DESIGN CONSIDERATIONS DUE TO SCALE EFFECTS IN 3D CONCRETE PRINTING

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Abstract. The effect of scale on different parameters of the 3D printing of concrete is explored through the design and fabrication of a 3D concrete printed pavilion. This study shows a significant gap exists between what can be generated through computer aided design (CAD) and subsequent computer aided manufacturing (generally based on CNC technology). In reality, the 3D concrete printing on the one hand poses manufacturing constraints (e.g. minimum curvature radii) due to material behaviour that is not included in current CAD/CAM software. On the other hand, the process also takes advantage of material behaviour and thus allows the creation of shapes and geometries that, too, can't be modelled and predicted by CAD/CAM software. Particularly in the 3D printing of concrete, there is not a 1:1 relation between toolpath and printed product, as is the case with CNC milling. Material deposition is dependent on system pressure, robot speed, nozzle section, layer stacking, curvature and more – all of which are scale dependent. This paper will discuss the design and manufacturing decisions based on the effects of scale on the structural design, printed and layered geometry, robot kinematics, material behaviour, assembly joints and logistical problems. Finally, by analysing a case study pavilion, it will be explore how 3D concrete printing structures can be extended and multiplied across scales and functional domains ranging from structural to architectural elements, so that we can understand how to address questions of scale in their design.

1. Introduction

Not many years back, the architectural profession was confined to a blank sheet of paper and set of hand tools (pencils, T-squares, compasses and so on) to start on a new design for every client. The introduction of computer aided design (CAD) changed this process. Desktop design software like AutoCAD, Revit, CATIA, Sketch-up, and so on, have substituted hand drawn design. With CAD being more detailed, easy to correct and replicable by simply 'click, drag and drop,' enormous freedom was granted to designers to perceive and visualise geometries which were difficult with manual drafting. Digital design further evolved to more complex CAD forms collectively known as 'computational design'. These approaches are responsible for the introduction of new freeform types of architecture known as 'blobitecture' or 'fluid architecture'. This further evolved to a more radical approach for digital design called 'algorithmic design' where the designers set out design criteria rather than determinate designs (Susskind, 2015).

In the 1990s, Digital Architecture was often criticized for not contributing enough to fill the gap between materialization and construction with CAD strategies. However, in the 2000s, with the widescale introduction of CNC machines in the market, the gap between what is physically feasible to build and digitally possible to design narrowed, eventually enabling designers and architects to bring their designs into the physical world from the virtual medium. The scope of the digitally controlled fabrication process widened with the introduction of industrial robots to architectural research (Lauer, 2014).

This generic, anthropomorphic and versatile nature of robots has inspired engineers, architects, researchers, etc., to equip these machines with tools for assembling, printing, milling, weaving, cutting or painting, etc. Even though in the field of building construction, robotic fabrication has been introduced recently, a remarkable amount of small yet sophisticated structures (icd.uni-stuttgart.de, 2016), have already been built displaying a high degree of special and structural differentiation, and have impressively demonstrated the flexibility of such robots. Even though a lot of proofs of concepts have been achieved through various research with high quality and intricacy using the full potential of CAD, CAM and CAE. until now large-scale applications in construction have barely been investigated (Lauer, 2014).

One of the manufacturing methods that has been enabled by the introduction of robots is 3D printing of parts in various materials, such as polymers, steel, glass (Klein *et al.* 2015), and concrete. Additive manufacturing of concrete is being developed and investigated by several private enterprises and academic institutions around the globe. Eindhoven University of Technology (TU/e) is operating a 3D Concrete Printing (3DCP) facility to research the potential of this method (Figure 1), which is expected to include increase of design freedom, mass customization, and reduction of CO_2 footprint, physical labour and material use (al, 2016).

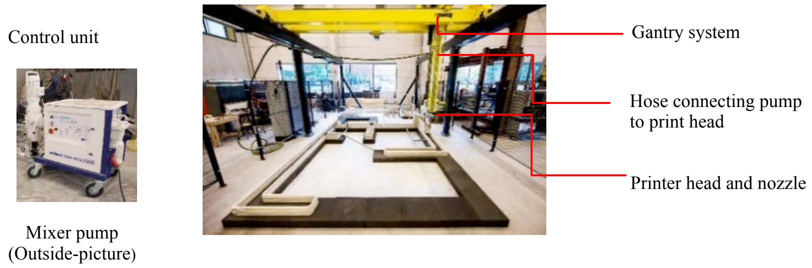

Figure 1. 3D printing facility at TU/e, with some examples of printed objects.

Although the term '3D printing' might suggest any shape can be printed with 3DCP, in fact what is printable is bound by specific constraints. The parameters governing the design of printable concrete objects have hardly been investigated. The objective of this paper is to show that scale is one of the governing parameters in the design of 3D concrete printed structures, by discussing a case study pavilion recently constructed at the TU/e.

2. State of the Art

Most of the existing efforts of 3D printing of concrete are based on the Contour Crafting method introduced by Prof. Behrokh khoshnevis (Hwang and Khoshnevis 2005) . This method uses the Fused Deposition Modelling principle, where layers upon layers of concrete filaments are deposited to obtain the required form. Similar pioneering research was done by the University of Loughborough (Lim *et al.*, 2011). Shanghai-based construction company Winsun (yhbm.com, 2016) and Total Kustom in Minnesota, United States (totalkustom.com, 2014) has shown commercial application of this process.

Another method of large scale 3D printing was introduced by D-shape, research pioneered by Enrico Dini which instead of using an extrusion process of printing, is done by Stereolithography that requires only mortar and an inorganic binder (d-shape.com, 2016) With 3D printing technology, entire constructions can be done without any human intervention. The main advantage of this system is being able to fabricate any kind of concave geometrical structures without the use of any kinds of mold or scaffoldings.

More extensive overviews are provided by Lim *et al.* (2011) and Wolfs (2015). The TU/e operates a 4-DOF gantry robot with a printed bed of 9 x 5 x 3 m. The facility, its capabilities and limitations are extensively described in Bos *et al.* (2016). For the research, a custom concrete mix was developed by SG Weber Beamix. The mortar is comprised of Portland cement (CEM I

52,5 R), siliceous aggregate , limestone filler and specific additives for ease of pumping, rheology.

3. Design and Fabrication of Concrete Pavilion

For the purpose of demonstrating and exploring the impact of scale on the capabilities of the TU/e 3DCP facility, a case study pavilion was constructed in the TU/e structures laboratory and presented during a public demonstration session on June 24, 2016. It helped in exploring design possibilities and understanding the relationship between a CAD design and its printability with the TU/e printer. The initial design of the pavilion was proposed by I'M Architects and Witteveen+Bos consulting engineers (Figure 2). The size of the pavilion amounts to 3.5 x 2.5 x 2 m with a layered dimensions of h x w = 10 x 40 mm. The design was based on initial understanding of 3DCP process and the capabilities of the printer available at the TU/e. However, while printing the pavilion there were numerous issues that were caused by the scaling up of the printed object, which needed to be addressed. Not all of these were initially anticipated and taken into account while doing experiments on small-scale prototypes. These issues are discussed further in the following sections. Eventually, the research team redesigned the pavilion to the capabilities of the printer. The final result is shown in Figure 3.

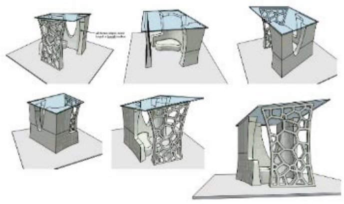

Figure 2. Initial proposal for the pavilion

Figure 3. 3D concrete printed pavilion

3.1 MATERIAL DEPOSITION

3DCP process as adopted at the TU/e is based on extruded deposition of concrete filament layers upon one another to print the desired form. The concrete used in this process is a viscous low slump concrete which is pumped though a hose to the print head mounted to the robot with an external pumping machine. The entire process of material extrusion depends on various tangible and intangible parameters, such as the pressure with which the concrete is pumped though the hose, speed of the robot kinematics, cross sectional opening of the nozzle which defines the dimensions of the printed filament, number of stacked layers and curvature of the printed geometry, and so on. All these mentioned parameters or variables are either directly or indirectly affected by scale of the printed form or printing time.

3.2 PRESSURE IN THE SYSTEM

As the scale of the element increases, the printing duration increases proportionally. The 3DCP facility uses a standard mixer-pump to mix and pump the concrete in two subsequent processes (Figure 1). This allows separate control of the mixing and pumping processes which is required to align the pumping with the printer movement. To obtain a linearly controllable pressure in the concrete flow, the pump mechanism uses a frequency-controlled positive displacement screw. While printing, the cement and other additives are mixed with water to produce concrete that lands in a vessel before being pumped to the print head under 1 to 3 bars (10-30 MPa) of pressure. During this process there is friction produced in the screw due to prolonged pumping of concrete. This results in a temperature increase within the pump, which affects the chemical hardening reaction of the concrete. With the long duration of printing the concrete, this further reduces its workability, which either results in corroding the insulated rubber in the pump or depositing substandard filament layers with poor structural properties.

The influence of this scale effect can be limited by restricting the number of layers in individual elements. This, however, leads to an increase of joints between the smaller elements, which in itself can be detrimental to the overall structural performance.

3.3 ROBOT KINEMATICS

3.3.1 Corners

The initial design (Figure 2) proposed by the architect had sharp or pointed edges. These had to be mellowed down to blunt edges because of the robot kinematics. The print head follows a toolpath, the path through space to produce the desired results. This toolpath is independent of any dimensions, so the robot kinematics moves along this toolpath with point blank accuracy without considering the dimensions of the printed filament. However, printed concrete filament naturally has a finite size, e.g. of 10 x 40 mm. This results in a difference in radius of curvature for the inner curve and the outer curve. With the toolpath being the centre line of the filament, if we make sharp turn in the toolpath (e.g. 90°) the material deposited in the smaller inner curve tends to pile up, thus affecting the section dimension of the filament (Figure 4a), while the outer curve tends to expand which also affects the dimension of the filament and can cause cracking. When printing continuous layers above one another, this error starts to build up and it eventually results in slanting of the layers on one side, which in turn results in substandard or even failure of the printed elements.

a b c d

Figure 4(a, b, c, d). (a) Irregular material deposition, (b) Tangential nozzle positioning to filament, (c) Concrete printing adopted by University of Loughborough, (d) Fileted curvatures

3.3.2 Translation and rotation interaction

Another scale effect, that actually *de*creases when scaling up, is related to interaction between translational and rotational movement. During printing, the nozzle head needs to be tangential to the toolpath, otherwise twisting in the layers will occur (Figure 4b). To avoid that, C-axis of the robot rotates keeping the nozzle head tangential to the toolpath. However, if the curvature of the toolpath is too steep the rotational axis of the robot cannot keep up with the translational axes. This causes jerky movements of the robot, and likewise affects filament. In addition, extremely pronounced or abrupt toolpaths can cause (frequency induced) vibrations in the print arm, which will result in poor print quality as well. These problems can be solved either by reducing the linear print speed, preferably in combination with scaling down the dimensions of the printed filament as demonstrated by the University of Loughborough (Figure 4c), or by scaling up the overall geometry so that curvatures become less extreme. In the pavilion project it was resolved by simply fileting two curves with enough radius of curvature that it did not affect the dimensions of the printed filament (Figure 4d).

3.3.3 Print Bed

The 3D printer having a printed bed of 9 x 5 x 3, has a direct relation to the scale of the element to be printed and has to be within that scale. However, the built forms, which require elements to be larger than the printed bed, need to be printed in parts. This means that during the design process these joints or the assembling of parts needs to be taken into account. While doing so it needs to be considered that whether it's a 4-axis gantry or 6-axis robotic, in most cases it has a flat printing bed due to concrete being a slow hardening printing material – while printing it settles on the printing bed due to its material properties unlike other 3D printed materials like plastic which dries immediately, and scaffolds can be printed in space to support any form of geometrical forms.

Each element of the pavilion was printed flat and stacked one above the other and this ease of assembly was an important consideration in the design of the pavilion (Figure 5a, b).

Figure 5(a,b). (a) Printing of elements flat in parts, (b) Assembly of the printed elements

3.4 DIMENSIONAL CROSS SECTION OF THE NOZZLE

The tip of the print head is a hollow cross sectional element through which the concrete is pushed out to form layers of concrete filament and the shape and area of the cross section of the nozzle governs the dimensions and the geometry of the concrete filament. The initial tests were conducted with nozzles of round cross sectional dimensions of Ø25 mm (491 mm^2); however, the resultant round filament was unstable as the number of layers deposited over each other increased. The geometry of the cross sectional opening was improved with a square cross section of 25 x 25 mm (625 mm^2). This resulted in increasing the extrusion pressure to synchronize with the speed of the robot kinematics as there is a direct relationship between the nozzle opening and extrusion pressure in the system. However, this did not have any significant negative effects as it increased the speed of the printing process, but as the number of layers increases it had stability issues as like the previous case and was restricted to a certain number of layers. Currently, a 40 x 10 mm (400 mm^2) opening is being used which has shown promising results in increasing the number of stacked layers and thereby increasing the scale of the printed element. In each of the above mentioned cases the scale and cross section of the nozzle plays a governing role in the layered geometry of the printed filament and in turn of the printed element.

3.5 LAYERED GEOMETRY

As mentioned earlier the dimensions and layered geometry of the printed filaments has a direct relation to the stacking capacity of the printed elements, and scale plays a clear role in the design of the printed elements. In theory irrespective of the design the printer can print all geometries with the same efficiency; however, material behavior changes with scale. While printing, the concrete filament deposited is in its dormant period which gains strength with time (Wolfs 2015). The initial design of the pavilion was adjusted considering this limitation of the printed geometry. While printing large curvatures, as the number of layers stacked upon each other increases, there is a horizontal pull in one direction which could be a result of substandard layer deposition as discussed earlier, or material deformation. Consequently, the layers start slanting in one direction ending up collapsing while printing.

During this phase the tool paths of large curvatures of the printed elements are broken down to smaller curves. These smaller curves provide enough stability for the printed layers without significantly affecting the overall design of the element.

4. Logistics

One of the most important scale dependent parameters in the construction or manufacturing process is logistics. The research direction adopted at the Technical University of Eindhoven on 3D concrete printing is to print smaller blocks of pre-fabricated elements and assemble them together to form larger objects (Figure 5a, b). The main argument to justify this approach is due to the fact that the printed design is limited within the printing bed of the robot. So to scale up the constructed element there can be only two solutions: either having a robot printing bed always larger than the building or printing in parts and assembling them. The latter approach is the most widely adopted approach for 3D concrete printing (totalkustom.com, 2014).

However, with this approach logistics plays an important role. For the printed pavilion according to the initial design the entire pavilion was printed in one go without dissecting the pavilion in parts. However, as discussed above, with problems of layer strength, and due to their heavy self-weight, the elements failed while moving them from the printed bed.

An important point to consider while comparing traditional construction with pre-fabricated 3DCP parts is the fact that the assembly of parts for traditional construction does not affect the design of the element. For example, for the construction of columns in a multistorey building, for each floor of columns that gets constructed, the reinforcement bars of the columns get welded together and the concrete column is casted within a mould. Here the reinforcement bars act as the assembly joint for the columns. But for 3DCP assembly of parts completely relies upon the interface joins between two elements, which may be joined with an adhesive or an interlocking joint.

Taking into consideration the assembly and logistical issues mentioned, it is extremely important that the overall design of the element considers this issue within the design problem.

In case of the pavilion being a temporary installation for stability the parts were stacked upon each other with hollow steel sections of 50 x 50 mm bars. However, for the ease of logistics, to move the pavilion there are no materials in the interface between two parts for adhesion, to easily disassemble it into parts to shift to another location.

5. Conclusion

Additive manufacturing with 3D concrete printing shows a promising alternative to traditional subtractive manufacturing, with which virtual computer aided designs can be more accurately realized with minimal or no manual inaccuracies. However, the technology is still in its infancy, and most structural and design research conducted at universities and research centers limit the scale of the prototypes manufactured. There are considerable avenues of research due to the effect of scaling up, which needs to be explored in detail to have an in-depth understanding of the limitations and potentials of this technology and to evolve it to be commercially applicable in the building industry.

The above discussed issues related to additive manufacturing also reveals limitations with the present CAD (computer aided design) processes to translate designs to computer aided manufacturing (CAM), taking the limitations of material and the manufacturing process into account. This upgrade in the process would transform the design and manufacturing process from "designed to manufacture" to "manufacture to design". The latter having the edge over the former with the fact that, at the stage of manufacturing, designs need not be compromised to meet the requirements of manufacturing.

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