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Robotic 3D Printing on inclined surfaces using adaptive formwork principles for prefabricated curve-like structures

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Abstract
3D Printing is revolutionizing the production of prefabricated modular structures in real scale. In the case of curve-like structures, the process mainly focuses on planar 2.5D Printing of modules due to geometrical and overhanging constraints. To overcome these limitations, the current work refers to the application of a robotic 3D Printing approach on inclined surfaces using cement-based material mixtures to produce prefabricated segments based on adaptive formwork principles. The approach aims to examine the effectiveness of the adaptive formworks to be applied in 3D Printing of inclined prefabricated modules, and in parallel to analyze results regarding their limitations and advantages occurred during 3D Printing in different size of curved segments, inclinations, and nozzle orientations. Initially, the study introduces three different surface types derived from a proposed adaptive pin-bed formwork, that are physically printed using respective disposal formworks. These initial experimentation aims to analyze 3D printed results in relation to the optimal number of layers of filament that can be printed, the width and height of printing filaments in each layer, the angle of printed material deposition before its potential instability (start falls) and, finally the appropriate composition of material mixtures and their ratio density (cement, sand, water, and superplasticizer). Then, the work introduces a shell structure, aiming to examine the joints of prefabricated parts through 3D Printing, and to provide the framework for the effective buildability of prefabricated curve-like segments on inclined surfaces towards their construction automation.

Keywords: Inclined surfaces, Prefabrication, 3D Printing, Construction scale, Cement-based materials.

1. Introduction
The evolution of computational design and digital fabrication applied for the development of complex structures has significant growth in architecture and construction industry in the 21st century. Since 1939 and the first 3D printed building using cement-based materials [1] there has been an increased tendency in research dealing with new digital fabrication strategies using different mechanisms as well as design methodologies. Among others, strategies include the application of adaptive or reusable molds for the development of complex morphologies and the application of 3D Printing techniques for the construction of prefabricated components that can be supported by formworks during assembly stage.

Nowadays, 3D Printing shows great potential for development with several case studies and projects being demonstrated in this direction. Projects include among others, the world's first 3D printed office building in Dubai [2], the 3D Housing 05 made by Arup and CLS Architects [3], the Europe's first 3D printed fully completed and furnished building located in Copenhagen [4], the 10 3D Printed Houses in China, the Stupino House in Russia, the YHNOVA House in France and the first two-story (371m2) 3D-printed concrete house in Huston [5].

On the other hand, obstacles are observed mainly in relation to the printing of complex geometries. For instance, extrusion-based 3D Printing is mainly applied to 2.5D shapes, limiting the printing of highly curved shapes. Only few examples have been implemented in real scale, attempting to combine advanced strategies like 3D Printing and formwork as support structures. Projects, among others, include the structural design and engineering of Striatus arch bridge in Venezia, a project designed by Block research group and Zaha Hadid architects. This project, with a total of 50m2, was an unreinforced masonry bridge composed of 3D-printed blocks made of concrete. The blocks were assembled and joined without mortar on site using a wooden framework as a supporting structure. Instead of applying 3D Printing based on typical horizontal deposition of concrete material in layers, the blocks were produced based on specific 3D Printing toolpath strategy at specific angles that were perpendicular to the flow of compressive forces. This was done to keep the layers of blocks well pressed together and to avoid the necessity for extra post-tensioning or reinforcement [6].

In another example, the 4TU research team used an adaptive temporary mold surface for the 3D printing of a shell outline and then for concrete casting used as infill in the body of shape. The ending result was a 2.5m x 2.5m shell structure that was partially 3D printed. The maximum 3D Printing slope was 35 degrees and the minimum turning radius was 150mm. Finally, a total of 9 partially printed panels were assembled through mortar joint to create a pavilion structure [7]. One of the main problems in 3D Printing with cement-based materials is the withstand in tensile forces without the use of reinforcing bars. In another project, a shell-shaped bench was developed with dimensions 7m x 5m x 2.5m. By using topology optimization, high structural rationality of the composite structure was derived, where the outer part was 3D printed, and the inner part was filled with ultra-high strength fiber reinforced concrete as a substitute of reinforcing bars [8]. Finally, in another example, an approach that included a multi-axis 3D Printing on a reconfigurable supporting system was introduced for the development of a material reduced shell structure using topology optimization principles to minimize the self-weight of the panels. Towards this direction, a temporary polystyrene mold was used as the supporting base for the 3D Printing of clay-based prefabricated parts, which formulated a pavilion structure [9].

The literature review has shown that several issues require further research and development in this direction. Also, more investigation is necessary, as most of the examples are limited either in the introduction of 2.5D contour crafting printing or in the introduction of methods where a mold is used to print the exterior parts of the shape and then the interior is casted with concrete. In addition, issues that require further investigation include design and assembly methods of prefabricated parts, identification of the maximum loads that structures can support and of the maximum and desired number of layers to be printed. Furthermore, issues regarding the detail of assembling the structural parts are important and require further investigation.

Through the literature and the knowledge derived from the construction industry, it can be observed that an economical solution to produce inclined panels is by using adaptive or variable molds [10]. This method provides a waste reduction of material used through the reuse of the same mold and it is less time consuming due the mold fitting time and the workforce required to fulfil the abovementioned tasks, leading to an overall reduction of construction cost. The use of adaptive mold in combination with 3D Printing has the potential to offer complete solutions for the construction of structural panels, providing improved construction and assembly methods that can overcome the existing barriers in the literature.

The following chapters of this paper present an offsite robotic 3D Printing process, considering existing limitations regarding 3D Printing of shell structures [11]. Starting with a preliminary investigation into the 3D Printing of samples on curved surfaces and after drawing some preliminary conclusions related to material mixture to evaluate the printing process parameters and production process, the work proceeds with the presentation of a case study. This refers to the design and 3D Printing of shell's structural parts, emphasizing their connection details. To validate the approach, several 1:2 and then 1:1 scale 3D Printing experiments are conducted, results are reported, and conclusions are drawn.

2. Methodology and process development

This research study focuses on 3D parametric modelling and 3D Printing on inclined surfaces for geometrical and material behavior testing of curve-like prefabricated parts. The 3D Printing is executed on inclined disposable molds to achieve the minimization of material waste and the reduction of construction time during the production of various curved-like shapes in actual scale. To achieve this, a series of methodological steps have been followed to eliminate the errors that might be encountered during the development of an overall 3D Printing process of a shell structure. Hence, this research examines: (a) Various surface curvatures, from flat surfaces to single and double surface curvatures, to check maximum and minimum possible overhanging limitations during the 3D Printing process, (b) The maximum possible 3D Printing angle of the nozzle that is mounted on the robotic arm before the concrete falls, (c) The composition of cement-based material mixtures to ascertain optimum printability, and (d) The design and 3D Printing of connection joints between prefabricated parts.

2.1. Design and preparation of the shell units

A total number of forty (40) different inclined surfaces have been designed as results of the adaptive formwork variability. Among them, four (4) inclined surfaces shown in Figure 1, covering a completely different case scenarios, have been selected for further experimentation. Three (3) of them have been processed for 3D Printing experimentation in the lab using an ABB industrial robot as shown in Figure 1 (i, ii and iii). The experimentation focused on determining the optimal material mixture, the width and height of printing filaments, the buildable number of filaments and the angle of printed material deposition before is starts falls.

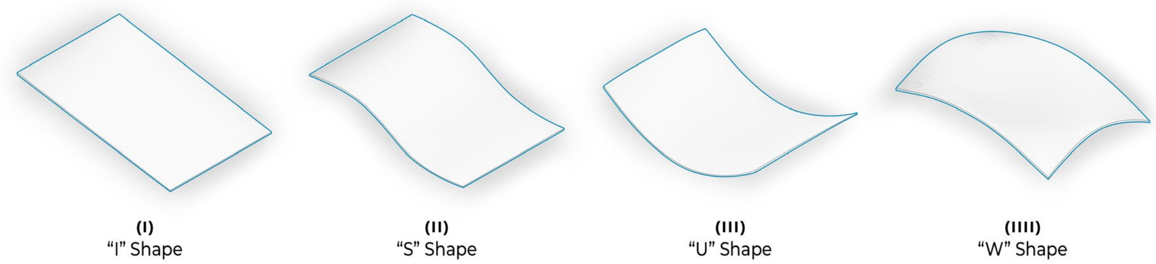

Figure 1: Four (4) inclined surfaces selected to be 3D printed

2.2. Material investigation

Through research and testing of various materials, such as cement and clay, cement was selected as the optimal one for 3D Printing due to its durability, cost-effectiveness, and suitability for use as material of implementation in real scale prefabricated parts.

The material mixture composition was Cement 40.42%, Sand 42.11%, Water 17.29%, and Superplasticizer 0.16%, with water/cement ratio 42.7%. (Table 1). This mix was tested and used during the winter period and the sand was slightly wet due to the weather conditions.

Table 1: Material mixture ratios and trial of 3D Printing in shape (C)

CASE STUDY	TRIALS	TEMPERATURE	LAYERS	MIXTURE			ROBOT HEIGHT / ROBOT SPEED	SUCCED / FAIL
				CEMENT	WATER	CLAY		
	1	26-30oC	1 Layers	15000gr	6200ml	14700gr	Height: 25mm / Speed 60	F
	2	26-30oC	1 Layers	15000gr	6200ml	14700gr	Height: 25mm / Speed 100	F
	3	26-30oC	2 Layers	15000gr	6200ml	14700gr	Height: 22mm / Speed 160	F
	4	26-30oC	3 Layers	15000gr	6200ml	14700gr	Height: 18mm / Speed 160	F
	5	26-30oC	4 Layers	15000gr	6200ml	14700gr	Height: 18mm / Speed 160	S

SECTIONS

	1		2		3		4		5		6		7		8	
	H	T	H	T	H	T	H	T	H	T	H	T	H	T	H	T
Layer 1	16mm	44mm	17mm	26mm	17mm	29mm	17mm	26mm	17mm	29mm	17mm	26mm	17mm	29mm	17mm	26mm
Layer 2	17mm	26mm	18mm	26mm	17mm	29mm	17mm	26mm	17mm	29mm	18mm	26mm	18mm	29mm	17mm	26mm
Layer 3	17mm	26mm	18mm	26mm	18mm	29mm	17mm	26mm	18mm	29mm	18mm	26mm	19mm	29mm	17mm	26mm
Layer 4	18mm	26mm	20mm	26mm	20mm	29mm	18mm	26mm	20mm	29mm	20mm	26mm	20mm	29mm	18mm	26mm

	9		10		11		12		13		14		15	
	H	T	H	T	H	T	H	T	H	T	H	T	H	T
Layer 1	17mm	29mm	17mm	26mm	17mm	29mm	17mm	26mm	17mm	29mm	17mm	26mm	16mm	26mm
Layer 2	19mm	29mm	18mm	26mm	18mm	29mm	17mm	26mm	18mm	29mm	18mm	26mm	17mm	26mm
Layer 3	19mm	29mm	18mm	26mm	19mm	29mm	17mm	26mm	19mm	29mm	18mm	26mm	17mm	26mm
Layer 4	19mm	29mm	20mm	26mm	20mm	29mm	18mm	26mm	20mm	29mm	20mm	26mm	29mm	26mm

2.3. First experiment - 3D Printing on inclined surfaces

To carry out the experiment, three (3) stages were followed, and the results derived in each stage provided feedback for the next experimentation (Figure 2).

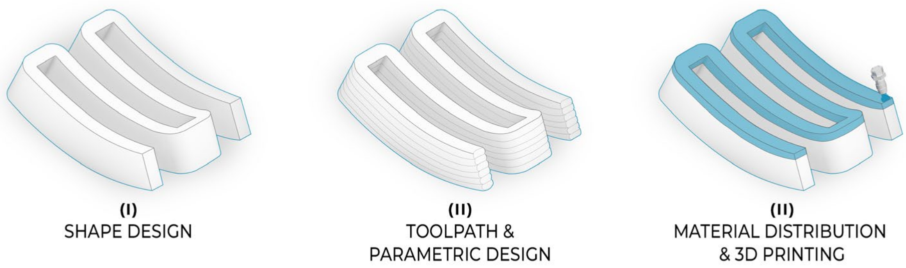

Figure 2: From design to printing phase on a curved surface (i) Shape design, (ii) Parametric design of the shape and preparation of the toolpath, (iii) Distribution of material during the printing process

2.3.1. 3D Printing pre-processing

The parametric design of shell structure aims at achieving flexibility and offers the possibility in selecting and modifying different shell shapes, using either two (2) or four (4) bases. For the purposes of this research, the three (3) selected printing examples as shown in Figure 1 (i, ii, and iii) have been examined. Initially, the printing environment and preparation of the proposed geometry has been achieved in the parametric design plug-in of Grasshopper. The robotic tool-path planning was developed in the Taco ABB plug-in [12] for Grasshopper, integrated with an in-house algorithm that achieves 3D Printing control seamlessly from design to robotic 3D Printing [13].

Figure 3 shows changes of the angles of the extruder in a linear movement until an entire line form (p1) to (p15) was printed using the extrusion-based 3D Printing approach with layers deposited layer by layer.

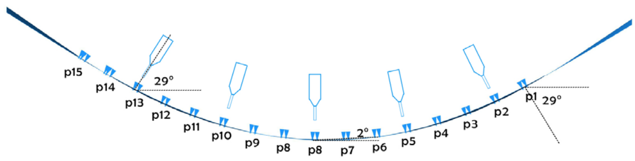

Figure 3: Different angles of extruder during the 3D Printing process

It was predetermined that two (2) different cases would be printed for each suggested geometry yielding a total of eight (8) unique case studies: (a) Vertical nozzle orientation of 90 degrees for four (4) layers, and (b) Vertical nozzle orientation of 90 degrees for six (6) layers.

2.3.2. 3D Printing of first experimental case study

The 3D Printing process aims at evaluating the approach and extracting information related to associated issues like the material mixtures, the printing speed, printing height and the durability of the printed inclined surface (Figure 4). More specifically, the four (4) inclined surfaces were tested by simulating the 3D Printing toolpath and then, the information was transferred to the robot for the 3D Printing process. To achieve a successful printing of the process (a) and (b), a total of nineteen (19) printing trials were conducted.

The extruder for 3D Printing was based on a pipe built into a pump mechanism and was used to control the speed and pressure of the material being ejected by the robot. In addition, for laboratory purposes, an independent hand-made formwork made with a polystyrene base was used. The prototype was physically implemented in 1:2 scale in the laboratory to evaluate the process based on construction-scale printing.

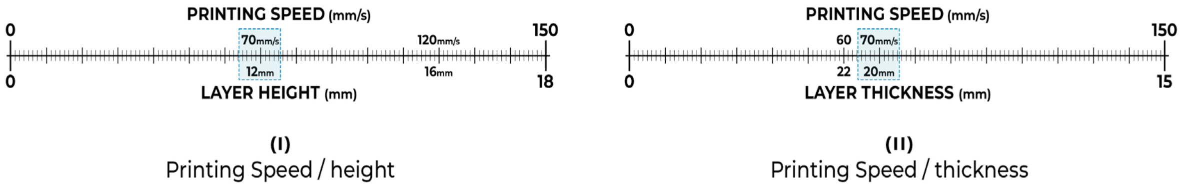

Figure 4: Different speed used (i) Printing speed / height, (ii) printing speed / thickness

2.3.3. Correlation between physical and digital results

Through the data extracted, it was evident that both the 4-layer and 6-layer prints had significant sedimentation in their lower sections, ranging from 12% at central points to 33% at the sides (Figure 5). In some cases, failures were observed due to continuous printing at a constant tilt of 9.5 degrees. However, in the cases where there was higher slope variation, ranging from 1 to 31.8 degrees the results were milder with sedimentation from 9.5% to 12%.

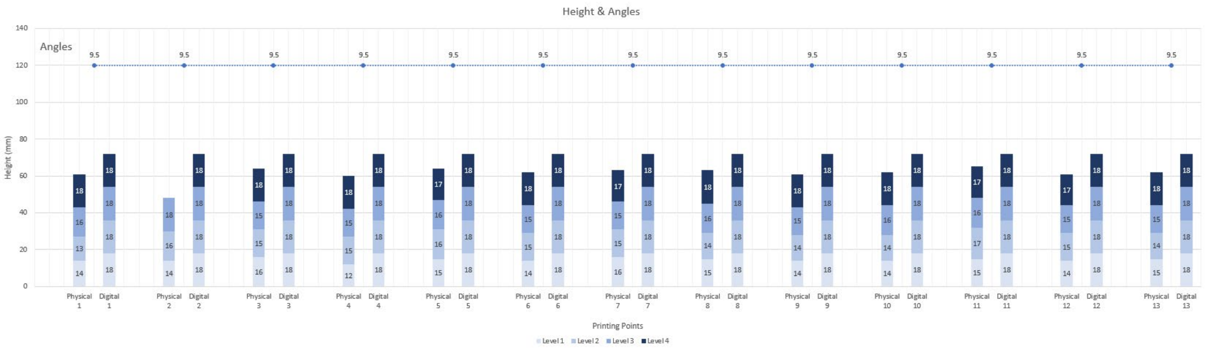

Figure 5: Printing heights (Physical vs Digital) for shapes with continuous slope of 9.5 degrees

Regarding the overall printing across all cases, the results extracted showed that in the cases with a high sedimentation in the first two (2) layers, the final printed object did not show big recalls. Specifically, the maximum deviation that was observed in the total height is presented at points 2, 6, 10 & 14 (Figure 6).

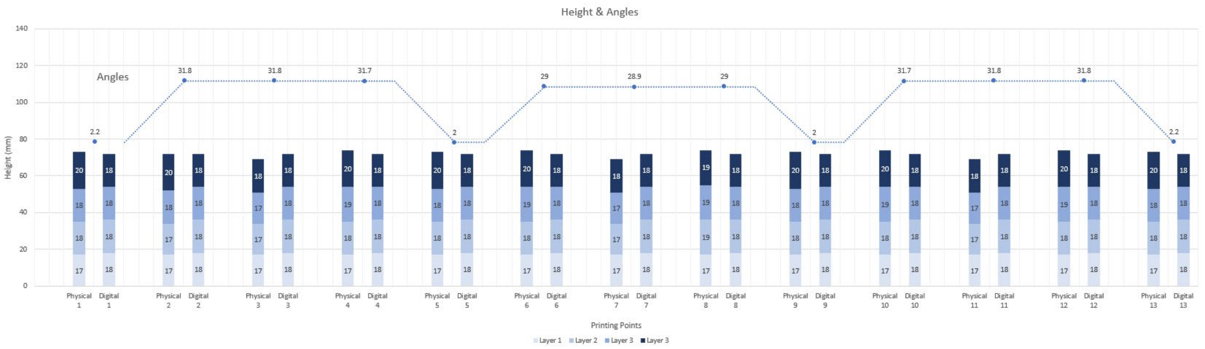

Figure 6: Printing heights (Physical vs Digital) for shapes with slope of 1 to 31.8 degrees

Also, the material was deposited uniformly with continuous extrusion during printing and the deviation from the digital inputs did not exceed 9% of the total height. As far as the exposure of the material is concerned, it was noted that as the printed layers were increased, wider widths were observed during printing due to self-weight. Also, the width increased to 30mm instead of the digital 26mm in the case of the sixth (6) layer (Figure 7), while this remained at 26mm in the case of fourth (4) layer (Figure 8). This was due to the absence of adjacent layer that results in an increase of thickness, losing at the same time height due to self-weight (Figure 7).

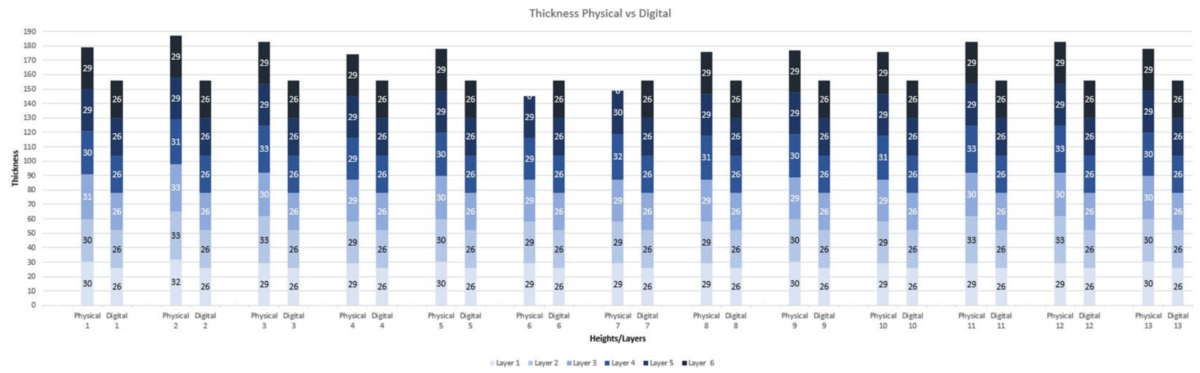

Figure 7: Printing thickness (Physical vs Digital) for shapes with total of 6 printing layers

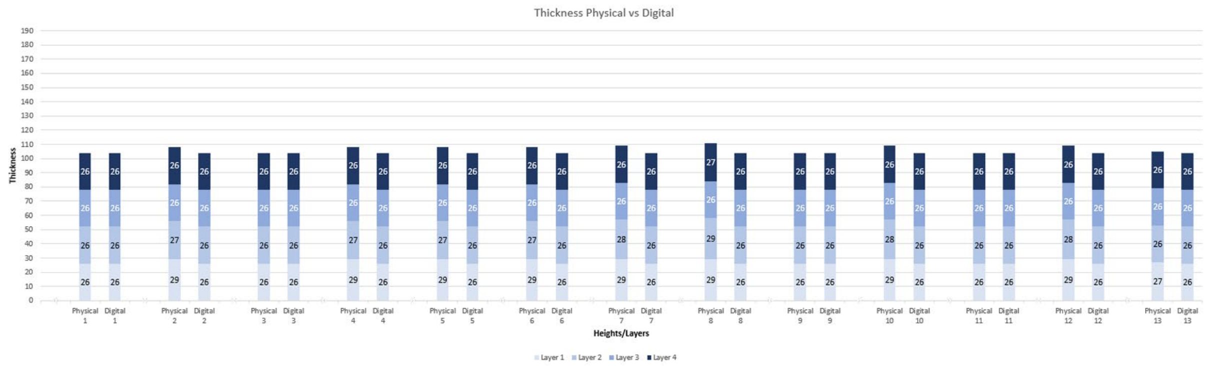

Figure 8: Printing thickness (Physical vs Digital) for shapes with total of 4 printing layers

2.4. Retrofitting and preparation of the second experiment

The transition from the first to the second phase of experimentation represents a progression in refining 3D Printing processes. While the first experiment focused on the examination of printing aspects such as material composition, printing parameters, and the maximum slope configurations, the second experiment focused on the investigation of the printed joints. By conducting a 1:1 experiment and focusing on the optimization of printed joints, this approach attempts to investigate the phases from the design up to the exploration of the printed joints optimization strategy.

3. Second experiment - 3D Printing of joints

The design of the printed joints of the prefabricated parts is an important aspect of the current research due to the special shape and the inability of printing the entire shells at once (due to the maximum slope). Hence, the necessity of finding the optimal printed joint requires special attention that is described in this part of the paper. The process follows five (5) steps: (a) the design investigation of the printed joints based on the nozzle thickness and height (Figure 9), (b) the overall division of the structure into parts for printing execution (Figure 10), (c) the material investigation (Figure 4), (d) the parametric control of the geometry and the preparation of the toolpath (Figure 11), and (e) the 3D Printing process to verify the results (Figure 12).

3.1. Design investigation of the printed joints

The extrusion-based 3D Printing method is followed with layers deposited in a cross-sectional arrangement to maximize the static behaviour of the printed results. The thickness of the nozzle was set to 15mm as the height was reduced from 16mm to 12mm, compared to the first experiment. To achieve the optimal deposition in each layer, a series of experiments involving printing with offset at 1/4, 1/3 and 1/2 of the layer's width were conducted (Figure 9).

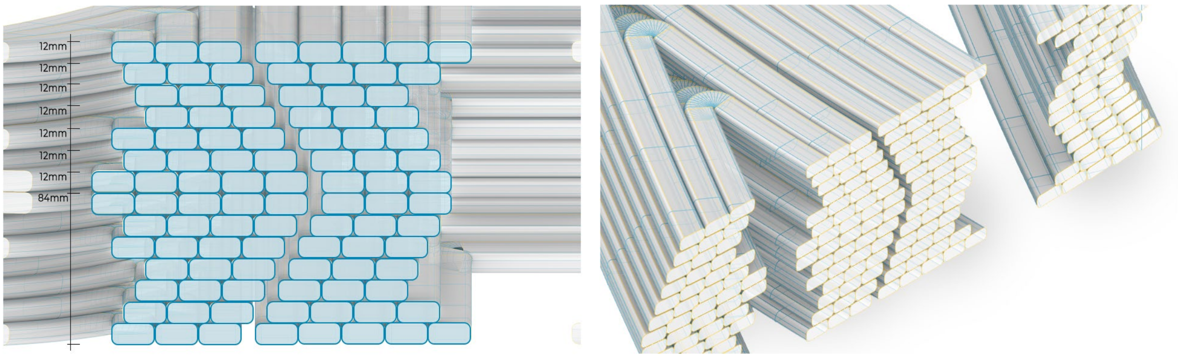

Figure 9: Case study showcase four (4) printed layers with offset ¼ (5mm), with height 12mm and total thickness 20mm per printed line

3.2. Overall division of the structure

For the division of the printed joints, a method with triangular sections was selected. The printed joints were sub-divided into two areas (a) upper triangular sections and, (b) lower triangular sections. The lower section necessitates its 3D Printing on a mold with opposite inclination compared to the upper section (Figure 10). As shown in Figure 10 each triangle is subjected to printing offset equivalent to 1/4 of the geometry of the bottom layer for 7 layers with total height of 70mm. Without the segregation of printing sections and the use of reverse molds, there is a higher possibility of structural collapse due to the overlap at a ratio of 3/4 from the 1st layer to the 7th layer.

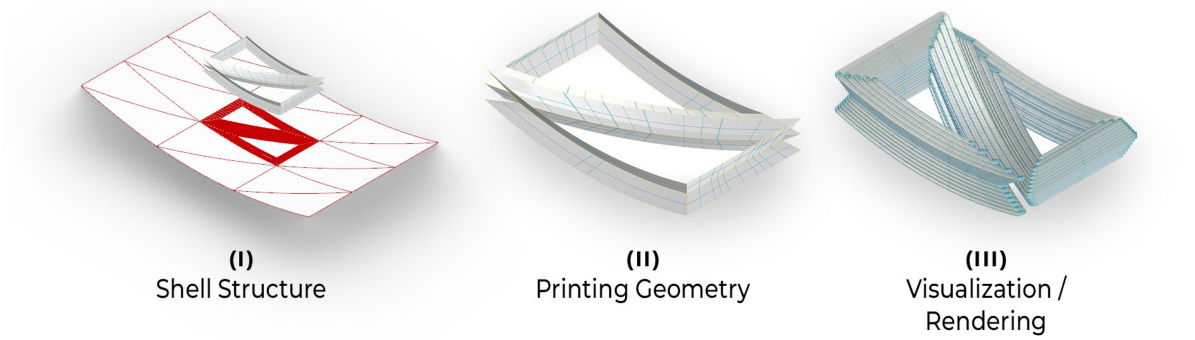

Figure 10: Structure division (i) from the shell to (ii) the printing unit to (iii) Visualization

3.3. Material investigation

The current experimental 3D Printing process utilizes concrete-based material with a superplasticizer. For this purpose, mixtures with high level of water and different compositions applied to four (4) experiments have been conducted as it is shown in Table 2. A series of print tests exploring the material based on printing speed and material thickness has been investigated as shown in Table 2. The mixture used during the experimental study has been achieved by using the composition Cement 41%, Sand 42.60%, water 16.26% and superplasticizer 0.14%, with water/cement ratio 39.6%. This mixture was tested and used during spring period.

Table 2: Material mixture ratios and trial of 3D Printing of the triangles in shape (C)

TRIAL	TEMPERATURE	LAYERS	MIXTURE			ROBOT HEIGHT / ROBOT SPEED	SUCCED / FAIL	Details
			CEMENT	WATER	CLAY			
Bottom layers Trial 1 (Scale 1:2)	26oC	4 Layers	12000gr	4500ml	12400gr	Height: 14mm / Thickness: 26mm / Speed 60	F	Printing height above the desired & very thick
Bottom layers Trial 2 (Scale 1:2)	26oC	4 Layers	12000gr	4800ml	12400gr	Height: 13mm / Thickness: 22mm / Speed 60	F	Printing height above the desired & printing detachment
Bottom layers Trial 3 (Scale 1:2)	26oC	4 Layers	12000gr	4800ml	12400gr	Height: 12mm / Thickness: 24mm / Speed 60	F	Printing height above the desired
Bottom layers Trial 4 (Scale 1:2)	26oC	4 Layers	12000gr	4800ml	12400gr	Height: 11mm / Thickness: 26mm / Speed 60	F	Printing height above the desired
Bottom layers Trial 5 (Scale 1:2)	26oC	4 Layers	12000gr	4800ml	12400gr	Height: 10mm / Thickness: 26mm / Speed 60	F	Printing height above the desired
Bottom layers Trial 6 (Scale 1:2)	26oC	4 Layers	12000gr	4800ml	12400gr	Height: 10mm / Thickness: 26mm / Speed 70	S	Successful printing
Upper layers Trial 1 (Scale 1:2)	24oC	4 Layers	12000gr	4800ml	12400gr	Height: 10mm / Thickness: 26mm / Speed 70	S	Successful printing printing detachment during curing time
Upper layers Trial 1 (Scale 1:1)	20oC	7 Layers	18000gr	6850ml	18600gr	Height: 12mm / Thickness: 20mm / Speed 70	S	Successful printing
Bottom layers Trial 1 (Scale 1:1)	20oC	7 Layers	18000gr	6850ml	18600gr	Height: 12mm / Thickness: 20mm / Speed 70	S	Successful printing

3.4. Preparation of the 3D Printing toolpath

Two (2) adjacent triangles sections of the shell were designed and investigated for printing at 1:1 scale. As it shown in Figure 9 and Figure 11, a linear deposition of material layer by layer with an offset of 1/4 of the bottom layer has been applied. For experimental purposes the following parameters have been used: a printing speed of 70mm/s, a printing width of 20mm, and a printing height of 10mm for the initial layer, subsequently to a height of 12mm for layers 2-7. These parameters have improved the printing result since fail printing spots and inaccuracies during the printing process have been reduced.

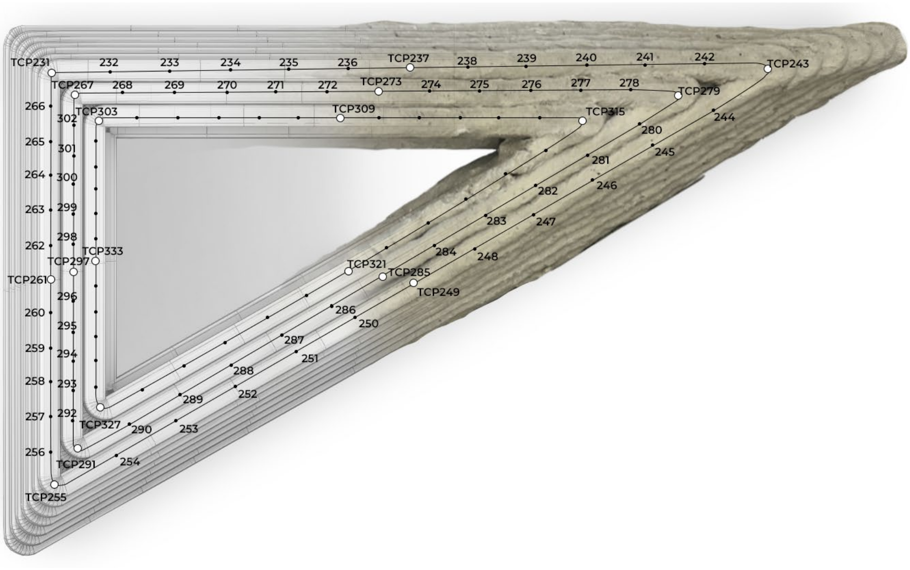

Figure 11: Printing toolpath

3.5. 3D Printing experimental setup and execution

To carry out the experiment, the ABB 2600 robotic arm and the Taco ABB plug-in in Grasshopper parametric environment have been used. Multiple series of printing trials have been conducted based on printing height, thickness, and overlap. The extruder was based on a 21.9mm pipe built into a pump mechanism that was used to control the speed and the pressure of the material being ejected by the robot. Specifically, the experimental setup involved the 3D Printing of the four (4) triangular units, as shown in Figure 12 (i). These units comprised two bottom sections joined with two upper sections through the application of epoxy resin, resulting in the creation of individual units that are joined together, as it is shown in Figure 12 (ii). To ensure successful results, a total of 13 printing trials were conducted (Figure 12).

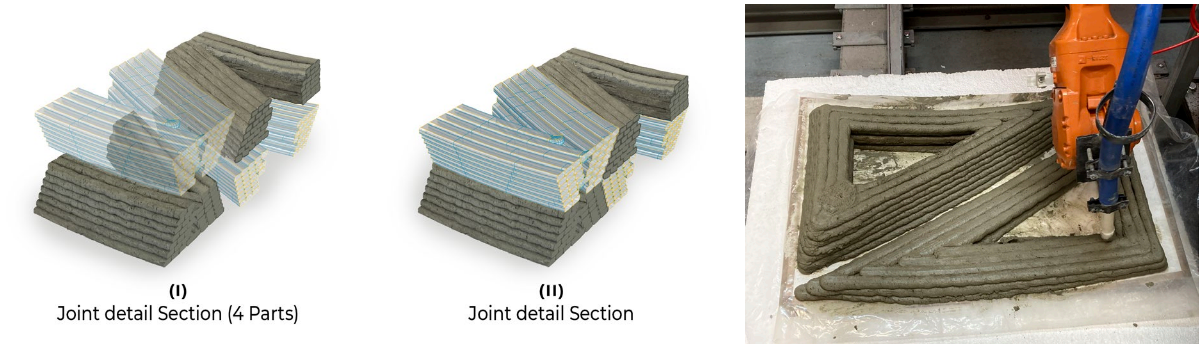

Figure 12: Left: Case study showcase four (4) sections parts (2 printed & 2 digital) with offset ¼ (5mm), with height 12mm and total thickness 20mm per printed line (i) Represent the 4 parts separate, (ii) the 4 parts joined together producing the joint. Right: Robotic 3D Printing execution

4. Conclusion

The value of the proposed integrated methodology holds considerable promise for advancing research and exploring potential applications in architecture and construction industry. While current usage of 3D Printing focuses on basic elements such as walls, slabs, and prefabricated parts, there is a significant potential for the 3D Printing of prefabricated components and free-form shells, both due to the economic aspects, time reduction and technological improvement. This paper attempts to develop a comprehensive review of the 3D Printing of curved parts involving three (3) main aspects: (a) material properties, (b) printed joints, (c) and overall 3D Printing methodology that incorporates adaptive molds. To achieve this, further research is required along with the assembly of an adaptive mold for the effective application of 3D Printing techniques in free-from shell structures development, thereby offering an innovative pathway for their integration into construction projects on a in real scale.

Alongside the physically developed of curve-like structures using the suggested 3D Printing approach, their design based on structural optimization will be examined. To achieve this, topology optimization strategies will be applied to investigate the design of curve-like structures that considers material distribution in areas with high stress concentration in conjunction with the 3D printing constraints. This will ensure a comprehensive approach that incorporates both design optimization and 3D printing development of curve-like structures.

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