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Effects of interlocking on interlayer adhesion and strength of structures in 3D printing of concrete

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ABSTRACT

3D printing of concrete uses computer controlled layering of cementitious material to fabricate structures. The paper presented here investigates the effect of interlocking on bond strength between layers of Contour Crafted structure using experimental approaches. A concrete mixture which is compatible with the existing extrusion system is used and different interlock configurations are tested. The results show that bonding strengths is sensitive to interlocking and it can be increased by an average of 26% as shown by splitting test.

1. Introduction

Bonding between layers in 3D printing is critical in many applications especially in 3D printing of concrete. Although in some cases bond strengths as strong as the bulk material (the monolithic segments) are achievable [1], a series of preliminary experiments on layered concrete fabrication show the vulnerability of the structures due to low strength at bond interfaces.

In this paper, proper mixture for Contour Crafting (CC) was developed and the bond strengths at interface were measured by different test methods. The outcome of the research is a detailed understanding of the application of interlocking on layers of 3D printed concrete structure for homogenous and sustainable fabrication.

1.1. Contour Crafting

Rapid mega-scale manufacturing [2], utilizing Building Information Modeling (BIM) in different phases of construction [3], passive design strategies [4], and sensing automation technology [5,6] are possible responses to lower down the cost of construction, improve energy efficiency, and increase occupants' satisfaction.

3D printing of concrete uses computer control layering of material to fabricate structures by integrating computer aided design (CAD) and computer aided manufacturing (CAM). The technology is based on additive manufacturing process which is deposition of successive layers of material to shape the object. Fig. 1 shows the process which starts with modeling the object that can be of almost any geometry. At second level, the 3D model was processed and sliced in layers. Finally, the object was fabricated through laying down cementitious material layer by layer.

Contour Crafting, D-shape [7], concrete printing [8], and selective deposition for ultra-high performance concrete [1] are four large scale additive manufacturing processes. D-shape technology was developed based on spraying bonding liquid on predefined area of the sand layer. Printing head as the core of the system moves along x-y-z axis and spreads the solid material in a uniform horizontal layer before spraying the bonding liquid. The printing head lifts up on the z-axis and the same sequence is repeated until the model is completed [9].

Concrete printing is another large scale additive manufacturing process based on the extrusion of cement mortar [8]. It is a digitally controlled additive manufacturing method based on freeform, layer-based, manufacturing technique [10]. 3D printing of ultra-high performance concrete is based on depositing layer by layer of concrete similar to FDM technique [1]. Le et al. [11] developed a high-performance printing concrete based on characteristic of self-compacting concrete and sprayed concrete.

Contour Crafting (CC) uses concrete, polymer, ceramic [12], and sulfur concrete [13] to build large scale objects. The trowel control mechanism is the main part of the machine. Fig. 2 shows one type of extrusion unit which carries uncured ceramic paste. The angle and orientation of the side trowel are adjustable to shape a complex geometry [14]. In CC, free form designs are achievable by utilizing robotic arm that is traversing in 3-dimensional space.

In 1999, Richard J. Russell II [16] completed his PhD dissertation on analyzing polystyrene melt flow using Contour Crafting through experimental approach. In 2002, Hongkyu Kwon [12] continued the

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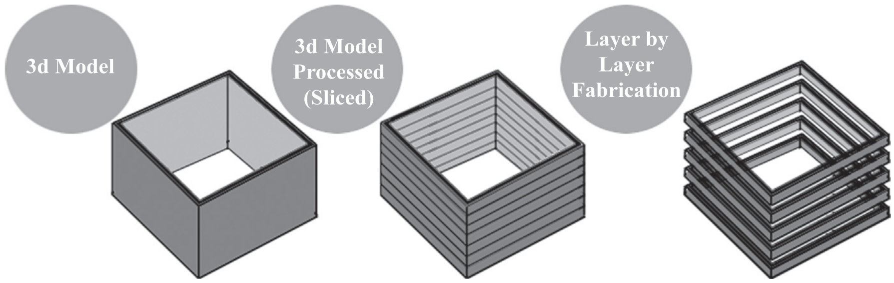

Fig. 1. Additive manufacturing process.

research on CC by using experimental approach for uncured ceramic material. He investigated the effect of side trowel on the capability and quality of the Contour Crafting process to fabricate 2.5D and 3D parts, and he concluded that the surface quality of the extruded part with trowels on two sides was better than a single side trowel on the exterior angle. Kwon also simulated the pattern of flow in the CC nozzle during fabrication processes with CFD software to study the effect of the pressure on the extrusion and geometry.

In 2005, Dooli Hwang [17] used experimental approach to study the application of Contour Crafting on a full scale concrete wall. His research showed that designing the setting time depends on time of deposition cycle, material delivery, CC machine preparation, and fabrication rate. He also added Bentonite ($A1_2O_3$-$5SiO_2$-$7H_2O$), plastic clay, to the mix to increase the paste plasticity and decrease the water seepage.

In 2012, Tony Di Carlo [18] applied experimental and numerical techniques to analyze the structural properties of fresh concrete subject to Contour Crafting. He developed a special mortar mixture which can be safely used for layered fabrication. His proposed cementitious mixture was suitable for freeform-layered fabrication and was tested for a full-scale demonstration. Di Carlo also studied the structural properties of fresh concrete for safe layering by developing analytical and numerical tools.

1.2. Layer interlocking

3D printed structure with interlocking of subsequent layers represents a new approach to support integrity of the structure. Interlocking layers are often used in the 3D printing of mechanical structures, jewelry, and parts with complex geometries.

Topological interlocking is a design principle for structures that elements are held together purely by geometrical constraints without binder or connector [19]. This type of assemblies provides an alternative to monolithic structures and can be effective in addressing some of the critical engineering problems [20–24]. It can also be applied to improve the performance of composite materials (e.g. sandwich panels) [25].

Topologically interlocked material is categorized as a class of granular crystal which is made of an assembly of polyhedral elements [26]. This fabrication technique allows some limited movement of the blocks and can be used to build mortarless structures [27]. Topologically interlocked structures are damage tolerant because of the structural defect and cracks contained in the individual units [28]. Therefore, the structure has higher resistance to fracture propagation [29].

Research by Schaare et al. [22] has shown potential of high energy absorption and self-reversible mechanical behavior in topologically interlocked cubes. Mechanical and functional properties including resistance to crack propagation, tolerance to local failure, and energy absorption are advantages of topological interlocking [19,30–32].

The critical challenge of 3D printing is the development of techniques that adhere to extruded layers to achieve a homogenous structure. The prime objective of this study is to investigate the impact of interlocking on the strength of structure in Contour Crafting.

1.3. Research significance

With a rapid increase in additive manufacturing and rapid prototyping in construction, there is a great interest in enhancing the structural integrity of the 3D printed structure. A possible solution to this problem can be top surface preparation of the substrate, application of different binders, and better managing of the curing process. The objective of this paper is to use experimental techniques to describe the effect of interlocking on layering of fresh concrete. The result of this research, which is based on material selection and the fabrication regime, may be used to introduce a methodology to enhance the bond interface of cementitious material used in 3D printing. The test results should be in the interest of designers and engineers involved in developing additive manufacturing, and especially for those involved in CC.

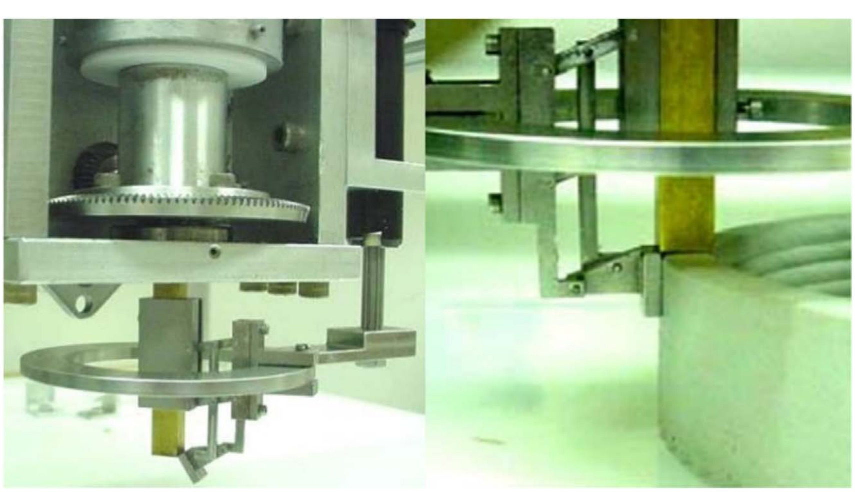

Fig. 2. Adjustable side trowel to shape different geometry [15].