. 7- Schematic of the proposed concrete delivery system (after Le et al. 2012[3])

In this proposed printing procedure, Container #1 contains the mix design presented in Table 1. This concrete is then pumped to Container #2, which provides the concrete with the necessary reinforcing fibers needed for the fiber-orienting procedure. In this container, the binder quantity is doubled by adding 50% Cement type I, 42% slag, and 8% straight steel fibers (13mm long and 0.16mm diameter) to the concrete batch. Thus, the sand to binder ratio becomes 1.5 to 2. Additionally, 33 $^{l}/_{m^3}$ superplasticizer is required to be added to Container #2. Pump #2 is then used to push the concrete through the delivery pipes and out the 9mm-diameter nozzle.

SUMMARY AND CONCLUSIONS

This study explored and proposed the implementation of two reinforcing methods, one involving post-tensioning tendons and the other steel-fiber orienting, to the cutting-edge technology of Precast Concrete 3-D Printing (PCP). The relevant technologies and their body of knowledge were investigated, including concrete 3-D printing, mix design of concrete 3-D printing, types of fibers used in concrete and the fiber-orienting method, and the post-tensioning method. This study proposed a post-tensioning procedure to reinforce PCP members against both shear and flexural forces in an effort to mimic the stirrups and longitudinal reinforcement in RC members. In addition, the application of the fiber-orienting method in Fiber-Reinforced Concrete (FRC) was explored to obviate the need for rebar reinforcement in PCP members. Implementation of this concept was proposed via a modified delivery system to print the fibers in such a way that their direction and placement are along with the stress trajectory of PCP members. The prevalence and industrialization of PCP members will be facilitated through the implementation of the proposed reinforcing methods explored in this study.

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