TOOLPATH SIMULATION, DESIGN AND MANIPULATION IN ROBOTIC 3D CONCRETE PRINTING

LUCA BRESEGHELLO[1], SANDRO SANIN[2] and
ROBERTO NABONI[3]
[1,3]*CREATE - University of Southern Denmark, Section for Civil and Architectural Engineering*
[1,3]*{lucab|ron}@iti.sdu.dk*
[2]*University of Innsbruck*
[2]*sandro.sanin@icloud.com*

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Abstract. *Digital fabrication is blurring the boundaries between design, manufacturing and material effects. More and more experimental design processes involve an intertwined investigation of these aspects, especially when it comes to additive techniques such as 3D Concrete Printing (3DCP). Conventional digital tools present limitations in the description of an object, which neglects material, textural, and machinic information. In this paper, we exploit the control of extrusion-based 3D printing via programmed layered toolpath as a design method for enhancing the control of the manufactured architectural elements. The paper presents an experimental framework for design, analysis and fabrication with 3DCP, developing a system for materializing interdependencies between geometry, material, performance. This is applied to a series of architectural artefacts which demonstrate the advantages and possibilities opened by the introduced workflow, expanding the design process towards higher control on the objects buildability, structural integrity and aesthetic.*

1. Introduction

3D Concrete Printing (3DCP) is a rapidly expanding technique, both in research and in the construction practice, promising high geometric freedom, reduced material consumption, and automation of construction. Most of its potential is yet to be fully exploited, mainly due to material limitations (Roussel 2018), and to a process that is still experimental (Suiker et al. 2020). Current studies on 3DCP are focusing on the performance and rheology of printing materials (Casagrande et al. 2020, Panda et al. 2019); the advancement in the printing technology (Craverio et al. 2020, Mechtcherine et al. 2019); the integration of reinforcements (Marchment & Sanjayan 2020, Bos et al. 2018); and the environmental and economical sustainability of the fabrication process (Mohammad et al. 2020, Kuzmenko et al. 2020). The complex interrelation of numerous parameters affects the printing outcomes, with unforeseen failures due to poor dimensional accuracy or mechanical performance (Wolfs, Bos and Salet 2018, Kruger et al. 2020). Limited research has been conducted to date on the design implications of

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3DCP, which demand specific modelling strategies for the manufacturing process (Carneau et al. 2019), compared to cast concrete elements.

Explorations in the design and control of the toolpath planning have been conducted, with a focus on different aspects. On the one hand, tools for controlling the printing process have been developed using agent-based path planning and printing simulation (Efthimiou, Grasser 2019; Stuart-Smith et al. 2020); implementing algorithms that output printing paths in static equilibrium (Bhooshan et al. 2018); and workflows for adaptive correction of the toolpath following geometric and fabrication constraints (Adilenidou et al. 2019). On the other hand, toolpath design strategies have been explored, focusing on emergent material patterns as an effect from the manipulation of the deposition speed (Mohite 2019); developing programmed patterns and surface articulation to demonstrate new material and aesthetic (Anton 2018; Westerlind, Vargas 2020). The existing research, however, does not provide instruments for quick and accurate printing simulation, analysis and visualization. In this work, we address this issue by introducing a modelling framework for 3DCP which allows designers to control and visualize the printing toolpath and the outcome of the printing process. This approach is used to enhance aspects of buildability, structural performance, and aesthetics during the printing process, where form and machining toolpaths are controlled simultaneously.

2. Methods

2.1. 3DCP WORKFLOW: DESIGN, MATERIALS, ANALYSIS, MACHINE

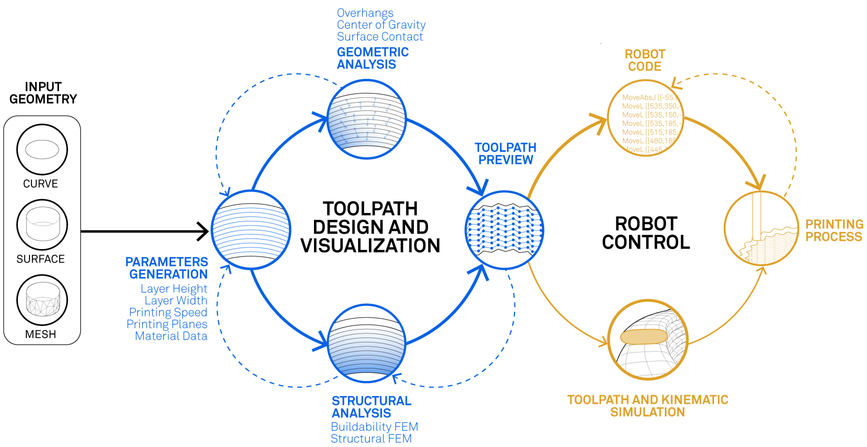

Figure 1. Design and Fabrication workflow for automated informed toolpath manipulation for 3DCP.

The standard 3DCP workflow includes the phases of design, the generation of a code for the printing machine, the preparation of a material mix and the printing process. The presented work builds on this by developing and integrating a set of design and analysis tools into the process. This is divided into two phases: (a) Toolpath Design and Visualization; (b) Robot Control, where the toolpath parameters are translated into motion command and a kinematic simulation of the printing procedure (Fig. 1).

2.2. FRAMEWORK FOR TOOLPATH DESIGN, ANALYSIS AND SIMULATION

For this reason, a reliable and agile numerical and visual preview of the layers is relevant to control the various printing parameters, to ensure a direct evaluation and control of the layers that constitute a print, for mechanical, tectonic and aesthetic purposes.

Parameters Generation - When a 3D digital model is translated into a toolpath for the layered extrusion, an approximation of the original shape is necessary. To address this transformation, we developed a framework from input 3D design to machine-readable code where a fast visualization of the printed outcome allows for the control of its geometrical characteristics. Developed in C-sharp within Grasshopper and Rhino, the framework firstly tackles the translation of an input geometry (surface, BReps, meshes or curve) into polylines at defined distances, defining the height H_x of the printed layers. Optionally, a spiralization of the toolpath is applied, constantly increasing the vertical position without an abrupt movement to change layer. The specific cross-sectional shape of the filament is determined by a series of parameters: considering the nozzle diameter, material mix, and the volumetric material flow as constant, the defining parameters for the layer shape are the movement speed, the layer height, and nozzle orientation (Comminal et al. 2020). The width W_x and in turn the sectional shape of the layer are a resultant of the other variables. These also determine surface contact S_x (Fig. 2).

Geometric and Structural Analysis - Once the printing parameters and the toolpath are defined, a series of analysis can be performed. On the one hand, an analysis of print overhangs, the centre of gravity and resisting section are graphically visualized (Naboni, Breseghello 2020); on the other hand, a Finite Element Analysis (FEA) is performed on the geometry resulting from the toolpath generation using Karamba for Grasshopper. A buckling simulation for the early-age behaviour of the concrete during the printing process developed by Vos et al. (2020) is employed to have immediate feedback on the stability of the generated toolpath.

Toolpath Preview - Given the influence of the layer generation process onto the 3D model and the importance of the layer shape on the quality, performance, and aesthetics of the print, the framework integrates a fast preview of the filament shape determined by the above-mentioned parameters, including information about the print, i.e. printing time, layer printing time, material quantities. The tool transforms the curve generated through the slicing process into a low poly mesh with the minimum number of control points (v_y) to describe the filament section, and subsequently into a Subdivision Surface (SubD) object, a high precision spline that provides a smooth curvilinear object representation from a polygonal mesh input.

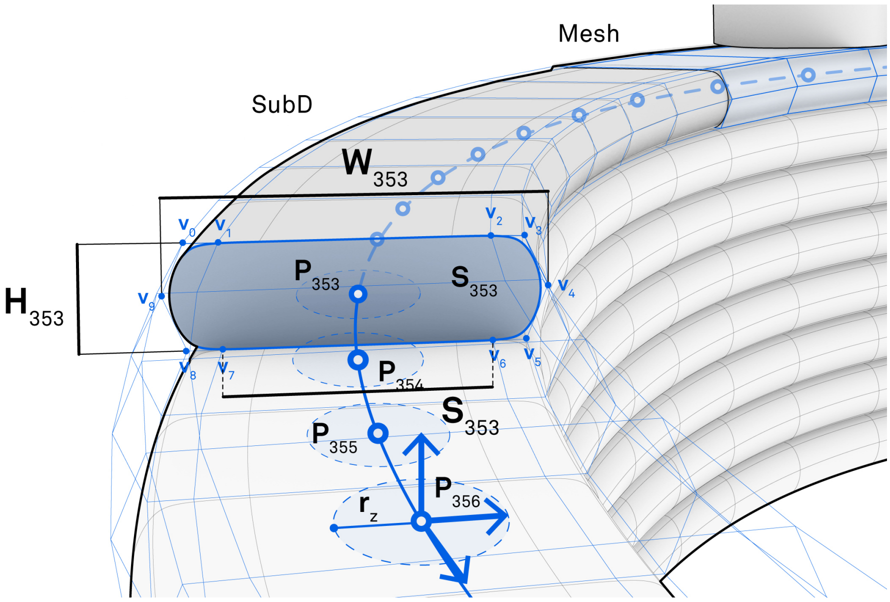

Figure 2. 3D preview of the toolpath and layer section with printing parameters and motion planes.

2.3. ROBOT CONTROL

Robot Code - The layer generation process outputs a set of 3D planes P_x that will serve as motion positions for the linear movement of the robot. The distance between these points is adaptive to the local curvature of the path with the goal of minimizing the number of planes and maintaining the closest fidelity to the input shape. The generated and analysed series of motion planes are then translated into a RAPID module file, integrating the printing speed, print zones(P_x), i.e. a parameter that determines the distance at which the robot computes the movement to the next point, and further additional movements for the pre and post-printing routine.

Printing Process - In parallel to the robot code generation, a kinematic simulation, as well as visualization of the final toolpath, are performed before being transferred to the robot controller. The presented framework is tested using the 3DCP facility of CREATE Lab at the University of Southern Denmark, which consists of an ABB 6650S industrial robot, a control unit and an extrusion system composed of a conveying pump and a circular printing head with a nozzle diameter of 25 mm. The employed cementitious material is based on a standard product for shotcrete with aggregates with a particle size of 2 mm and an addition of an accelerator with low content of calcium-chloride, and a small dosage of polypropylene fibres. The tests are run adding to the premixed powder 16.5% of water, 1.5% of accelerant admixtures and 0.1 % of fibres. The system is based on a batch-mixing process, where the accelerating admixture is added to the mixer. This process provides a constant material composition but creates a defined printing timeframe where the material has optimal mechanical resistance and capacity to flow through the pumping system.

2.4. EXPERIMENTING WITH TOOLPATH DESIGN MANIPULATIONS

The developed framework is tested on a fabrication experiment, where multiple toolpath design manipulations are applied to the design of a 400 mm diameter hollow cylindrical elements. The goal is understanding the influence of different parameters variations on successfully printing a column with a height of at least 2 m. The column design and proportion highlight two highly recognized challenges of 3DCP: one the one hand, its slenderness stresses on a stability-driven failure mechanism, i.e. elastic buckling; on the other hand, the relatively small diameter of the element and the short printing time for every layer enables a strength-based failure mechanism, i.e. plastic collapse (Fig. 3). These mechanisms are influenced by the fabrication parameters, i.e. motion speed, layer section, accuracy and consistency, by the early-age material characteristics and its mechanical evolution in time, as well as by the shape of the printed object, its centre of mass, the overhangs and the consequent toolpath design. The modelling framework for the design and manipulation of the printing toolpath, is tested on the presented experiment, developing methods of increasing the buildability while printing, i.e. the capacity of a layer to support the subsequent layers, and the structural resistance of the printed object through a series of informed manipulations of the toolpath parameters.

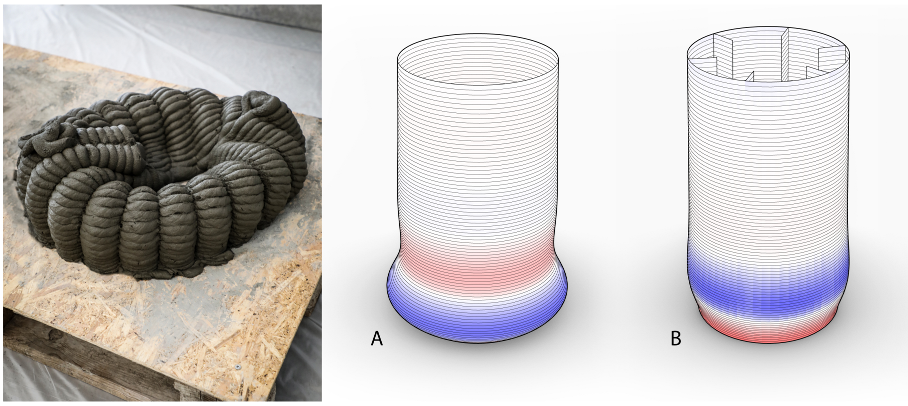

Figure 3. Collapsed 3D print (left) and FEM simulation highlighting the buckling effect on a plain column (A) and a ribbed column (B) (right).

The first developed manipulation method is based on the transformation of the target positions in the XY world plane (Fig. 4 - left). This strategy offers the chance to create ribs along the printing path by moving every n-th plane inward and outward according to the direction normal to the curve on the XY plane. Different parameters are here defined to control the manipulation: the resolution defines the distance between manipulated points; the amplitude defines the distance of the new plane from its original position; the pattern defines which points are moved. This can result in very dense and short in-and-out movements as well as in a few, deep, ribs along the toolpath. A series of weaving patterns are generated by shifting the movement of the planes in consecutive layers and creating an interlocking print with the material collapsing onto the layer below. The second strategy (Fig. 4 - centre) takes advantage of the movement rate of the robot to vary the amount of material extruded at every portion of the toolpath. This allows to locally control the width of the layer without creating any additional movement to the path, in turn offering a punctual control over the section, larger when the movement is slowed down and thinner when the motion speed is increased. The third manipulation (Fig. 4 - right) logic builds on a gradual movement on the vertical axis that creates a variation in the layer height according to a defined pattern. On the one hand, a constant speed and the change of height of the layers are defining a change of width. On the other hand, it is possible to manipulate the speed to maintain a constant section along the toolpath. These manipulations can be gradually controlled by coupling their generative parameters to external inputs such as the above-mentioned structural analysis.

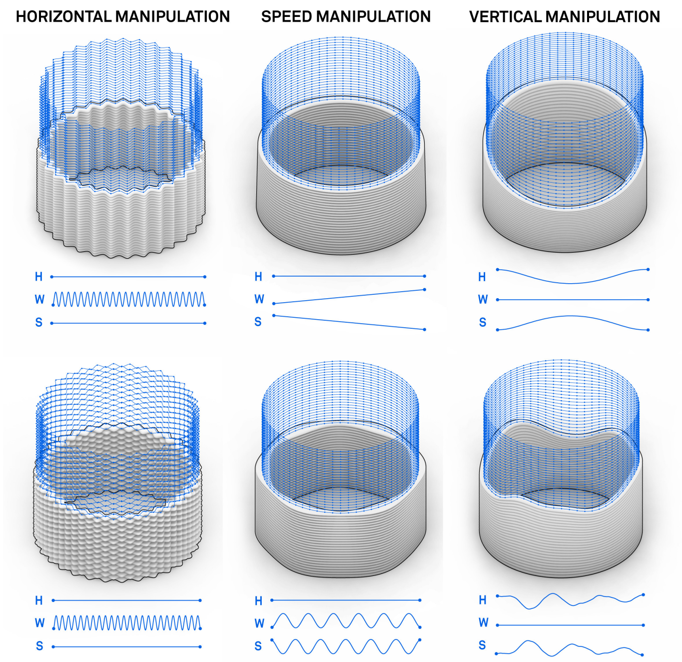

Figure 4. Toolpath variations applied to cylindrical columns: (left) transformation of target positions in the horizontal plane; (centre) variation of the robot's speed to deposit material when it is needed; (right) non-planar printing through variation in the vertical direction. The graphs are showing the evolution of layer height (H), print section width (W) and speed (S) during one layer of printing.

3. Results and Discussion

The work developed the proposed method of toolpath manipulation and visualization and tested it to improve the printing buildability of slender construction elements. The design manipulation and code generation workflow was tested practically by means of manufacturing a total of 17 columns with 9 different toolpath variations. Eight different circular elements with the same diameter and heights varying between 0.7 m and 1.70 m have been partially printed using different manipulations of the print path (Fig. 5). The process was interrupted due to the closing of the printing window, i.e. material too viscous to be pumped, or imperfections that caused layer adhesion problems. Other test columns presented failures throughout the process, either causing an interruption of the printing process and a partial result or a full collapse of the printed object.

Figure 5. Details of patterns from the C3DP columns designed through toolpath manipulation.

The highest column printed within the experiment's framework reached a height of 2.30 m, weighing about 280 Kg (Fig. 6). The toolpath presented a horizontal modulation shifted every second layer with variable amplitude in its height, starting from 150 mm at the first layer and linearly converging to zero and to a linear path. The column was printed at a constant speed of 300 mm/s generating an average layer time of approximately 4.5 s and a total printing time of around 10 minutes for the 230 layers. The layer size was defined as 10 mm height and 35 mm width. However, the shifted nature of the pattern generates an emergent variation of the section and an interlocking pattern between consecutive layers. The developed framework for the design and manipulation of printing toolpath for 3DCP provided a sufficiently accurate and agile tool during the design process, offering possibilities for control and variation of the toolpath given external inputs, e.g. structural analysis, as well as providing a fast visualization of the parameters in play and of of the printing process. The accuracy of the preview is limited to a geometric construct, approximating emergent physical and material behaviours in favour of responsive modelling feedback (Fig. 7).

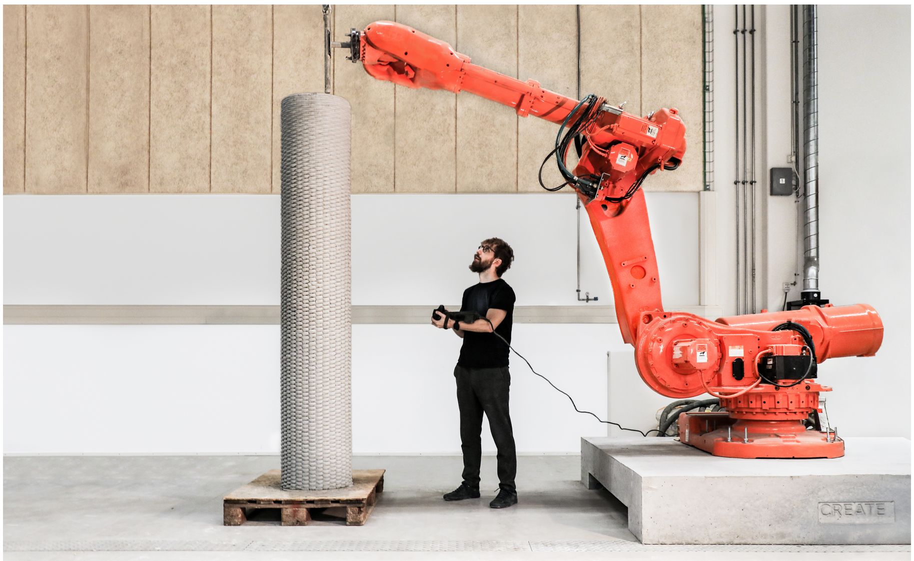

Figure 6. Concrete 3D Printed hollow column presenting an alternated XY toolpath manipulation.

Figure 7. Distance-based comparison between a 3D scanned C3DP column and its 3D digital model designed through toolpath manipulation.

4. Conclusions

This paper explored toolpath manipulations as a design method for 3DCP, based on agile digital tooling for controlling and visualizing the geometry of the print path. The presented framework proved the seamless integration of the manipulation and analysis operations within the design and fabrication process of concrete elements.

The work provides a base for the development of novel design solutions based on the manipulation of the toolpath, which could greatly benefit the fabrication process as well as generate novel aesthetic and performative solutions in the realm of construction. Future works will look into further development of the visualization tool, to provide anticipation of the dimensional features and physical behaviour of the layers for different printing and material conditions. The approach will be applied in future to the enhancement of buildability and structural properties in 3DCP, as well as applied in the design of specific aesthetic features.

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References

Adilenidou, Y., Ahmed, Z.Y., Bos, F. and Colletti, M.: 2020, Unprintable Forms, *eCAADe*, 168-177.

Anton, A. and Abdelmahgoub, A.: 2018, Ceramic Components - Computational Design for Bespoke Robotic 3D Printing on Curved Support, *eCAADe*, 71-78.

Anton, A., Yoo, A., Bedarf, P., Reiter, L., Wangler, T. and Dillenburger, B.: 2019, Vertical Modulations, *ACADIA 19*, 596-605.

Bhooshan, S., Van Mele, T. and Block, P.: 2018, Equilibrium-Aware Shape Design for Concrete Printing, *Design Modeling Symposium: Humanizing Digital Reality*, 493-508.

Bos, F.P., Ahmed, Z.Y., Wolfs, R. and Salet, T.A.: 2018, 3D Printing Concrete with Reinforcement, *High Tech Concrete: Where Technology and Engineering Meet - Proceedings of the 2017 fib Symposium*, **1**, 2484-2493.

Carneau, P., Mesnil, R., Roussel, N. and Baverel, O.: 2019, An exploration of 3d printing design space inspired by masonry, *Proceedings of the IASS Annual Symposium*, **6**(November), 1-9.

Casagrande, L., Esposito, L., Menna, C., Asprone, D. and Auricchio, F.: 2020, Effect of testing procedures on buildability properties of 3D-printable concrete, *Construction and Building Materials*, **245**, 118286.

Comminal, R., Leal da Silva, W.R., Andersen, T.J., Stang, H. and Spangenberg, J.: 2020, Modelling of 3D concrete printing based on computational fluid dynamics, *Cement and Concrete Research*, **138**(August), 106256.

Craveiro, F., Nazarian, S., Bartolo, H., Bartolo, P.J. and Pinto Duarte, J.: 2020, An automated system for 3D printing functionally graded concrete-based materials, *Additive Manufacturing*, **33**(January), 101146.

Efthimiou, E., Grasser, G. and Grasser, G.: 2018, Liquid rock – Agent based modeling for concrete printing, *Advances in Architectural Geometry*, 236-255.

Kruger, J., Cho, S., Zeranka, S., Viljoen, C. and van Zijl, G.: 2020, 3D concrete printer parameter optimisation for high rate digital construction avoiding plastic collapse, *Composites Part B: Engineering*, **183**(October 2019), 107660.

Kuzmenko, K., Gaudilliere, N., Dirrenberger, J. and Baverel, O. 2020, Assessing the Environmental Viability of 3D Concrete Printing Technology, *in* C. Gengnagel, O. Baverel, O. Burry, M. Ramsgaard Thomsen and S. Weinzierl (eds.), *Design Modeling Symposium*, Springer International Publishing.

Marchment, T. and Sanjayan, J.: 2020, Mesh reinforcing method for 3D Concrete Printing, *Automation in Construction*, **109**(June 2019), 102992.

Mechtcherine, V., Nerella, V.N., Will, F., Nather, M., Otto, J. and Krause, M.: 2019, Large-scale digital concrete construction – CONPrint3D concept for on-site, monolithic 3D-printing, *Automation in Construction*, **107**(August), 102933.

Mohammad, M., Masad, E. and Al-Ghamdi, S. G.: 2020, 3D concrete printing sustainability: A comparative life cycle assessment of four construction method scenarios, *Buildings*, **10 (12)**, 1–20..

Mohite, A., Kochneva, M. and Kotnik, T.: 2019, Speed of Deposition - Vehicle for structural and aesthetic expression in CAM, *eCAADe*, 729-738.

Naboni, R. and Breseghello, L. 2020, High-Resolution Additive Formwork for Building-Scale Concrete Panels, *in* F. P. Bos, S. S. Lucas, R. J. M. Wolfs and T. A. M. Salet (eds.), *Second RILEM International Conference on Concrete and Digital Fabrication - Digital Concrete 2020. DC 2020. RILEM Bookseries*, Springer, Cham.

Panda, B., Mohamed, N.A.N., Paul, S.C., Singh, G.V., Tan, M.J. and Savija, B.: 2019, The effect of material fresh properties and process parameters on buildability and interlayer adhesion of 3D printed concrete, *Materials*, **12**(13), 1-12.

Pham, L., Lu, G. and Tran, P.: 2020, Influences of Printing Pattern on Mechanical Performance of Three-Dimensional-Printed Fiber-Reinforced Concrete, *3D Printing and Additive Manufacturing*, **1**(February), 1-17.

Roussel, N.: 2018, Rheological requirements for printable concretes, *Cement and Concrete Research*, **112**(May), 76-85.

Suiker, A.S., Wolfs, R.J., Lucas, S.M. and Salet, T.A.: 2020, Elastic buckling and plastic collapse during 3D concrete printing, *Cement and Concrete Research*, **135**(January), 106016.

Vos, J., Wu, S., Preisinger, C., Tam, M. and Xiong Neng, N.: 2020, "Buckling Simulation for 3D Printing in Fresh Concrete" . Available from <https://www.karamba3d.com/examples/moderate/buckling-simulation-for-3d-printing-in-fresh-concrete>.

Westerlind, H. and Hern'andez, J.: 2020, Knitting Concrete, *RILEM Bookseries*, **28**(September), 988-997.

Wolfs, R., Bos, F.P. and Salet, T.A.: 2018, Early age mechanical behaviour of 3D printed concrete: Numerical modelling and experimental testing, *Cement and Concrete Research*, **106**(May 2017), 103-116.