DEVELOPMENT OF A VIABLE CONCRETE PRINTING PROCESS

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ABSTRACT: A novel Concrete Printing process has been developed, inspired and informed by advances in 3D printing, which has the potential to produce highly customised building components. Whilst still in their infancy, these technologies could create a new era of architecture that is better adapted to the environment and integrated with engineering function. This paper describes the development of a viable concrete printing process with a practical example in designing and manufacturing a concrete component (called Wonder Bench) that includes service voids and reinforcement. The challenges met and those still to be overcome particularly in the evaluation of the manufacturing tolerances of prints are also discussed.

Keywords*: Concrete Printing, Construction Automation, Digital Fabrication, Additive Manufacturing*

1. INTRODUCTION

Additive (also known as rapid or layered) manufacturing (AM) is now an integral part of modern product development [1], having been commercialised over the last two decades. This is particularly apparent in the fields of aerospace and automotive manufacturing, and for a wide range of medical applications and production of prototyping models for aesthetic and functional testing.

This paper describes a research aimed at developing what has been called a 'Concrete Printing' process and discusses the potential of the technique as well as future challenges. A prototype printing system has been built within a 5.4m (L) x 4.4m (W) x 5.4m (H) frame. Conventional construction materials including gypsum and commercial pre-packaged mortars were investigated to identify various printing parameters, such as machine and pump speed, nozzle shape and size, material characteristics and mechanical properties. The preliminary experiments identified a number of issues including limited printing volume; speed and resolution; and material constraints. The printing process was improved and a fibre-reinforced high performance cementitious material developed with key characteristics of pumpability, printability, buildability and open time. Printed examples using the refined process and developed material are presented in detail in the following discussion.

2. FREEFORM CONSTRUCTION

Conventional construction processes share the concept of mould-based shaping. AM processes have advantages over conventional construction and manufacturing processes because: (i) they are able to build customised parts without extra tools or moulds [2, 3]; (ii) the cost-per-part of AM-based components are constant, in that they do not change through volume [4]; (iii) they offer construction automation and the promise of design freedom [2, 4]; and (iv) they have the potential of building in additional functionality into structures [3]. However, AM processes generally struggle to compete with conventional construction and manufacturing processes such as injection moulding on slow printing speed, accuracy, surface finish, usable materials and mechanical properties [2].

AM processes are commonly used in product design in the aerospace and automotive industries and increasingly in medical applications and modelling in architecture, generally manufacturing small components. Recent research and practice such as Contour Crafting [5], D-Shape [6] and Concrete Printing [7] have created a new thread of large scale processes adopting AM techniques as an alternative way of constructing building or architectural components. Despite the potential, AM processes have their own challenges; slower build time than cast-based manufacturing result from the layered printing approach; and print resolution (detail) depends on layer thickness.

3. CONCRETE PRINTING

Concrete Printing is the focus of this paper, which uses an extrusion technique to deposit the required build material (Figure 1). The process consists of data preparation similar to most AM processes, material preparation, and printing using a cement-based mortar, which satisfies specific characteristics and mechanical properties. The details of the process, materials and prototype system have been described elsewhere [8, 9].

Figure 1: The printing frame of Concrete Printing.

3.1 DATA PREPARATION

Data preparation is similar to other AM processes except for an additional post-processing step that optimises the generated printing path of the deposition head in order to reduce the printing time as well as possible material over-print due to nozzle on/off operation, by minimising the non-printing movements of the deposition head. The potential reduction in build time is dependent on build complexity, i.e. higher build complexity has more scope for print-time minimisation. A printing component is designed as a 3D CAD model, converted as an STL file format, sliced with a desired layer depth, a printing path for each layer generated, and a G-Code file for printing created.

3.2 MATERIAL PREPARATION

Cement and gypsum based materials have been used in the investigation. A key factor in the selection of these materials was having ubiquitous familiarity at an industrial level. Initial printing tests were carried out using various nozzle diameters from 4 to 22mm. Since the printing process requires a continuous high degree of control of the material during printing, a high-performance build material has been developed. The density of the concrete is approximately 2300kg/m^3; the mix produces a high strength material, which is more than three times as strong in compression and in flexure as conventional cast construction materials. Less than 20% of the strength is lost with the printed material due to the presence of small voids created in layers of the printed material; however, the creation of a high strength mix, where the average compressive strength of the cast mix was in the range 100~110 MPa, has resulted in an acceptable strength for component manufacture, in excess of 80~88 MPa.

3.3 DELIVERY AND PRINTING

In order to maintain the freshness of the material and maximise strength, the delivery path should be short and material fed in small batches. Material was mixed, placed in a hopper on the top of the printing head and then extruded as a pre-defined filament shape. The current flow rate for printing is set to less than 1.4 kg/min to support the small nozzle diameter of 9 mm.

Cement hydrates through a complex process of crystallisation. This may partly account for the observed relative independence of strength and print direction; however it also means that there is a limited time to print the wet mix before it begins to set. The critical issue here is the consistent rheology of the fresh material to enable it to move smoothly through each part of the delivery process, yet retain sufficient rigidity once it leaves the nozzle. There are strong parallels here with the production of wet process sprayed concrete which also needs to balance workability for pumping and adhesion following ejection from the nozzle, although in this case the process has the advantage of the momentum of the sprayed material providing compaction [10].

4. PRINTING EXAMPLE: WONDER BENCH

The resultant vertical surface resolution using this extrusion-based approach is quite visible even with a 6mm layer thickness, and on the same scale as a mortar joint in brickwork. The principle affect on the design for the component, however, is to work with this as a feature rather than to cover it, or hide it by finishing because the unique aesthetic, transparently reflecting the build process, engaged designers' interests. In order to demonstrate the scale of the process a wall-like artifact (i.e. Wonder Bench) has been designed and printed. The footprint is 2.0 by 0.9m with a 0.8m height, and the weight is approximately 1 tonne (Figure 2).

Figure 2: The printed Wonder Bench

The bench consists of 128 layers with an average printing time of 20 minutes/layer, and the backside has a dedicated concave-convex surface while the front side has a smoother surface with an integrated seat in order to demonstrate the resolution of the print. The top layer covers two thirds of the artefact to reveal the internal structure. The artefact includes 12 voids that minimise weight, and could be utilised as acoustic structure, thermal insulation, and/or path for other building services. The voids consist of various sizes and shapes to follow the curved shape of the artifact (Figure 3).

Figure 3*:* Internal structure including functional voids and reinforcement. The rectangular shaped steel plates are the customised washers for threaded rebar for post-tensioning.

The component also demonstrates a reinforcement strategy suitable for large components printed using additive manufacturing. A total of 23 voids were carefully designed to form conduits for the post placement of reinforcement (see the gray holes in Figure 4).

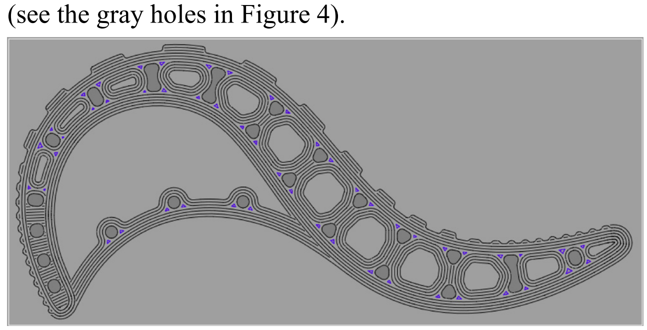

Figure 4: A plan view of the wall-like artefact. The lines indicate the centre line of filaments.

These were post tensioned and grouted to put the part in to a predetermined compression. This approach offers a simple workable method of incorporating tensile capacity into large cement-based components, making the direct manufacture of large construction components possible.

5. TOLERANCE MEASUREMENT OF PRINTS

Printing of non-rectilinear components with wet concrete could cause result in differences between the CAD and final printed geometry, particularly in the vertical alignment of print surfaces. Moreover, the particle size of materials such as sand limits the minimum depth of each filament, consequently affecting the resolution. Thus, evaluating the manufacturing tolerances of printed components against the original CAD model is necessary to ensure satisfactory print quality. Visualising the errors in 3D components with a systematic measurement technique could be an intuitive way to track the build error.

Figure 5: CAD, print and scan model of starfish shape. The filament size of this example is 22 by 15mm to emphasise the error areas.

Initially, we tested a starfish shape (Figure 5) using a 3D laser scanning technique with Leica ScanStation 2. This is a promising geometric data collection tool for construction with its fast sampling rate and high accuracy able to capture up to 50,000 points per second with minimum <1mm point spacing through the full range. The tolerance between CAD and printed models was evaluated as follows. First, the starfish shape was designed in CAD with three reference points and printed. The printed shape was scanned to generate a point cloud, the data noise was tidied and then projected on the original CAD surface. The Z heights of both CAD and scanned data were sampled on regular X and Y grids, and the data exported to MatLab. The data were meshed as a surface, and the Z heights along specified sections interpolated. Finally, the error information was generated.

One problem with overall surface plots of the differences between design and scanned data is that there is too much information to be useful. Thus, a contour plot reduces the Z difference information in 3D to 2D, and was filtered, in this early case, to ignore errors below 10 mm, which focused the plotted data on the worst areas only (Figure 6). A footprint plot of the X and Y data clearly shows there is a significant overprint due to dribbles by nozzle on/off operation.

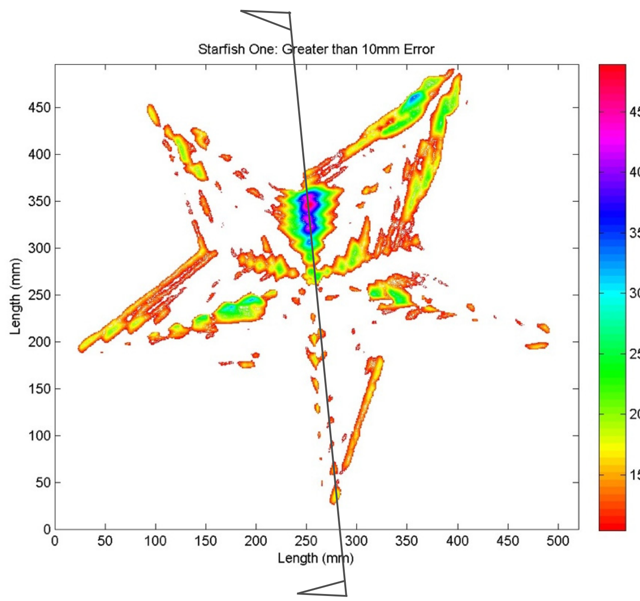

Figure 6: Surface error contour plot of the scanned data using 10mm error filter, and section axis for the analysis. The error scale is given on the right in mm.

Sectional analysis revealed the Z height data from both the design and the scanned surface, plotted together with the error (Figure 7). Dotted line in the upper graph is the actual Z height of each scanned point on the section. The red line in the bottom graph shows the error in Z values.

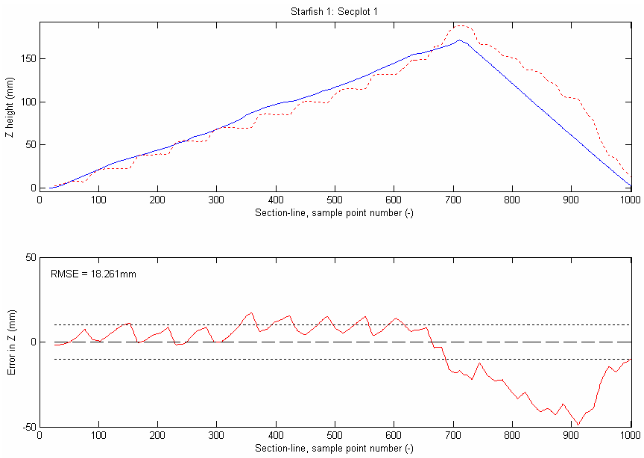

Figure 7: Section analysis for most overprinted area.

However, the comparison between a CAD model with a smooth surface inclination (left picture in Figure 5) and printed model with a stepped surface inclination (right picture in Figure 5) cannot provide an accurate evaluation because the surface textures are different. This means that the CAD model should be redesigned to match the print model, to represent the individual filament surface (Figure 8).

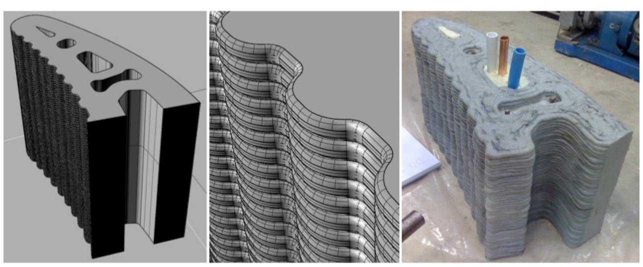

Figure 8: Filament-based CAD and printed model.

The other problem is related to the print size. Because construction components are large-scale, the data preparation is non-trivial. For example, the Wonder Bench in Figure 2 took 3.5 hours of scan time from five positions, and around 4 million points were collected. Despite the high accuracy of the laser scanner, the scanned data were not good enough to evaluate the surface tolerance (Figure 9). This is the bench was scanned with a fixed height (1 m), and thus the bottom part of each filament was not scanned properly; consequently, the horizontal strip pattern on the surface became unclear. To increase the accuracy, particularly to detect the filament shapes on the surface, the object needs to be scanned from more positions and angles. Further research is ongoing to gain an efficient surface capture procedure.

Figure 9: Details of printed and scanned surface of the Wonder Bench.

6. CONCLUSIONS

The additive manufacture of full-scale construction components is a new concept, but one that is beginning to become a reality. The current work in the area is promising and offers an innovative way of manufacturing construction and architectural components. The following discussions can be drawn from the research presented here:

- A Concrete Printing process has been demonstrated which facilitates freedom of design without labour-intensive formworks and precision of manufacture with functional voids, which is not possible with conventional construction processes.
- An in-house high-performance cementitious material has been developed with a high strength (around 100~110 MPa in compression), which is approximately three times that of conventional concrete, in order to compensate for the weaker structure of layered components.

- A laser scanning technique has been tested to evaluate the manufacturing tolerances of printed components against the original CAD model particularly on a surface resolution although further research is needed to establish a systematic approach to increase efficiency in the surface capture procedure.

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