ABSTRACT

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## Abstract

An automated 3DCP toolpath optimization method is developed and demonstrated on a $4\,m \times 4\,m$ post-tensioned modular floor structure. The method includes (1) buildability optimization via normal-driven spherical shape analogy, (2) curve number reduction through adaptive Booleaning, (3) "nonstop" globally continuous toolpath with detouring travel lines, and alternative methods of (4) curved slicing and (5) infill generation.

## CCS Concepts

• **Computing methodologies → Shape modeling**; • **Applied computing → Computer-aided design**.

## Keywords

3D concrete printing, funicular floor, post-tensioning, toolpath optimization, continuous toolpath, buildability, design for manufacturing

## 1 Introduction

The geometric flexibility offered by 3D concrete printing (3DCP) enables the development of structurally efficient assemblies by integrating freeform geometries and spatially differentiating material properties and functionalities, thereby advancing performance-driven design approaches in construction. Our previous work has established a Toolpath-based framework for 3DCP toolpath design, which converts shell surfaces into non-parallel, planar, and as-continuous-as-possible toolpaths [Zhi et al. 2025]. By connecting the surface and the toolpath as twins, we introduced buildability and surface quality optimization methods that enhance the design's printability and reliability for spatial joinery. [Zhi and Akbarzadeh 2025]. By applying these methods to the fabrication of a full-scale architectural structure, we verify their effectiveness, introduce new processing techniques, and expand the framework's application in toolpath optimization under diverse design and fabrication constraints.

## 2 Design

The design and implementation of a prefabricated, 3DCP funicular concrete beam across multiple scales has demonstrated the potential for structurally efficient and architecturally expressive modular spanning systems [Akbarzadeh et al. 2024]. Through the integration of advanced geometrical design with emerging construction technologies, such prefabricated 3DCP structures offer a means to address multiple performance objectives. In particular, embedding periodic anticlastic surface geometries within an optimized force distribution enables efficient load transfer while minimizing material usage. When combined with 3DCP and post-tensioned modular assembly, these geometrically designed systems can achieve significant improvements in structural capacity [Chai et al. 2024; Ororbia et al. 2024; Yavartanoo et al. 2025], thermal regulation [Wang et al. 2024], carbon sequestration potential [Yu et al. 2025], and overall sustainability [Ororbia et al. 2025]. Building on the prefabricated funicular concrete beam, a modular floor structural concept was developed. The floor concept advances the beam's design principles by employing a hybrid structural strategy that includes post-tensioned beam modules, designed to carry both tension and compression forces, arranged to form a framing

system that supports a compression-dominant arch. The resulting geometry-informed force distribution, combined with modular prefabrication, contributes to a lightweight yet efficient spanning floor system that is competitive with conventional post-tensioned concrete floors.

We have designed a 4 m × 4 m post-tensioned 3DCP modular floor structure. Periodic anticlastic surfaces are box-morphed and embedded in a two-way funicular configuration to form the initial design, which is then thickened using volumetric modeling methods [Bernhard et al. 2018] for slicing. The floor is segmented into four cast capitals and 24 printed components, 8 of which are used as endpieces with post-tensioning anchorages. The segmentation planes/surfaces are offset using the method by [Zhi et al. 2025] to ensure precise side-by-side spatial integration.

## 3 Toolpath optimization

### 3.1 Buildability optimization

Buildability is the ability of a print scheme to remain self-supporting during and after printing. The method of "*normal-driven stylization*" [Liu and Jacobson 2021] stylizes a mesh to exhibit spherical shape analogy using a reference shape. The vertices are deformed such that their normal directions match the spherical reference shape while the topology and local shapes are preserved. We have implemented this iterative method to reduce the overhang of a mesh using a spindle-shaped reference [Zhi and Akbarzadeh 2025]. The smooth sides of the mesh and the faces that serve as conduits are locked in the optimization. The optimization algorithm is performed on the input three times, iteratively. As a result, the total weight of the vertices exceeding an overhang of 1.5 decreased from 0.39% to 0.14%, while that of 1.0 decreased from 0.87% to 0.38%. In the original mesh, an extreme bridge is formed by two "cliffs". As the optimization algorithm deforms the vertices, the protruding cliffs are "smoothed out" to become straight (highlighted by the white arrows), thereby redistributing and reducing the extreme overhangs. The scaled fabrication model and the construction-scale concrete print show that the optimized bridge is now buildable.

### 3.2 Curve number reduction

For creating a continuous toolpath, we prefer layers with fewer curves [Zhong et al. 2023]. If curves are closed, each layer can be organized as a series of solid regions, which is compatible with the precise and reliable methods of offsetting and Boolean operations [Johnson 2025]. By the Boolean union or difference between the main toolpath and an auxiliary toolpath consisting of small rectangles, we can create "bridges" that simplify or merge these regions, thereby reducing the number of curves [Zhi et al. 2025]. For aesthetics and advantages in continuous toolpath planning, we prefer bridges to be aligned, which can be achieved by modeling a box and slicing it to serve as the auxiliary toolpath.

However, for a toolpath with intricate topology, some layers may experience an increase in the number of curves after Booleaning. In light of this, we implemented a filter that decides, per layer, to accept or reject the result of Booleaning according to the number of curves before and after. This *adaptive Booleaning* method aligns bridges across layers, although some layers may be skipped. In this study, the semi-automated process effectively concealed the

bridging points on the bottom and side faces of the floor. They are aligned across adjacent segments, creating a clean and consistent reading.

### 3.3 "Nonstop" globally continuous toolpath

After the number of curves per layer is minimized, we can generate as-continuous-as-possible toolpaths to minimize seam defects [Zhi et al. 2025]. In this case study, we expand the method of continuous printing of a porous geometry to be compatible with extruding systems that can not stop and start cleanly. We first project the toolpath curves on the ground plane, solve the convex hull polygon, and offset it with a clearance. By extruding it vertically, we get an extruded offset convex hull that wraps the toolpath with this clearance. If the nozzle tool center point (TCP) is *on* this convex hull, the nozzle will not collide with the print body, and the dripping material will fall on the ground. Then the seam points of the toolpath curves are placed to be closest to this convex hull. Compared with detouring travel lines on a toolpath printed layer by layer, this composite method reduces material waste by 90.0% for our design. Out of the total material usage, only 0.4% was used by travel lines.

### 3.4 Curved slicing

Curved slicing uses non-planar 3D curves as a toolpath. This study uses primarily non-parallel planar toolpaths to align the layer normals to the post-tensioning direction. Curved slicing is applied in the center dome to create clean, uniform layer lines and create force-informed interlocking. We use a series of interpolation surfaces as intersectors for slicing. For the moderately curved geometries investigated in this study, the unified UVs of the interpolation surfaces allow for mutual conversion between the curved toolpath and an accompanying planar toolpath; therefore, we can use processing methods exclusive to planar toolpaths.

### 3.5 Infill generation for printing formwork

The endpieces of the post-tensioned spanning structure must be solid for dispersing stress and include conduits for the cables. To use the print body as formwork for casting, we need a filled bottom face. In this study, we utilize the *region* property of closed toolpath curves to generate self-filling continuous curves in a three-step manner. Firstly, the wall curve is iteratively offset inward until it fills the space. Then they are organized into regions with holes, which can be simplified *parallely* by adding U-turn bridges. Lastly, a greedy search merges the simplified regions using additional bridges. The method is fast and guarantees one continuous curve for each region.

## 4 Scaled fabrication model

We have used an off-the-shelf fused deposition modeling (FDM) printer with a 1 mm nozzle replacement to print 1:10 scaled fabrication models (SFM) [Zhi et al. 2024] to verify the geometric design, the segmentation scheme, and the toolpaths (Figure 1).

## 5 Full-scale printing

The full-scale printing setup involves an ABB® IRB6640 robotic arm, a MAI®MULTIMIX-3D pump, and a 3D Potter Mixcell extruder. Two-component (2K) material was used (SIKACRETE®-752

**Figure 1:** 40 cm×40 cm **1:10 SFM of the final floor: components and the complete model. Threaded rods are used to mimic post-tensioning cables.**

F and SIKA® SIGUNIT® L-5601 AF). All toolpaths were printed successfully without visible deformations or alterations. After curing, the floor modules were assembled, closely resembling the digital model and SFM.

## 6 Closing remarks

This study demonstrates the development and validation of an automated 3D concrete printing toolpath optimization method, tailored for complex modular structural systems such as the floor structure presented. Through the integration of buildability optimization, curve number reduction, and globally continuous toolpath planning, the proposed framework enhances the efficiency and precision of the 3DCP process.

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