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Exploration of the advancements and potential of 3DCP

ABSTRACT

The commercial environment for 3D concrete printing (3DCP) has grown rapidly since its debut, keeping pace with advancements in applicable materials, manufacturing techniques/know-hows and considers the state of the art of 3DCP technology in the construction industry. This paper aims to review current technologies in the field of 3DCP and define how far the technology has reached with the help of some experimental method to realize it in 3DCP houses. For that purpose, this paper starts with a market research, reviewing several promising 3D concrete printers, examples of wall layouts used by several companies, and at last some 3D printed projects already in the world, providing a solid ground of how far did this technology reach.

The second part of the paper reviews the challenges in the printing process and limitations in architectural design to produce a large scale structure using 3DCP , as well as demonstrating a numerical simulation of distinct structures to validate the study’s findings. Moreover, there are some handpicked examples of competitive 3D printers that show great progress in the market, and real-world examples show what results can be expected. This information is then used to find out how 3DCP could evolve in the future and what opportunities this technology might bring.

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Keywords: 3D concrete printing, additive manufacturing, 3DCP specifications, 3DCP market study, challenges, limitations, numerical simulation.

Image created with Adobe Firefly

1. Introduction

There is a common argument that the construction industry frequently encounters difficulties in finishing projects within the allocated time and budget. Additionally, the industry experiences reduced productivity levels compared to other sectors. These problems are worsened by the shortage of skilled labor in both developed and developing nations.[1] 3D concrete printing (3DCP) is a form of additive manufacturing in the construction industry that promises cheaper, more efficient construction process due its less need for labor, faster, more efficient supply chain of materials, elimination of formworks and temporary scaffolding. Moreover, it provides a more flexible way to build freeform buildings with less cost and time than traditional construction techniques. Therefore, 3DCP is recognized as a mean to pave the way for the digitization of the construction industry, encompassing the building process from design to build.

Nonetheless 3DCP is a technology that is still in its infancy, where it still cannot deliver its promises to the construction industry especially for large scale projects. A lot of research has been done to develop this technology as shown in Fig. 1(a), a very steep leap in the numbers of researches was done from the year 2016 to 2022. Showing also that most of the researches that ~~was~~ were done mainly targeted to find the optimal material properties to be used, whereas it includes much more parameters to be developed to achieve its most efficient state. Moreover as shown in Fig. 1(b) the highest number of project done with 3DCP is in the housing industry to try to find an efficient solution for the current housing crisis that is all around the world according to Hilber and Schöni (2022).[2]

There are 3 types of 3DCP according to Mechtcherine et al. (2020) [3] , material extrusion, particle bed binging and material jetting. This paper will mainly review the state of the extrusion based method in 3DCP as it is the most dominant method, in not only small scale projects but also in large scale. By reviewing the latest market available 3DCP, ongoing or completed projects using 3DCP, reviewing previous studies and literature that identifies all main challenges and a numerical simulation technique for 3DCP, this paper is aiming to identify how far did this technology reach and how far it still needs to go.

2. Research Method

To achieve this goal, this paper commences with a thorough market analysis, examining various promising 3D concrete printers, examining wall configurations employed by different companies, and finally, scrutinizing existing 3D printed projects worldwide. This

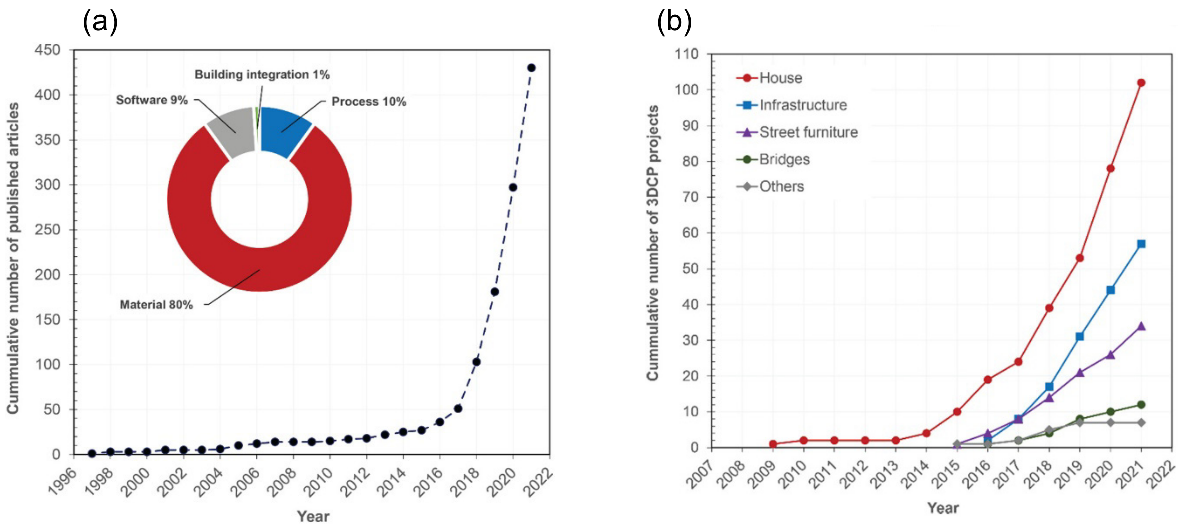


Fig. 1 (a) Trends of scientific publications on extrusion-based 3DCP since 1997 **(b)** Cumulative number of projects sorted by category. Ref.[1]

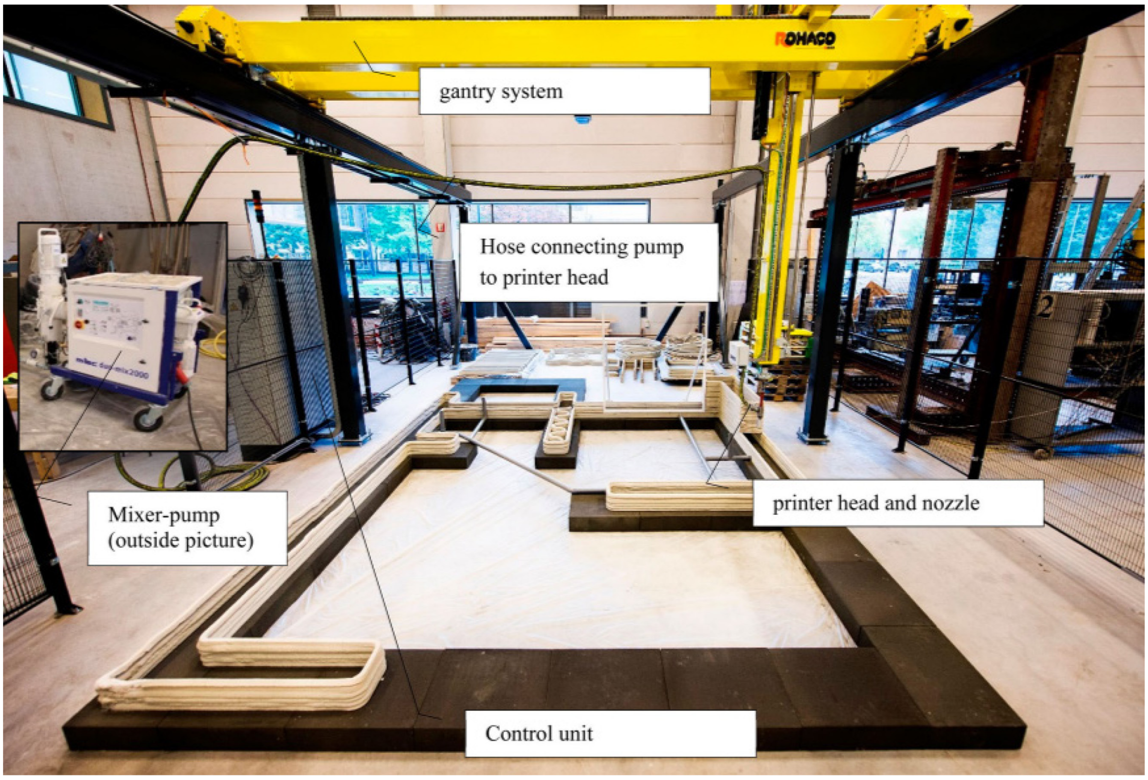


Fig. 2 Printing process using a gantry printer system. Ref.[4]

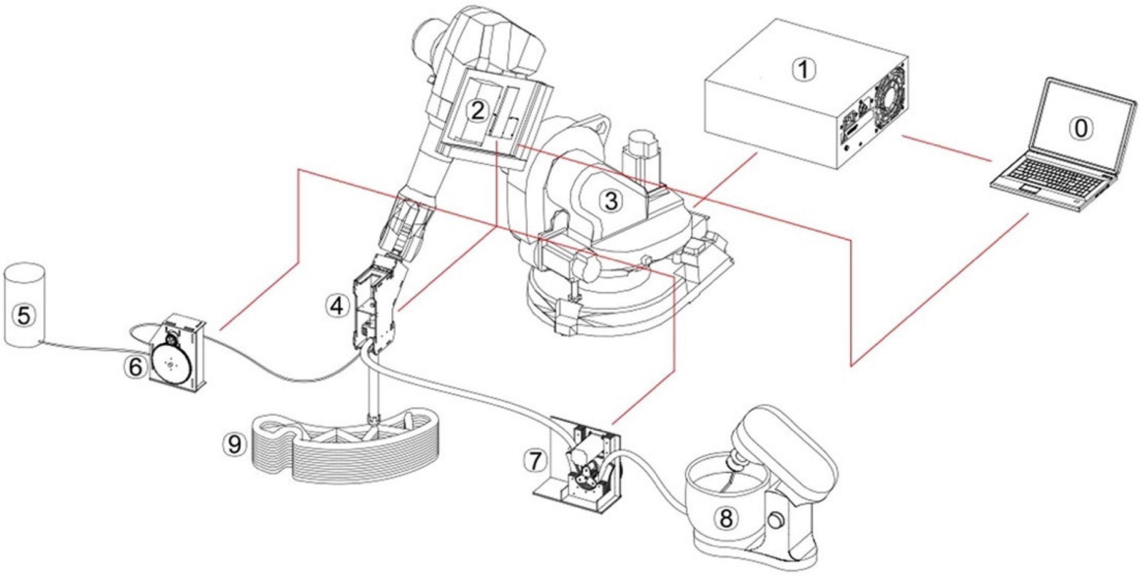


Fig. 3 Printing setup using a robotic printing arm system. Ref.[4]

establishes a robust foundation for assessing the extent of advancement in this technology.

The subsequent section of the paper addresses the hurdles encountered in the printing process and the constraints in architectural design when creating a large-scale structure using 3D Concrete Printing (3DCP). Additionally, it includes a numerical simulation of diverse structures to substantiate the findings of this study. Furthermore, selected instances of competitive 3D printers that exhibit significant progress in the market are presented, along with real-world cases that illustrate the anticipated outcomes. This data is then utilized to anticipate the potential evolution of 3DCP and the opportunities it may present in the future.

3. Market Study

3.1 Printers

There are several different companies which offer specialized 3DCP for on- and off-site manufacturing. These printers can be divided into Robotic printers and gantry systems. The former are 3D printers that use an extruder as the manipulator on a robotic arm of some sort and in the latter an extruder follows along rails which are supported by a fixed metal framework, also called the gantry.

All gantry concrete 3D printers, regardless of the size of the printed element, consist of the following main elements: the actual gantry system, which has a print head and nozzle mounted on it, as well as a mixer pump for mixing concrete and feeding it into the print head, a hose connecting the mixer and print head, and a control computer to monitor and direct the printing process **Error! Reference source not found.**. In Fig. 2(a) layout of a gantry printer is shown. The advantage of gantry systems are the greater accuracy in printing, which also results in smaller tolerances and the ability to expand the work space to a unlimited sizes.

A robotic system on the other hand is quite different, since these systems are usually way smaller and do not require much time to setup. A print head mounted atop of a robot, two pneumatic pumps, one for the premix and one for the accelerator, and a premix mixer, all of which are separate from the print head, and make up the robotic 3D printer. The pumps and the print head are both controlled by a microprocessor. An example for a robotic printer can be seen in Fig. 3.

One company that manufactures a gantry system printer is ICON, their printer, called Vulcan, is able to print on-site and provide a print head movement in all three axes while orienting itself perfectly vertical, which helps improve print quality [1]. Vulcan is able to print objects up to 3.2 m (10.5 ft) tall and 11.125 m (36.5 ft) wide while the length is without limitations, reason is that the system utilizes wheels to move the whole system in one direction [5]. The printer extrudes concrete bead, commonly used term for filament, similar to the FDM printing layer by layer [1].

Lavacrete, ICON's proprietary printing material, is used in conjunction with the Magma cement mixer and ICON's software, called BuildOS, for communication between the components [5].

COBOD designs and provides gantry system printers, called BOD, for automated construction companies. The printhead for BOD 2 is mounted on a metal structure that can freely move in three axes and print walls up to 14.5 m wide and 8.1 m tall at a speed of up to 1000 mm per second. However, this speed is restricted to 250 mm per second by EU standards. The length is, similar to the Vulcan, not limited in regards of, that more frameworks can be added to increase it [7]. The layers extruded from the BOD2 printer are anywhere from 30 to 300 mm wide and anywhere from 5 to 30 mm tall (depending on mortar consistency) [1]. A hopper is installed on the printing nozzle to improve consistency and test materials in small batches. Material feeding can be done by a printhead hopper, Mixer-pump, or reservoir. The BOD2 uses G-code data to create CAD files and sensor mapping to compensate for uneven slabs. [7] Further official printer specifications can be seen in the following tables.

Black Buffalo is another company which manufactures gantry system printers called Nexcon. It can print up to a maximum area of 8m x 8m x 8m and additionally it is able to print up to 3 stories tall. Similar to the BOD2, the NEXCON can be extended by adding tracks. Scalability is achieved by adding additional tracks, allowing relocation without disassembling the printer. The nozzle has an implemented hopper design, cameras, and swappable nozzle tips for different applications. Cleaning of the machine can be done by predefined interfaces and just requires flushing of the machine and rinsing of the nozzle. Black Buffalo also provides their own printing material, called concrete Ink, which is specifically designed to work with the printer[10]. Black Buffalo follows the Occupational Safety and Health Administration's standard of 249 mm per second (9.8 inch per second) [1].

SQ4D is also a company that manufactures 3D printers using a gantry system. Their printer is called ARCS and is like the previously mentioned printers also able to print on-site. Although SQ4D does not mention any specifications, it is known that they printed a 176.5 square meter object in 48 hours of print time [1].

Description	Unit	Value
Product	–	3D Construction Printer
Model	–	BOD2
Measurements (length x width x height)	[m]	Contact us to see size guide
Weight	[kg]	5390
Current	[A]	32
Voltage	[V]	380-480 3 phases, + N + PE (WYE)
Frequency	[Hz]	50/60
Short circuit current IKmin	[A]	500
Short circuit current, IKmax	[A]	1200
Leakage current	[mA]	300
Max. speed (X-axis)	[mm/s]	250
Max. speed (Y-axis)	[mm/s]	250
Max. speed (Z-axis)	[mm/s]	50
Sound level	[dB(A)]	Less than 70
Required bed plate flatness	[mm/m]	10
Movement system	–	Servo
Safety elements	–	The emergency stop function includes emergency stop push-buttons as input components, which are located in the following locations of the machine: • 1x on each of the Z-axis • 3x on the printhead • 1x on the operator's controller panel • 1x on the main E-box
Connection	–	Wifi or LAN
Software	–	Soft-NA and COBOD Web Control Interface
Interface	–	Web Client (through browsers like Chrome, Safari)
Recommended operating temperature	[°C]	5-35

Table 1 BOD2 specifications [8]

Description	Unit	Value
Max printing length	[m]	No limit
Max printing width	[m]	14.6
Max printing height	[m]	8.1 + height of the concrete bases to which the printer is mounted
Max printing speed	[mm/s]	Up to 1000 (1 m/s)
Layer height	[mm]	5-40
Layer width	[mm]	30-300
Material flow	[m3/h]	Up to 7.2
Max aggregate size	[mm]	10
Printer setup time	[h]	4-6
Printer takedown time	[h]	2-3

Table 2 BOD2 additional specifications [8]

MACHINE SPECS	
PRINTABLE STORIES	1-3
RAIL SYSTEM	Stationary
PRINTER SIZE (W x L x H)	14.5m x 11.4m x 10.6m
BUILD AREA	8m x 8m x 8m
WEIGHT	19 tons
NOZZLE SIZE	35-50mm (diameter)
ASSEMBLY	
ASSEMBLY TIME	1-3 days
# OF CONTAINERS	3
# OF OPERATORS	2-3
MISC. MACHINERY	
SILO CAPACITY	10 tons
PRINTHEAD WEIGHT	100kg
POWER	
POWER CONSUMPTION	10 kW
TOTAL CONSUMPTION	33kW
RATED VOLTAGE	AC 3 Phase 220 V
FREQUENCY	50/60 Hz
MIN RATED BREAKING CURRENT	35 kA
MAX RATED BREAKING CURRENT	50 kA
SPEED	
MAX SPEED (X AXIS)	0.25m/second
MAX SPEED (Y AXIS)	0.25m /second
MAX SPEED (Z AXIS)	0.05m /second
PUMP	
ROTOR PUMP	Semi-Automatic
PUMP SOFTWARE	Semi-Automatic

Table 3 NEXCON specifications. Ref. [10]

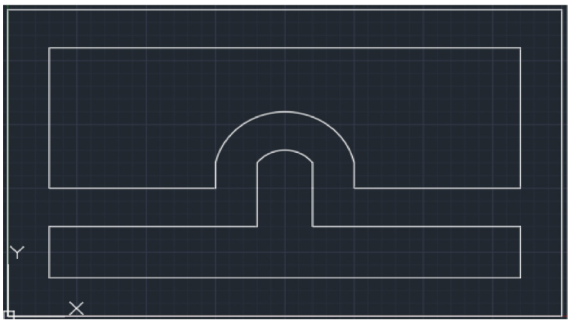


Fig. 2 Drawing Mimicking ICON wall configuration. Ref. [4]

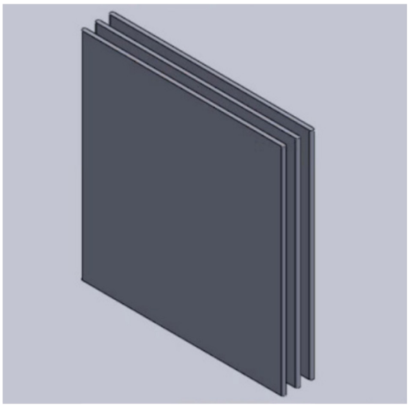


Fig. 5 Drawing Mimicking COBOD wall configuration. Ref. [4]

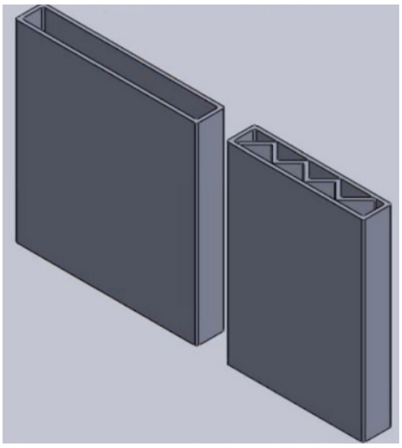


Fig. 6 Black Buffalo wall configuration options [1]

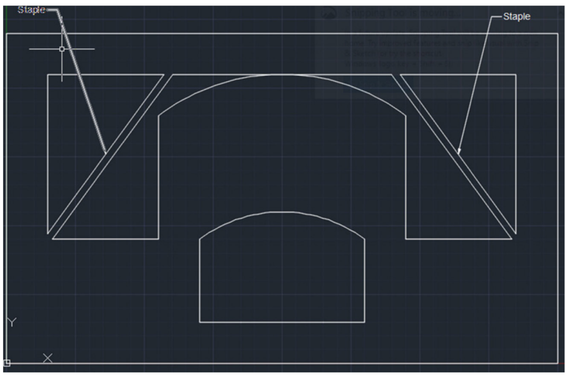


Fig. 7 SQ4D Typica wall configuration. Ref. [4]

CyBe is the first company that manufactures gantry system printers as well as robotic printers. They provide four different printer variations called CyBe G (Gantry), CyBe RT (Robot Track), CyBe RC (Robot Crawler) and the CyBe R (Robot). The Gantry 3D printer is a large-scale, stationary 3D printer used to print prefabricated elements for assembly on site. The robot track system can be used to prefabricate whole houses, with extendable reach for larger printed elements. The robot crawler system is a mobile 3D printer designed for on-site and factory printing, with hydraulic feet and a rotating nozzle to create complex shapes and wall-textures. The robot system is stationary and is designed for off-site and facility-based printing. The work area is shaped like a donut and has a range of 2.65 m x 3.2 m. The printer has a speed of 500 mm/s and can use different types of mortar [12].

3.2 Formwork configuration

Companies design formwork geometries with unique details to ensure stability and thermal insulation [1].

ICON for example prints hollow shells with a special design, which contains three cavity spaces. These cavities then are filled with spray foam for thermal insulation or rebar and concrete for stability [1]. A replication of this design can be seen in the following .

Walls printed by COBOD’s printer are used as formwork for filling material and can be filled with or without vertical reinforcement. Also, for their walls that utilize three cavities, concrete is filled into the interior cavity, while the exterior cavities is filled with insulation to improve thermal insulation.

Black Buffalo prints hollow walls, which then are filled with insulation, concrete, and reinforcement. Also, during the printing metal reinforcement is placed between subsequent layers. Furthermore, Black Buffalo has experimented with zigzag pattern walls to create two cavities, which can be used each for reinforcement and concrete and insulation respectably [1].

SQ4D designs walls acting like formwork. The cavity present within the wall is able to be filled with structural columns, utilities, and insulation. While also putting strengthening materials inside the cavity SQ4D also inserts metal staples in the still wet concrete to better connect the inside and outside layer [1]. An estimated model of this was done with the information found on SQ4D’s website and can be seen in .

3.3 Built Projects

The Chicon house, ICON's first creation, received the first American government approval for a three-dimensional (3D) printed home. ICON used the predecessor of their Vulcan printer to manufacture these houses. All walls (approximately 55.74-74.32 square meters (600–800 square ft)) were allegedly printed in 24h.The house itself cost about $10,000 to print in complete.

Another project of ICON is a whole community with 100 homes including 8 different designs, as shown in the following. These floorplans come in 24 different elecations ranging from 146 to 196 square meter (1.573 to 2.112 square feet). The project is located in Texas Hill country, US, and is called the Genisis Collection at Wolf Ranch. According to ICON, the project finishes in the near future reservations start in 2023 [6].

The first 3D printed house in Borneo, a large island in Asia, was designed by the company SCIB and printed with the BOD2. The house is a 90 square meter 3D printed house completed in around 46 hours. The total length of the print was over 9 km and was extruded in a total of 145 layers each of 2 cm height. Afterwards the walls were plastered to protect the walls from the high humidity which is common in that region.

SQ4D has listed the first 3D-printed home in the United States. The property was printed on-site with the ARCS 3D printer and listed at a price of $299,999, which is around half of what a similar property in the region would cost. This home, built with concrete using the ARCS 3D printer, is located in the United States and has approximately 130 square meters of living space, including 3 bedrooms 2 full bathrooms and an open floor plan plus a 70 square meter car garage [11].

4. Challenges and Limitations

Due to the nature of depositing concrete filament layer by layer, the outcome of the printing process is dependent on the interplay between the material, printing machine, and the design of the object to be printed. Hence, it is imperative to establish a cohesive relationship between these three components, as opposed to solely optimizing individual components [15]. Despite the substantial potential of 3DCP, the technology is faced with a series of challenges and limitations that must be addressed to attain its successful implementation. This brings us to the concept of the buildability of a 3DCP mass. In which it refers to the ability of the printed layers to maintain their shape with the gradual increases of load induced by the and limitations that affect the output of a 3DCP process.

4.1 Challenges in Printing Process

Time Intervals

The interval between each consecutive subsequent layers. The following sections aim to comprehensively state these challenges

layer during the 3DCP process is a crucial factor that can impact both the buildability and the strength of the interlayer bonds. Increasing this interval can result in better stability of the deposited layer's shape but may also decrease the interlayer bond strength due to the higher likelihood of air void formation at the interface. On the other hand, decreasing the time between layers can cause irregular deformations in the printed layers as the bottom layer may not have enough stiffness to support the weight of the next layer. This could ultimately lead to failure of the print as the continued load will become too much for the bottom layer to sustain.

According to a study by Chen et al. (2020) [15], the impact of time interval on air void formation between two consecutive layers was examined. As shown in Error! Reference source not found., the findings showed that before the upper layer was placed, the first layer's cross-section was rough. However, after 20 seconds the upper layer was added, the cross-section revealed a seamless and well-bonded connection between the two

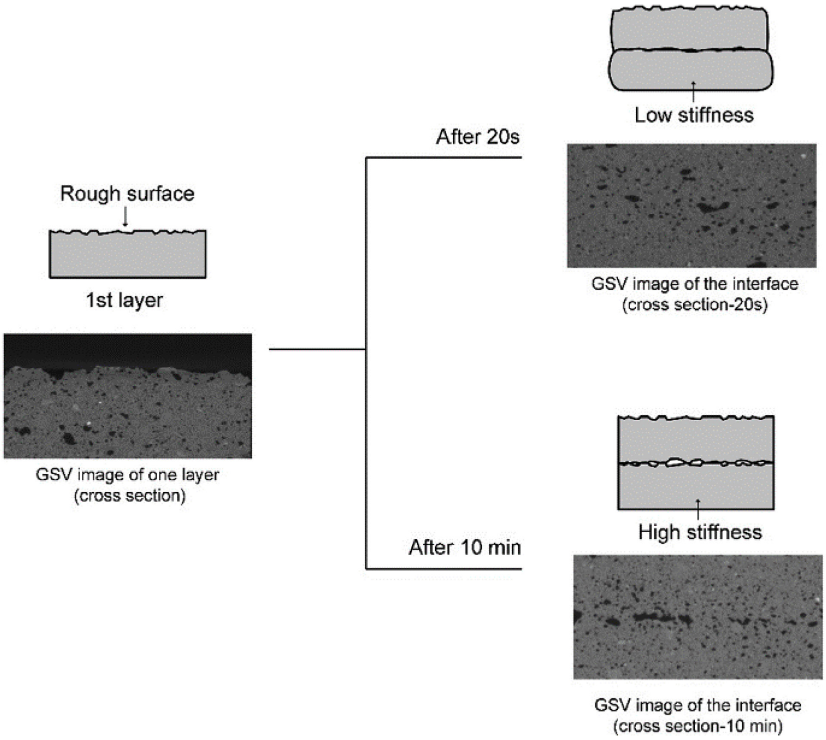


Fig. 8. Illustration of the influences of extending the time interval on air void formation at the interface. Ref.[16]

layers. The bottom layer, however, showed significant shape deformation due to the weight of the top layer. In a second test where the time interval between layers was 10 minutes, the bottom layer showed no deformation, significant air voids were observed between the layers, leading to a weak interlayer bond.

Extrusion Nozzle Variables

Another critical challenge for the buildability of a 3DCP process is the shape of the extrusion nozzle. In the case of a down-flow direction with a round opening Fig. 9**Fig.** (a), the new layer compresses the substrate layer upon deposition, leading to a combination of the weight of the new layer and the force applied by the nozzle acting on the bottom layer. The deformation of the substrate layers can be reduced by adjusting the nozzle standoff distance but may also result in material collapse once the load reaches the yield stress of the substrate, as shown in Fig. 10. A high nozzle standoff distance can cause buckling failure before material failure, which can be exacerbated by misalignment of the printing path or a dropped layer process. Using a back-flow or hybrid back- and down-flow nozzle with a rectangular opening Fig. 9(b) can increase the contact area between layers, resulting in a more stable printing process. [16] [14].

(a)

(b)

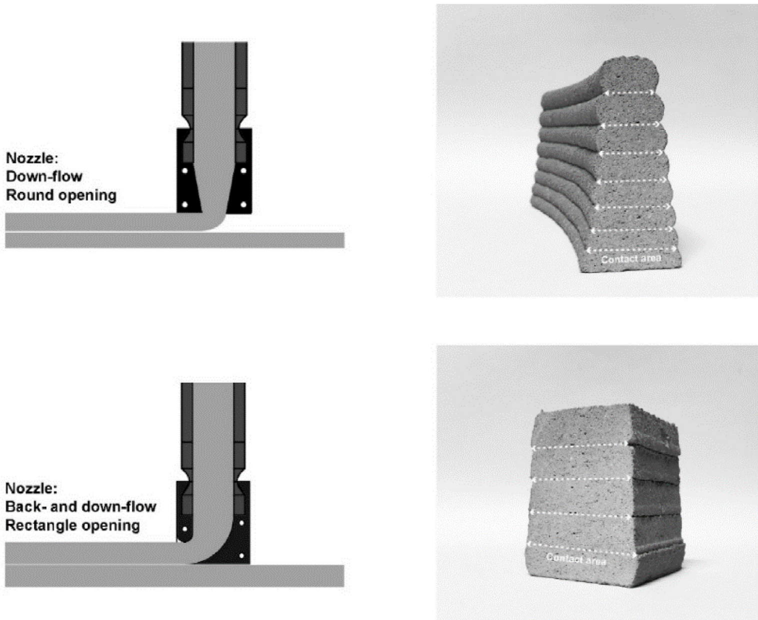


Fig. 9 (a) Illustration of the printing using the down-flow nozzle with a round opening and the cross-section of the printed sample. (b) Illustration of the printing using the back- and down-flow nozzle with a rectangle opening and the cross-section of the printed sample. The dashed line represents the contact area between layers. Ref. [17]

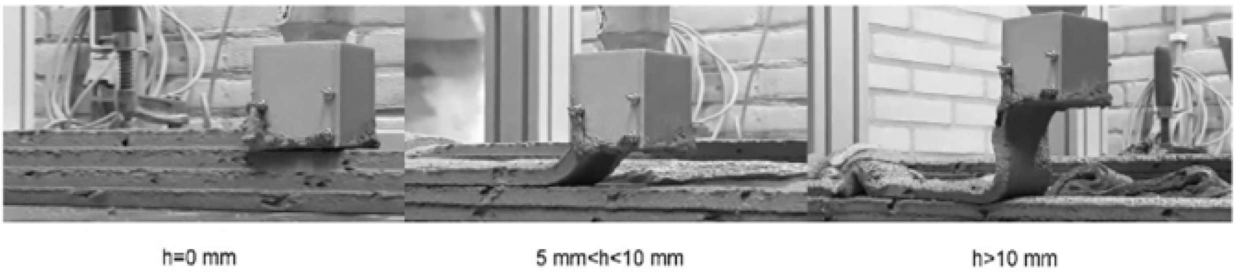


Fig. 10 Increasing the nozzle standoff distance h could lead to the inaccurate layer deposition Ref. [15]

Print Speed / Material Flow Rate

The ratio between the flow of material outside the extrusion nozzle and the speed of the nozzle is one of the other buildability challenges in 3DCP. Tay et al. (2019) [17] conducted an experiment to test the extruded concrete state with different material flow speed and print speed ratios. This experiment was done with all other parameters kept constant. As shown in Fig. 11, high flow rates and slow travel speeds resulted in a larger filament surface area. This was because a greater amount of material was extruded than expected, causing the material to be pushed in the lateral direction onto the substrate.

Although the excess material deposited improved the bonding between layers, leading to better mechanical strength, however, resulted in poor surface finish and poor geometric resolution. On the other hand, large breaks were found in low flow rates and fast travel speeds. These breaks were caused by the disproportionate slow flow rate of the material exiting the nozzle, causing a friction force between the substrate and the material which resulted in shear and breakages. Fig. shows a schematic overview of the results of the experiment and defining it into four regions. Each of which theoretically gives an

expected result for different flow rate and print speed ratio. Stating that printing processes in regions B and C produces the best extrusion output with a sacrifice of either the stability of the extrusion or the overall print time. [17]

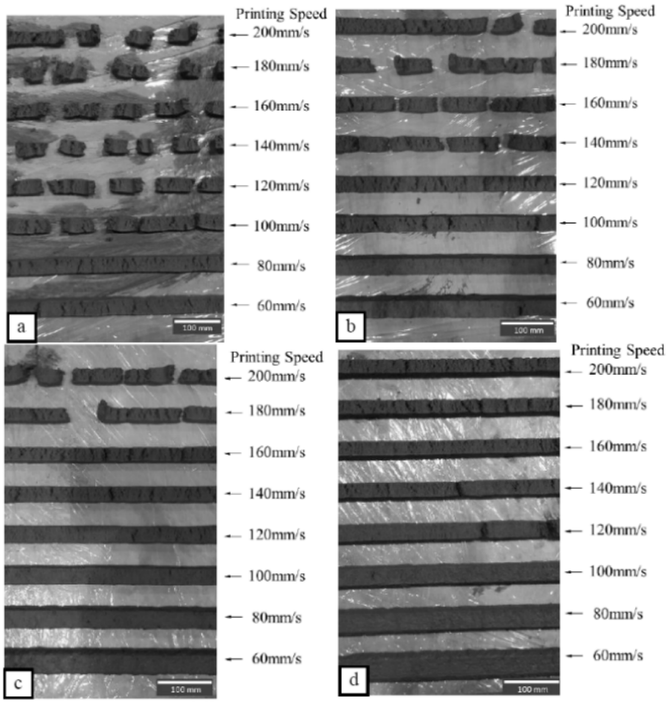


Fig. 11 Filament printed with different flow rate (a) flow rate: 37.9 ml/s (b) flow rate: 45.2 ml/s (c) flow rate: 48.0 ml/s (d) flow rate: 51.3 ml/s. Ref. [18]

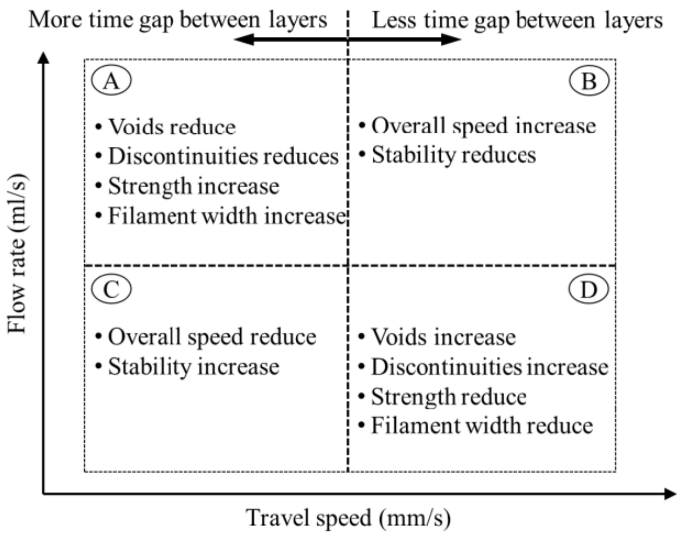


Fig. 12. Effects of flow rate and travel speed on the printed Ref. [18]

As discussed before the structural integrity of the printed layers is one of most crucial parameter to take in consideration in the printing process, whereas in a design point of view the flow rate and print speed ration plays an important role in the final look of the extruded layers. Fig. 12 shows the difference in the final output of a 3DCP object with a well implemented ratio and without.[18] Both experiments look like the object is stable but with the difference in the outer surface finishing quality, however inadequate material deposition can result in even more detrimental effects, such as the formation of voids that can weaken the structure. It is important to be cautious during and after the printing process to enhance the surface quality and precision of the dimensions.[15]

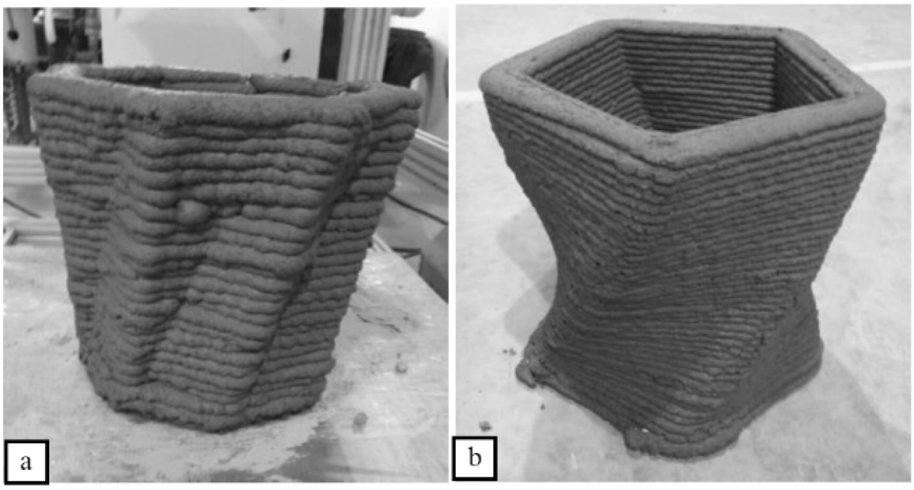


Fig. 12. (a) Poor balance between travel speed and flow rate (b) proper balance Ref.[19]

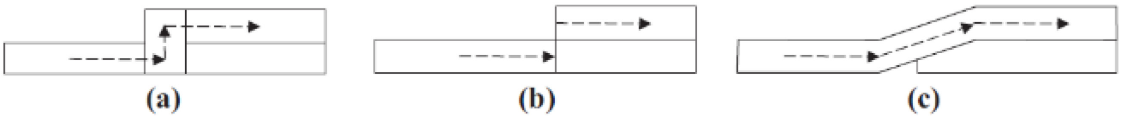


Fig. 13 Stacking strategy. (a)Moving vertically with extrusion. (b)Moving vertically without extrusion. (c) Moving gradually with extrusion. Ref. [19]

Transition to consecutive layer

The stacking of planar extrusion layers is the fundamental concept of 3DCP.In this stacking process a challenge is faced by setting the tool path of the nozzle to increase its height to start extruding the upper layer. Where a sudden up movement would cause a gap in between the endpoints of the printed layer, so some strategies were introduced by Bos et al. (2016) [20]. Fig. 13 shows schematically the tool path strategies that could be used to efficiently transition to the consecutive layer. Fig. 13(a) the toolpath moves vertically from the first layer to the second layer while continuously extruding the filament. This results in a vertical filament being extruded during the layer transition.

However, this vertical filament can be prevented if the nozzle stops providing the concrete material while moving to the next layer, as demonstrated in Fig. 13(b). The third strategy is that the print head moves upward gradually from the printing surface, with the upward movement evenly distributed over a significant portion of the filament deposition plane Fig. 13(c). Bos et al. (2016) stated that theoretically the second strategy shown in Fig. 13(b) would produce the smoothest results with no excess material and no voids between the layers. [20] A note to be taken that, the selection of stacking strategy may depend on material property, desired texture and extrusion mechanism.[19]

4.2 Limitations in Design

Geometry

When designing a structure to be 3DCP, many parameters should be taken into consideration to achieve the buildability and structural integrity of the print. Firstly, are the corners or the transition of the extrusion’s direction of flow on the same plane. Many factors should be taken in consideration while introducing a corner as it causes a disparity in the rate of material deposition between the interior and exterior of the filament, particularly near the corner center Fig. 14. This discrepancy can cause the outer edge of the filament to tear and the section to become distorted if it becomes too pronounced. To avoid these issues, it is necessary to maintain a minimum radius of curvature. However this radius depends on the extruded filament size, material properties, and print speed/flowrate ratio.[17][19][20]

Fig. 14 Excess material deposition while forming a corner. Ref. [24]

Overhangs mean the deviation of the central path of the extruding layer from the previous extruded layer, causing a cantilevered non-centrally stacked layer. Due the influence of gravity on elements that lack support structures and the limited tensile strength of a freshly extruded concrete, deformation or even failure in the print will occur as shown in Fig. 15. Thus, a maximum angle of overhangs should be taken in consideration in the design process to ensure the buildability of the structure Fig. 15(b). This angle is influenced by the properties of the concrete that is used as well as the overall shape of the structure.well as the overall shape of the structure. Concluding from this that in architectural structures openings could be printed with no lintel support to allow the layers to be extruded using the maximum overhangs angle slope design of the opening as shown in Fig. 16. [19][17]

Build Area

According to Appolloni and D'Alessandro (2021) [21] the minimum livable housing requirement for a single person is an area of $6m^2$ and a height of 2.4m. Thus, in large scale printing process the build area is limited by the size of the printer. As shown in Table 4 the available capacities of 3DCP printers in the market thus architectural designs are limited with those dimensions. Furthermore, using a relatively large 3DCP with a single nozzle for the printing process may result in a prolonged build time as well as creating a new challenge of transporting and setting up the printer on the site. (Ko, 2021b). [19][24]

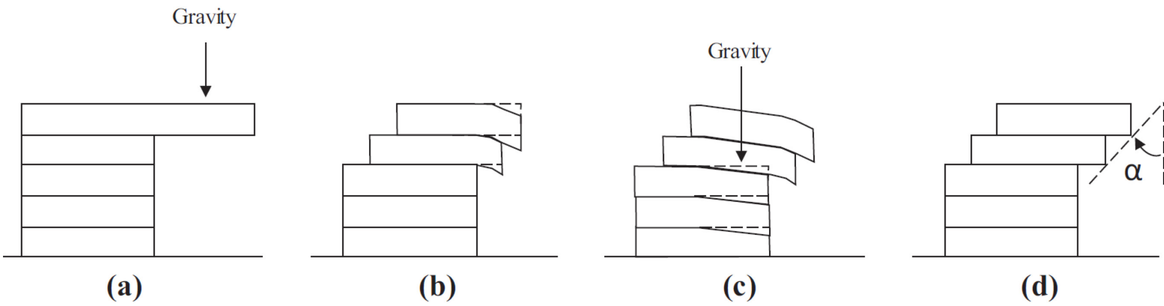


Fig. 15 Overhanging issues (exaggerated for demonstration). (a) Gravity effect. (b) Overhanging deformation. (c) Uneven deformation. (d) Overhanging angle (α). Ref.

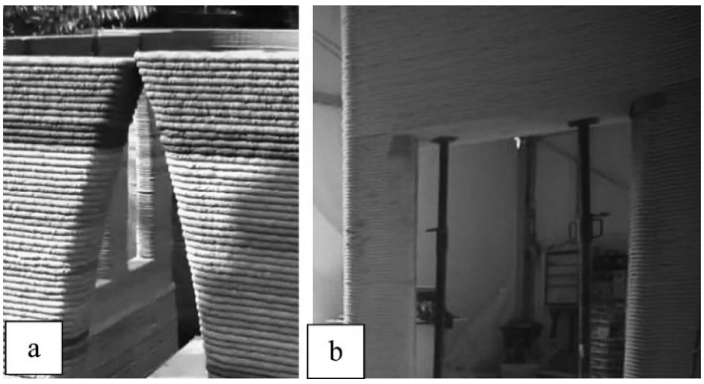


Fig. 16 Different techniques used for printing overhangs. (a) support-less closed structure design to support subsequent overhanging layer (b) wood planks with supporting scaffolding. Ref.

Manufacturer	Model	Process	Type of System	Materials	Capacity (m)
BETABRAM	*P1V2*	*Extrusion*	*Gantry Based*	*Concrete*	*16 × 8.2 × 3*
COBOD	*BOD2*	*Extrusion*	*Gantry Based*	*Concrete*	*1.9 × 2.1 × 1.5*[a]
Constructions-3D	*Maxi Printer*	*Extrusion*	*Robotic Arm*	*Concrete*	*13 × 13 × 10*
CYBE	*RC 3DP*	*Extrusion*	*Robotic Arm*	*Concrete*	
ICON	*Vulcan II*		*Gantry Based*	*Concrete*	*8.5 × 8.5 × 2.6*
MUDBOTS	*3D Printer 664*	*Extrusion*	*Gantry Based*	*Concrete*	*1.8 × 1.8 × 1.2*
	3D Printer 10,108				*3 × 3 × 2.4*
	3D Printer 18,189				*5.5 × 5.5 × 2.7*
	3D Printer 25,259				*7.6 × 7.6 × 2.7*
	3D Printer 252,512				*7.6 × 7.6 × 3.6*
	3D Printer 50,509				*o*
	3D Printer 501,009				*15 × 30 × 2.7*
TOTAL KUSTOM	*Stroy Bot 6.2*	*Extrusion*	*Gantry Based*	*Concrete, Polymer, Ceramics*	*10 × 20 × 6*
	Stroy Bot 7.1				*10 × 20 × 4*
	Labyrinth 3D				*5 × 5 × 3*
	Architect's Printer				*1 × 0.5 × 0.5*
WASP	*Crane WASP*	*Extrusion*	*Delta*	*Earth-based, concrete, Geopolymer*	*Ø 6.3 x 3*

[a] Custom Configurations offered.

Table 4 Commercially available Concrete 3D printers. Ref.[25]

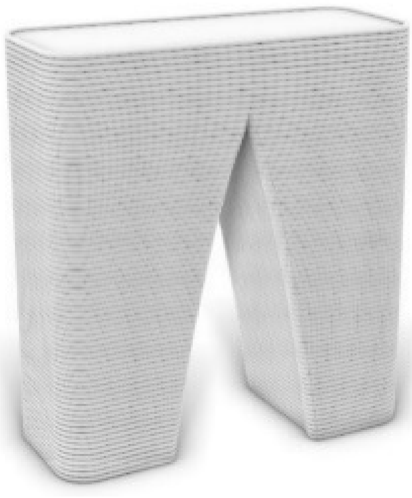
5. Numerical Case Study

The aim of this case study is to evaluate the buildability of three distinct 3D concrete structures using numerical simulation using CobraPrint (Rhino3D Grasshopper plugin) and Abaqus software, as well as testing the reliability of this type of simulation. The buildability of each structure was evaluated by changing a single factor, the print speed (mm/s), while keeping the material properties (Table 5) constant throughout the simulation. The study focused on the structural integrity of the printed objects , and the analysis was

Density	**2500 kg/m³**
Young's Modulus	0.0032 * t + 0.048 N/mm²
Poisson's ratio	0.22
Cohesion	0.00003 * t + 0.004 N/mm²
Friction angle	20°
Dilation angle	13°

Table 5 Material constant properties used in the numerical simulation.

(c)



(a)

(b)

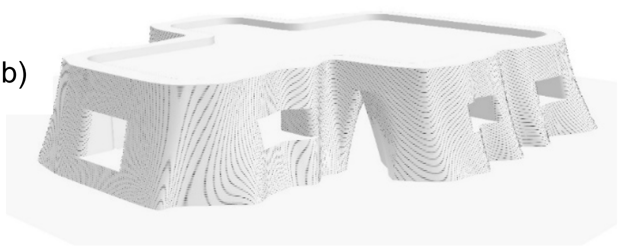


Fig. 17 (a)Structure I a semi roofed dwelling (b) Structure II was an extremely curved organic wall with an incline, (b) Structure III was a wall section with a door opening without the use of a "Lintel" support.

conducted without taking into account the presence of any openings. This study provides valuable insights into the buildability of 3D concrete structures and deformation of the mass due to the impact of print speed on the printing process, as well as an overview of the technical issues and analyze the numerical modeling and simulation techniques that have been used in related literature.[24][26]

5.1 Simulations Results

Structure I

In this simulation it aims to test the ability of printing of a dwelling (Fig. 18 (a)) that could be printed with the least about of human intervention in the building process by printing most of the roof of the mass with the maximum overhang angle of 45° was used as discussed previously. The material properties used in all the study was constant as stated before and is shown in Table 5.

As shown in Fig. 18 three trials were done on the dwelling structure. In the first trial Fig. 18 (a) a print speed of 100 mm/s was used. The simulation failed at the 14th layer which is at the height of about 3.4 meters or in other words the interlayer connection between the 14th and the 13th printed layers was not sufficient enough to receive further layers to print.

Thus, the high value of deformation so the misalignment of the layers to occur. Lower speeds was simulated at 60 mm/s (Fig. 18 (b)) and 15 mm/s (Fig. 18 (c)). In the 60 mm/s simulation it failed for the same reasons as the 100 mm/s simulation, but the deformation of the structure was less and continued till the 20th layer which is equivalent to the height of about 4.8 meters. A full print was achieved at the speed of 15 mm/s, the result will be discussed further in section 0.

Structure II

Structure II Fig. 19 was simulated to test an exterior walls of a 3 room house, its design aimed to show how 3DCP build organic formed walls with lower cost than traditional construction. The maximum overhang angle used to design the walls was 30°. Three simulations were done at 100 m/s, 70mm/s, and 25 mm/s.

Fig. 17 shows the results of 70mm/s (Fig. 19) and 25 mm/s (Fig. 20), whereas at speed 100 mm/s the speed was so high for the size of the structure so after printing the first layer the second layer was immediately misaligned with the first one as the deformation was too high.

As for the second simulation (70 mm/s) the simulation failed the 12th layer which is equivalent to a height of 2.3 meters, as the walls on the sides of the structure had a very high overhang angle similar to the rest of the building whereas it has a straight section profile thus there was no perpendicular

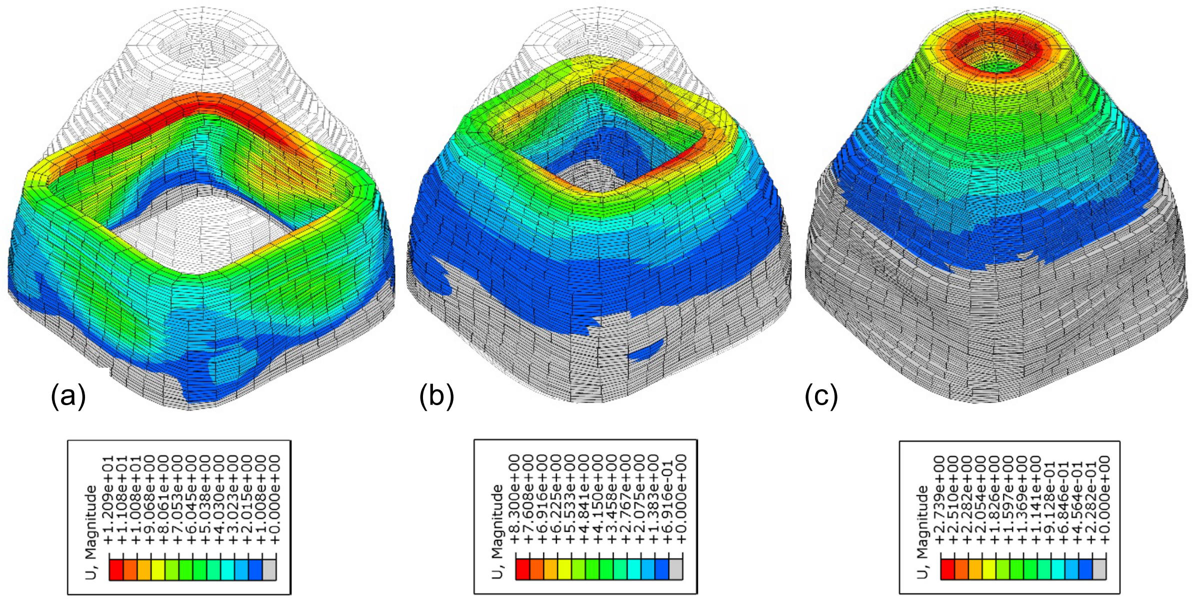


Fig. 18 Simulation final output at speeds: (a) 100 mm/s (b) 60 mm/s (c) 15 mm/s.

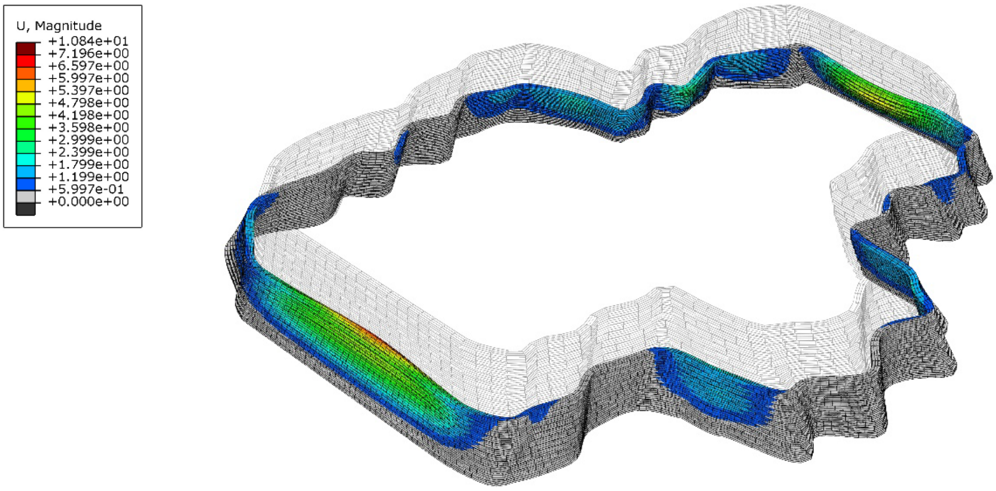


Fig. 19 Simulation of Structure II at speed 70mm/s.

(b)

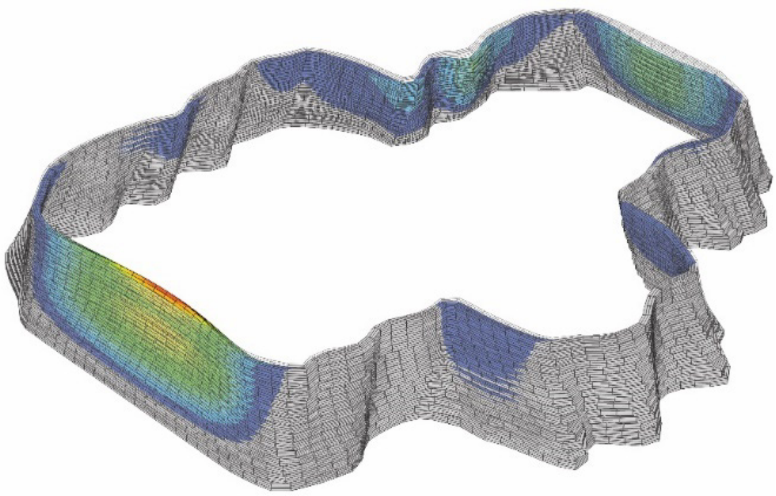


Fig. 20 Simulation of Structure II at speed 25 mm/s.

support to hold its weight while printing at this speed, before the concrete hardens and be able to sustain the compression caused by the upper layers overhangs. Furthermore, at speed 25 mm/s the print was successful and detailed analysis will be discussed in section 4.2.

Structure III

Lastly, a numerical simulation was performed for a section of a wall opening resembling a door as discussed in section 4.2. This way of design could open ways to create opening in 3DCP without any external support, but it raises the question of the value of architectural design aesthetics and functionality. However design has no limits and merging it with modern technologies could allow us to do what is now called the impossible. The door section has an overhang angle of 13° and not symmetrical, 2 simulations was done for this structure one at print speed 50 mm/s Fig. 21(a) and 10 mm/s Fig. 21(b). The 50 mm/s speed failed at the 11^{th} layer (height=3.1 meters) as the 2 sides of the mass got highly deformed and buckled not allow further layers to be printed. Whereas at speed 10 mm/s the print was successful with minimal deformations.

5.2 Simulation Findings

As seen clearly in the sections of the three simulations done (Fig. 22) the deformations are of a very high value which is imminent due to the elasticity property of the concrete used. On the other hand, as stated before the main purpose of this study was to test the effect of print speed on the value of deformation of the printed object, and that was proved positively. Form literature review it states techniques are

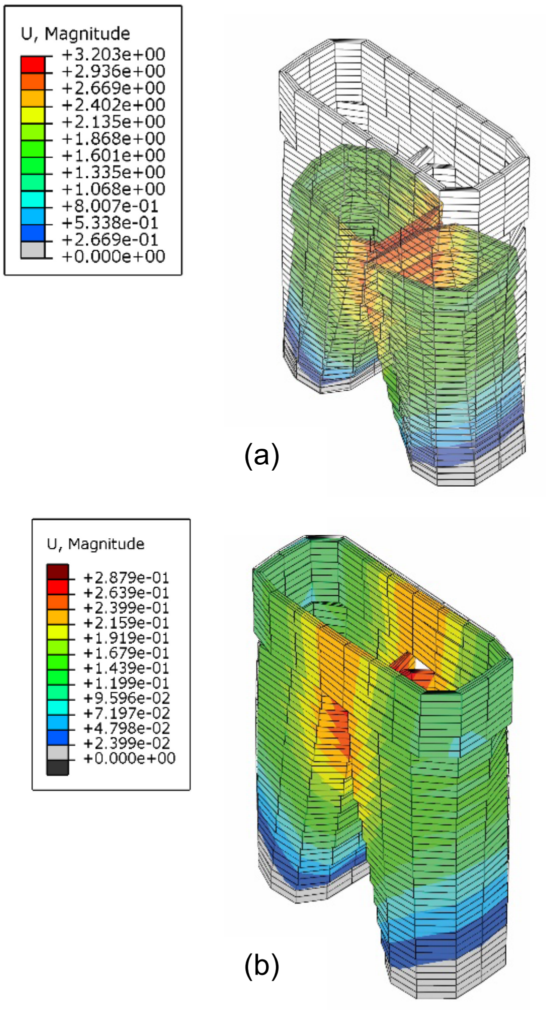


Fig. 21 Structure III simulation results at speeds: (a) 50 mm/s (b) 10 mm/s

used to spray or add rapid hardener to the extruded concrete to decrease the amount of time the concrete needs to have sufficient tensile strength to receive new layers loads, thus having a fast print speed with near to zero deformation in the structure.

Analyzing structure I Fig. 22(a), the final print was printed with all layers but due to the deformation and compressive loads the whole structure buckled downwards. whereas due to very long section of continuous overhangs , structure II Fig. 22(b) showed high tensile stress in the straight sections of the print with a very high deformation value but due to the slow print speed the concrete layers had strong interlayer bond to withstand the tension. Finally in Structure III (Fig.22 (c)) due to the compact design the deformation was not very high where as in the high print speed it collapsed after relatively low height. This proves that print speed cannot be a fixed number for all prints, it involves a study of the shape of the mass, material properties and much more.

This technique of simulation is very primary that does not take into consideration a lot of factors in 3DCP, which is a complex process and involves various physics stages, making it difficult to determine the impact of each parameter on mechanical performance during printing. Thus, the optimal process parameters are typically developed by trial-and-error experiments, which is time-

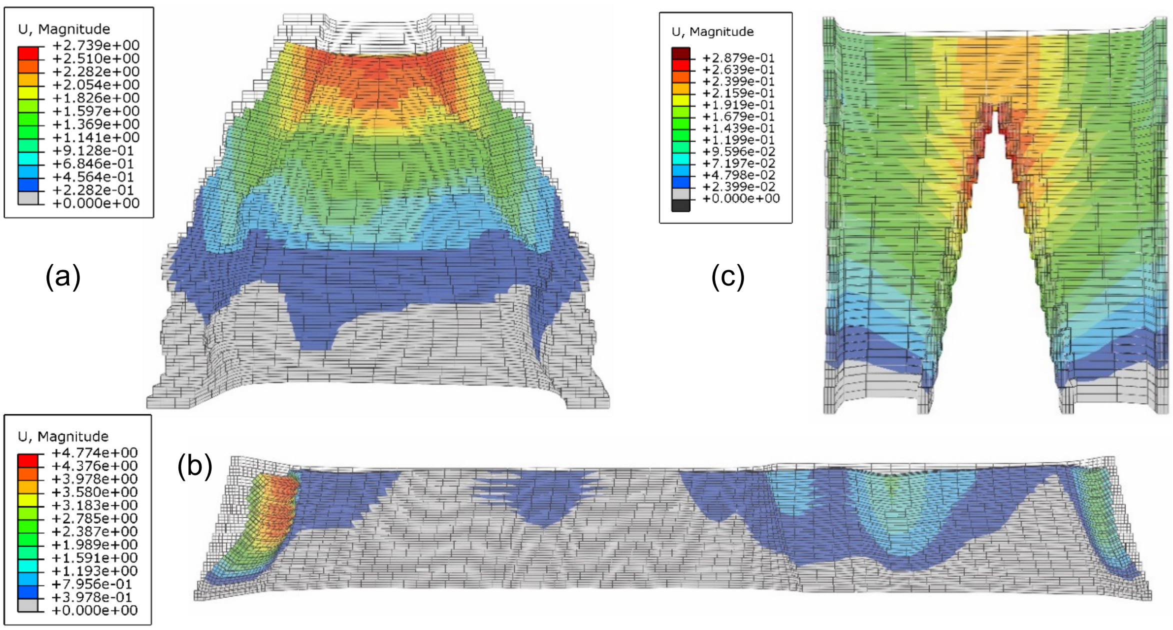


Fig. 22 Sections showing deformation of structures after print. (a) Structure I (b) Structure II (c) Structure III.

consuming and expensive for large structures. Numerical modeling and simulations are essential to predict material performance and avoid extensive trial-and-error, particularly for mature, larger-scale applications of 3DCP. [25]

6. Conclusion

Concluding from the market study , literature review and numerical simulation:

- High opportunities in market available 3DCP where presented, each type of printer has its pros and cons . As gantry systems has its advantage of high precision while a huge drawback in assemble and setting up it. On the other hand, robotic 3DCP are more compact and easier to set up, whereas produces less accurate extrusion-based prints.
- Market available 3DCP promises high speed printing, however, in realty due to the structural integrity for the prints, lower speeds are used and are not shared publicly to find solutions to make the technology faster, thus slowing the rate of development of 3DCP in construction.
- Due to the market competition 3DCP developments are taking a slow track due to the lack of information sharing.
- Standardized testing procedures should be implemented to make information sharing more efficient and reliable.
- Further investigation and research are required to enable greater integration of the technology into construction, as is the case with additive manufacturing in other sectors, in order to take advantage of the advancements made so far.
- Guidelines for geometry design and build tolerance control are required for better building integration, making 3DCP more buildable and reduction in testing costs.
- The importance of a more reliable digital twin or simulation of the printing process needs to be developed to make the technology develop in a faster rate and reduce experimentation costs is crucial.

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