# 3D CONCRETE PRINTING FRAME STRUCTURE IN GRANULAR MEDIUM

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**Abstract.** The field of architecture is experiencing an increase in demand for custom fabrication methods, driven by the advancements in digital design tools and techniques. However, in conventional concrete construction systems, achieving extensive customization often leads to high costs and prolonged fabrication times due to the complexities associated with formwork fabrication. This paper presents an alternative 3D concrete printing method named Concrete Printing in Granular Medium (CPGM). Unlike the current layered extrusion 3D printed concrete technology, CPGM extrudes concrete within a granular medium, which enables greater freedom in printable geometry without being limited by gravity constraints. The primary aim of CPGM is to facilitate the rapid fabrication of intricate concrete elements by removing the stacking process involved in layered extrusion. This paper outlines the design and fabrication workflow of the CPGM method and presents a case study involving creating a scaled model of a single-objective optimized concrete frame structure. Through proof-of-concept projects, the paper explores the potential benefits, current challenges, and future development of CPGM.

**Keywords.** Injection 3D Printed Concrete, Concrete Frame Structure, Optimized Concrete Structure, Rapid 3D Printing, Granular Particle 3D Printing

## 1. Introduction

Architects have mainly relied on a layered extrusion method for 3D printing concrete structures. This method prints material layer by layer in a planar path, following the slices of the 3D object. Although it eliminates the need for formwork fabrication, it has limitations. For instance, it only allows for load-bearing wall structures and restricts the printable volume and fabrication speed. To overcome these challenges, this study introduces an alternative fabrication technique called Concrete Printing in Granular Medium (CPGM). This method aims to achieve rapid 3D printing of non-standard concrete frame structures.

CPGM utilizes Injection 3D printing technology to extrude concrete along a three-dimensional path within a bed of granular particles. This method allows for the rapid fabrication of highly customized gradient cross-sectional diameter frame structures

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with minimal formwork. The robotically operated long nozzle plunges into the granular medium and extrudes concrete without geometric constraints. Granular particles support the extruded concrete, providing counter pressure to the hydrostatic pressure of the concrete to maintain its printed form.

This manufacturing process has evolved from the principles of Rapid Liquid Printing (RLP) developed by the Self Assembly Lab at MIT and Injection 3D Concrete Printing (I3DCP) pioneered by Norman Hack (Xiao et al., 2022). Both RLP and I3DCP have previously faced limitations related to the materials they can employ and the quantity they can print, primarily due to buoyancy issues with the liquid support medium (Darweesh et al., 2023). Moreover, liquid support materials pose challenges to application on construction sites concerning leaking, contamination by other construction materials, and evaporation. The CPGM method employs ubiquitous and easily reusable granular material, such as sand, as a support medium to temporarily sustain printed concrete structures without submersion, improving RLP and I3DCP for architectural use.

As an initial step in developing this fabrication methodology, this research presents a series of proof-of-concept experiments designed to evaluate the feasibility of 3D printing concrete frame structures within a granular medium. The paper also demonstrates the workflow for digitally designing and fabricating concrete frame structures using CPGM. The frame structure is designed through a generative design approach, where optimization involves considering design variables such as angles, lengths, and section sizes of structural elements. The objective is to minimize the sum of axial forces and the volume of structural elements. The digitally designed frame structure is then translated into a toolpath for the robotically operated extruder. This toolpath enables the 3D printing of concrete elements with gradient cross-sectional diameter by controlling the nozzle movement speed. Slower nozzle movement results in thicker printed concrete elements. This method simplifies the fabrication of highly customized shapes and sizes of concrete elements, achieved through structural optimization. A long-nose ram extruder injects concrete into the granular medium based on the predetermined toolpath and speed. When the 3D-printed concrete elements are cured, and the granular medium container is disassembled, the printed structure emerges as the sand naturally flows under the influence of gravity, revealing its intended form.

This paper proposes an alternative in concrete fabrication, eliminating the need for traditional formwork construction and deconstruction, which typically consumes more than half of the resources in conventional concrete construction (Jipa & Dillenburger, 2022). Moreover, CPGM provides solutions to the constraints associated with layered extrusion 3DPC, including limitations on printable geometries and printing speed. As illustrated in Figure 1, the CPGM method envisions that concrete frame structures can be designed and constructed with gradient cross-sectional diameter and customized shapes without complicated formwork or gravity constraints.


*Figure 1. Toward adaptable concrete structure fabrication. (a) A concrete column constructed with conventional formwork construction - Reprinted from npgallery.nps.gov. (b) Laboratory scale case study of concrete frame structure and slab constructed by CPGM method.*

## 2. State of the Art

The Injection 3D printing technology used in this study employs two different approaches. The first approach involves directly injecting the printing material into a liquid medium. This allows for 3D printing without the need for planar slicing, as the nozzle is free to move within the carrier liquid. One example of this approach is Buoyant Extrusion, which extrudes thermoset polymers into a buoyant medium (Johns et al., 2014). Another example is Rapid Liquid Printing, which was developed by the Self-Assembly Lab at MIT. This method eliminates gravity constraints and layering requirements by printing silicon material into a gel medium (Hajash et al., 2017). Technische Universität Braunschweig has also explored extruding concrete into a liquid medium such as gel and limestone suspension (Hack et al., 2020). However, these approaches have a common challenge of engineering the carrier liquid based on the density of the printing material to maintain the 3D printed shape without sinking or floating (Lowke et al., 2021).

The second approach is non-planar granular 3D printing (NGP) technology, which injects epoxy resin into granular particles to bond them and create three-dimensional objects. NGP shares similar fabrication strategies with binder jetting additive manufacturing but has an advantage in printing speed by eliminating the layering process characteristic of other binder-jetting 3D printing methods.

## 3. Methods

### 3.1. FABRICATION SETUP AND PARAMETERS

The CPGM uses a robotic fabrication system to create concrete structures. The system includes a linear actuator ram extruder mounted directly onto a 6-axis robot arm (KR10R1100). The ram extruder is operated by a controller that consists of an Arduino

UNO, a custom breakout board, and a DM542T-Stepper Motor Driver. The controller manages the start, stop, and speed of the extrusion process. The ram extruder pushes the concrete mixture through a 9mm inner diameter and 241.8mm long aluminium nozzle into a granular medium. The concrete mix for CPGM consists of Portland cement type I, 0.5-1.0mm coarse sand in a ratio of 1:2 and a 0.3 ratio of water. For the proper viscosity of the concrete mix for smoother extrusion, a superplasticizer is added to the mix in a 1% ratio to the weight of the cement.

The granular medium is also an important setup for CPGM. Granular particles are a 3D printing medium, a hosting material of 3D printing concrete, utilized to overcome the challenges of layer extrusion. One of the critical challenges in 3DPC is maintaining the printed form without deformation under the pressure of upper layers. This challenge is addressed by precisely controlling the material rheology. However, achieving the proper viscosity of the concrete, which needs to be pumpable until it reaches the nozzle end and then rapidly solidified for adequate strength, remains a complex task (Jipa & Dillenburger, 2022). Casting concrete into 3D printed formwork has less problem with material rheology, but designing and constructing 3D printed formwork capable of withstanding the hydrostatic pressure of concrete demands excessive construction resources (Burger et al., 2020). Using granular particles as a 3D printing medium could solve the stated challenges of layer extrusion and 3D-printed formwork. During the CPGM fabrication, the counter-pressure from the granular medium (p) sustains the 3D printed shapes, neutralizing the hydrostatic pressure of the concrete (Figure 2).

The described fabrication setup enables the CPGM method to 3D print linear concrete elements of various sizes without the need for formwork. As depicted in Figure 2, the cross-section diameter of the 3D printed elements (d) is disproportionate to the speed of the nozzle movement (V). This allows for the fabrication of different-sized elements designed in the digital design stage by simply adjusting the speed of the nozzle movement, facilitating high customization of concrete frame structure without complicating the fabrication process.

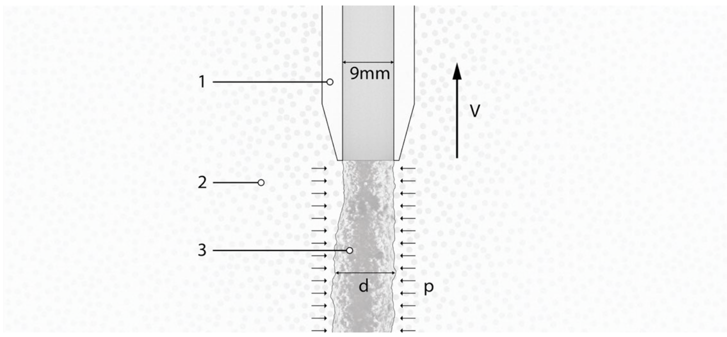


*Figure 2. Fabrication parameters: The cross-sectional diameter of the 3D printed element is disproportionate to nozzle speed V. Extruded form is sustained by counter pressure p. 1 Aluminium nozzle. 2 granular particles. 3 Extruded concrete.*

## 3.2. DIGITAL DESIGN

CPGM fabrication workflow starts with generating the digital model and toolpath. This digital design process demonstration aims to understand better how the CPGM method enables the seamless workflow from digital frame structure design to fabricating tangible structure. As the design process is illustrated in Figure 3, the initial phase involves defining design variables and establishing an objective for structural optimization. For the first case study, as described in Figure 3(a), various design variables, such as the distance between columns, column height, bottom and top column locations, and sizes of concrete elements, were identified for the three-level tripod structure design.

The next step is conducting a structural analysis of different design options to determine the minimal axial forces(F) and element mass(M) of the entire concrete elements, which can be described as ΣF*M. The analysis employs the Grasshopper plugin Karamba 3D, as illustrated in Figure 3(b) (Preisinger & Heimrath, 2014). The optimized design option is selected based on the analysis results, considering different combinations of design variables and their ΣF*M values. This case study uses the Grasshopper plugin Design Space Exploration tool developed by Digital Structure at MIT for the optimization process. (Brown, Jusiega, and Mueller, 2020). A three-story tripod frame structure with variable member sizes at 370 mm height is chosen from design options with comparable objective values and given volume.

The final step of the digital design process is generating a linear toolpath with variable nozzle moving speed, considering the specified form and size of elements. In Figure 3(c), the darker zone of the toolpath indicates a slower toolpath, resulting in thicker cross-sections of 3D-printed concrete elements. The brighter zone signifies a faster nozzle speed for fabricating thinner elements. The speed range of the toolpath in this case study design varies from 3 mm/s to 20 mm/s. This toolpath, created through KUKA|prc, is intended to be executed on a 6-axis robot KR10R1100 (Braumann & Brell-Cokcan, 2015).

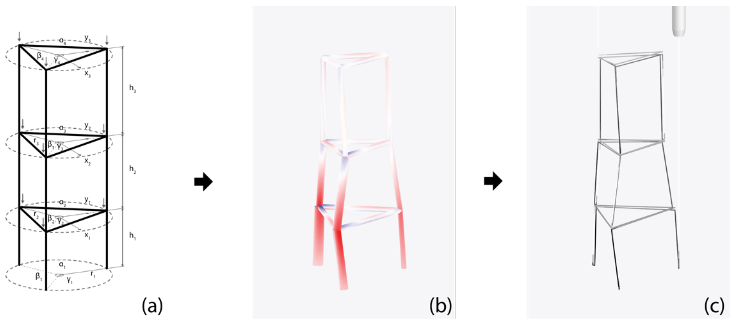


*Figure 3. Digital design workflow. (a) Defining design parameters. (b) Conducting structural analysis and optimizing for a single objective with minimal axial forces and mass of entire structure. (c) Creating a toolpath with a variable nozzle speed, according to the cross-sectional diameter of each element.*

## 3.3. FABRICATION

Following the generation of the digital model and toolpath, the fabrication process begins by preparing a granular medium container. In the case study uses three vertically stackable granular containers to create a structure that surpasses the length of the printing nozzle. Given that the nozzle length imposes restrictions on the 3D printable height in the CPGM method, the granular container is divided into three segments to ensure that the 3D printing height remains within the nozzle length(180 X 180 X 135 mm). These containers lack a bottom and top face, allowing them to be stacked to extend the height of the granular medium for continuous printing.


*Figure 4. The sequence of fabricating tripod frame structure. (a) First-level concrete printing. (b) Second-level fabrication. (c) Third-level fabrication.*

After preparing the granular containers and calibrating the tool-center-point to the desired homing location, the bottom container with 1 mm effective-size rounded silica sand. Following this, the 6-axis robot plunges the nozzle into the granular container, initiating 3D printing from the bottom (Figure 4(a)). After completing the first-level print, the second-level container is affixed to the first-layer container and filled with granular material (Figure 4(b)). This process is repeated until the 3D printing is completed (Figure 4(c)).

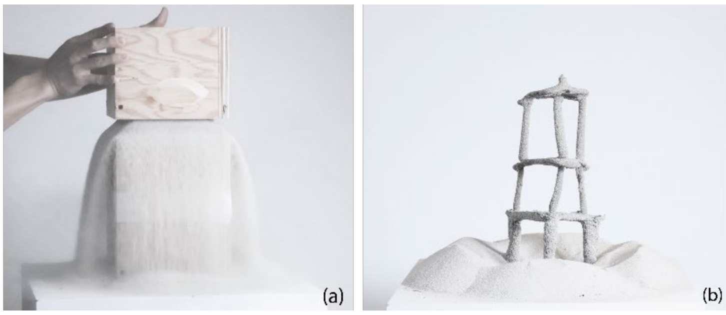


*Figure 5. (a) Demoulding granular particle container. (b) Result of tripod frame structure.*

The 3D printed result undergoes a 48-hour curing period within the granular container. The demolding process is straightforward. Remove the tapes connecting the wooden boxes and lift or disassemble the boxes. The granular medium falls under gravity without an additional complicated formwork removal process, as depicted in Figure 5(a). Once all granular containers are removed, the 3D printed concrete structure is revealed, as shown in Figure 5(b). The granular particles can be reused for subsequent prints with minimal waste.

The case study project demonstrates the workflow and fabrication method of CPGM. By repeating the case study's learnings, the author presents the second case study, creating a 1:30 scale model of a 4 m tall, one-story concrete column and beam with a slab. The granular particle container (500 X 250 X 150 mm) is filled with rounded silica sand, including reused particles from the first case study. Through an optimization process, the generative model strategically places five vertical columns to minimize the ΣF*M of the column and beam structure, supporting a 15mm thickness slab. Figure 6(a) illustrates the fabrication process, while Figure 6(b) displays the result of the second case study.

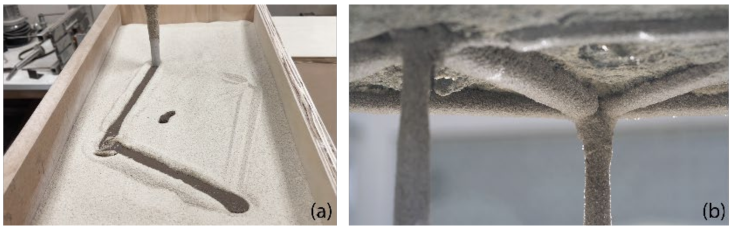


*Figure 6. The scaled model of a concrete column and beam with a slab by the CPGM method. (a) Concrete printing within and above granular medium. (b) Result after granular particles removed.*

## 4. Conclusion

This research presents several small-scale experiments to demonstrate the feasibility of the CPGM method. The first experiment involves creating a tripod frame structure. The second one applies the same workflow and fabrication method to produce single-story concrete columns, beams, and slabs. The digital design process, optimization, toolpath generation, and digital fabrication with the CPGM method enable a smooth transition from form-finding to fabrication.

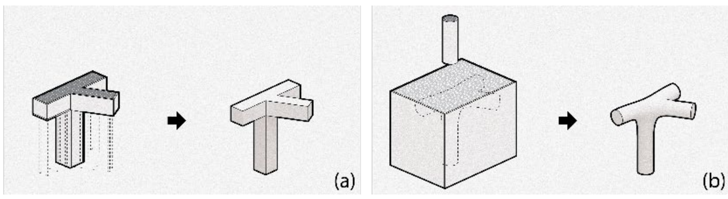


*Figure 7. (a) Conventional formwork casting fabrication that requires complex formwork and supports. (b) Frame structure created by CPGM method.*

The study demonstrates that using the CPGM method for construction offers several benefits compared to layered extrusion 3DPC and conventional formwork casting systems. The CPGM method, employing a simpler toolpath, allows for the rapid 3D printing of concrete with variable cross-sectional diameters compared to layered extrusion 3DPC. The CPGM method also enables the fabrication of horizontal beam elements without gravity constraints, which is shown in Figure 6(b). The CPGM method requires minimal formwork, making it a better fit for creating highly customized elements that align with the digital design generated from the optimization process. Figure 7 visually compares the conventional formwork construction and the CPGM method.

The paper suggests exploring reinforcement methods, improving the fabrication setup for larger-scale construction, and enhancing the accuracy of CPGM fabrication as the next steps. Various reinforcement strategies can be explored, such as extruding a metal cable with concrete or following a prefabricated reinforcement with the nozzle. Scaling up fabrication could involve attaching the concrete extruder end effector to an industrial-scale gantry machine instead of a fixed robotic arm. For better accuracy of CPGM, material studies could determine the proper viscosity and strength to prevent disconnection or oversized strands.

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