PolyBrick 2.0: Design and Fabrication of Load Responsive Structural Lattices for Clay Additive Manufacturing

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ABSTRACT: Various methods of large scale additive manufacturing (AM) are finding growing application within architectural practice and on-site construction. This creates a large interest in the adaptive reinvestigation and reclamation of both traditional and novel materials within an architectural application. The plastic nature and controllable rheology of wetstate clay makes it an ideal material for this type of AM. PolyBrick 2.0 emphasizes the potential to rethink additively manufactured structural modules with customized clay recipes. In this paper, we present a comprehensive workflow for the bio-inspired algorzithmic generation of load responsive lattices, realized by materially informed custom AM methodologies and toolpathing strategies. As a result of the presented workflows, a load responsive and material efficient brick module (PolyBrick 2.0) is developed and novel fabrication tools and pipelines are established for higher print success and fidelity.

1 INTRODUCTION

1.1 *Potentials for AMTs in Design and Engineering Applications*

Additive manufacturing technologies (AMTs) are gaining increasing application within architectural practice and on-site construction. " […] The prevalence of 3D printing within the worlds of architectural practice and architectural academia has been evidence of the evolution of 3D printing from a novel and exclusive prototyping tool to a ubiquitous and accessible fabrication medium" (Huang, 2016). This technology (AM) "is characterized by processes that are built up layer-by-layer, in contrast to traditional fabrication methods based on material removal" (Mueller, 2017). This enables "a large degree of customization paired with high efficiency and precision" (Dillenburger and Hansmeyer, 2014). Hence, combined with parametrically driven computer aided design (CAD) technologies, AM demonstrates great potential to allow designers to achieve *forms* and mechanical and material properties formerly regarded as impossible (Dillenburger and Hansmeyer, 2014).

A commonly employed additive manufacturing technology at the architectural scale is the paste deposition modeling (PDM) (Ruscitti et al., 2019) of earthen, clay and cementitious pastes. Ronald Rael and Virginia San Fratello's "Mud Frontiers" serve as an excellent example of the effective utilization of PDM with earthen pastes. Broadly, PDM is defined as the incremental layered deposition of a plastic material out of a nozzle aperture to create novel and complex forms. (Ruscitti et al. 2019) The plastic nature and controllable rheology of wetstate clay makes it an ideal material for the architectural scale utilization of this type of AM. For example, Il, AlOthman and Garcia del Castillo's work "Responsive Spatial Print" (Im, AlOthman & Garcia del Castillo, 2018) utilize a robotically driven PDM system for the additive manufacturing of a porous "doubly-curved" wall geometry. Authors thereby demonstrate how clay AM tools combined with rigorous computational design methodologies expand novel design and architectural applications of clay. Anton & Abdelmahgoub's (2019) research "Ceramic Components" demonstrates possibilities of geometric non-standardization in clay component fabrication and illustrate how this can be methodically achieved via robotically driven extrusion of clay pastes. Lange's et al.'s "Ceramic Information Pavilion" utilize a PDM system mounted robotic arm to "revitalize brick specials for contemporary architectural practices that focuses on specificity in brick construction systems rather than uniformity" (Lange et al., 2019).

1.2 *Opportunities in Design for Additive Manufacturing*

The PolyBrick 2.0 line of research presented in this paper, investigates the potential of the symbiotic utilization of additive manufacturing technologies and generative computational tools in the design and fabrication of clay/ceramic modules, particularly in load bearing applications. As such, this paper touches upon the importance of AM enabled non-standardization in materially efficient architectural design, and proceeds to shift the primary focus on outlining proposed expansions to fabrication technologies and methods to manufacture such non-standard modules at a construction scale. In the following sections, the previously established workflow for the bio-inspired algorithmic generation of load responsive lattices (Birol, Lu, Sekkin et al., 2019) is reiterated. The performance metrics of PolyBrick lattices are compared to standard load bearing lattices to highlight observed structural and material advantages. Subsequently, constraints and failure mechanisms associated with robotic paste deposition modeling of PolyBrick modules are analyzed. Two strategies are proposed to increase fabrication success and fidelity of PolyBrick lattices and porous/lattice structures at large, namely fabrication-aware geometry analysis and adaptation (1), and geometry-aware slicing and contour sequencing (2).

2 METHODS

2.1 *Algorithmic Methods: Bio-Inspired Load Bearing Lattice Generation*

Central to the PolyBrick research is the aim to embrace both the plastic nature of clay as a material and propose robust pipelines for design for biomimetic design for mass customization.

Natural precedents present a highly customized and "non-standard" modality of load bearing. One particular example, trabecular bone, is an adaptive system that regulates its structure "according to components of its loading regime and mechanical environment" (Hart et. al, 2017). Hence, its manifestation is a dynamic anisotropic lattice that is a function of its loading condition. Informed by this phenomenon, PolyBrick modules are generated through a stress-tensor informed ellipsoid packing algorithm; a lattice is created by the stitching of ellipsoid centers. This lattice is thickened locally based on strut stress parameters, creating a digital mesh model. Hence, porous components of load-responsive directionality, density, and thickness -- much like the trabecular lattice – are generatively designed for structural applications.

Comparative mechanical analysis of various standard lattice typologies and PolyBrick lattices suggest superior performance obtained through load responsivity present in PolyBrick lattices (Lu et al., 2020). This initial part of the processes, further detailed in previous papers (Birol, Lu & Sekkin et al., 2019) (Lu et al., 2020) showcase how the expansion of formal possibilities within this new paradigm in design can enhance performance efficiencies and design possibilities. The algorithmic process is compiled as a Grasshopper plug-in compatible with use with Rhino (Birol, Lu & Sekkin et al., 2019) (Lu et al., 2020).

2.1.1 *Overview of Extrusion Assemblies and Toolpath Generation Methods*

Through analysis of available clay and ceramic AMTs (Birol, 2021) mechanic piston driven paste deposition modelling (Ruscitti et al., 2019) of wetstate clay is determined to be the most suitable form of AMT to realize PolyBrick 2.0 geometries within desired scale and time constraints (Birol, Teng, Moghadasi et al., in review). This method of clay additive manufacturing is favored for the ability to achieve a high range of scales and resolutions, high control over clay body properties, and the high degree of freedom in toolpath generation (Birol, 2021).

Two assemblies of mechanical piston driven PDM extruders are utilized: PotterBot 9 Pro and a novelly developed clay extrusion assembly (CERA II) mounted onto the 6 axis industry robotic arm ABB IRB 4600 (Fig. 1). PotterBot 9 Pro is a “single-step” extrusion assembly with a mechanical piston (Ruscitti et al., 2019). The print toolpath is sent to the system as GCode, which can be generated either through a generic slicing software, such as Simplify, or through custom string editing operations established as part of our custom Grasshopper pipelines for Rhino. Contouring is done at a layer height that is 40% - 50% of the utilized nozzle diameter. Print TCP (tool center point) speed is set to 2000 mm/min. PotterBot executes the print through a 2 axis motion of the print bed (X,Y axes) combined with a 1 axis motion of the extruder (Z axis). CERA II is designed and fabricated in house as a “two-steps” mechanical extrusion assembly (Ruscitti et al., 2019) (Birol, Teng, Moghadasi et. al, in prep.) including a mechanical extrusion and feeding system. The toolpath is generated via geometry contouring, whereby the z-axis distance is set to 40% - 50% of the nozzle diameter to ensure proper layer adhesion. The countour curves are subdivided into curve points, and consecutively sent to the robotic arm using MACHINA for Grasshopper and MACHINA Bridge software on the command computer. This extruder assembly executes the sent toolpath via the 6 axis motion of ABB IRB 4600.

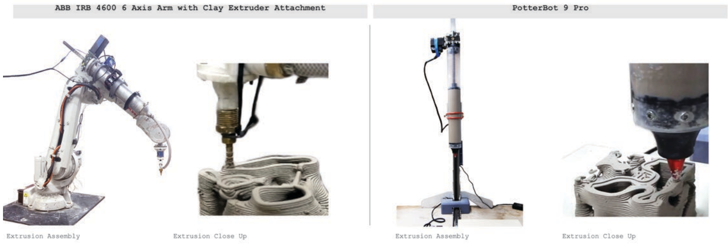

Figure 1. CERA II assembly and mounting (left), a PolyBrick print in action using CERA II (middle left), PotterBot 9 assembly, PolyBrick print in action using PotterBot 9

2.2 *Methods for Geometry Manipulation and Toolpathing in Printing 3D Lattice Structures via Extrusion Based Clay Additive Manufacturing*

Extrusion and prototyping experiments are designed to establish metrics of fabrication constraints, in regard to PolyBrick geometries. All prints are executed using 10:3 clay to water mix ratio of Georgie’s high fire stoneware clay powder. This mix is selected as it demonstrates the highest viscosity without causing over-pressurization in either of the clay extruders. Higher proportions of clay to water amount to bead inconsistency and over-excretion of the motor leading to clogs and motor failure. Higher proportions of water to clay are result in lower bead stability post-extrusion, thereby causing excessive dispersion and deformation of print beads and prototypes. Fiber additives such as concrete fibers are additionally tested and shown to increase bridging performance.

For the design of control experiments, geometry trends within PolyBrick lattices are identified and isolated (Fig. 2). Parameters of highest achievable bridging distance, bridge curvature, incidence angle from print bed, surface curvature are identified to impact printability and are consequently addressed in further algorithmic workflows with the aim to increase print success (Section 2.3.2.)

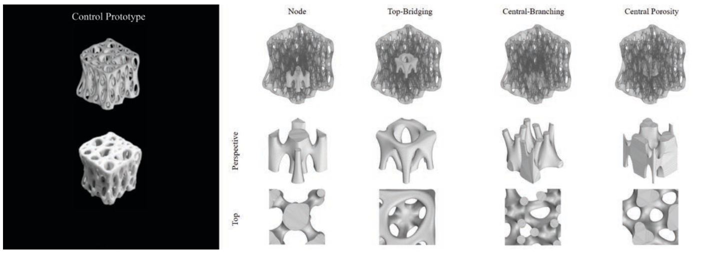

Figure 2. A central node represents a condition in which more than two struts come together (second row). A central porosity (top-bridging), adjacent to a node, is the condition in which two or more struts diverge to create hollow localities (fifth row). A bridge, at the global scale, represents a condition in which a strut spans unsupported for some distance between two support (third row)s. A branch, or more specifically a central branching condition is an instance in which multiple diverging struts span vertically and outwards (fourth row). The collective spatial juxtaposition of these conditions make up PolyBrick lattices**.**

2.2.1 *Geometry Analysis and Adaptation for Increased Print Success*

Empirical observation of print results establishes metrics of evaluation for overall print success prediction. Several geometry failures are recorded, particularly in instances of "bridging" and branching and surface contouring, as follows: (1) stability driven failures (Breseghello et al., 2021), (2) Height driven failures (Breseghello et al., 2021), (3) Bridge curvature angle driven failures (Fig. 3), (4) Bridge span driven failures, and (5) Surface curvature angle or surface concavity driven failures (Fig. 3). Of these failures, 3-5 are addressed with the implementation of the following printability analysis and geometry adaptation algorithm, and 1 and 2 are addressed through a geometry specific toolpathing algorithm (2.2.3). Experimental data is collected regarding highest achievable strut height, and lowest achievable unsupported incidence angle. Additionally bridge behavior and success observations indicate that shorter spans of unsupported bridging and higher bridge curvature angles amount to higher bridge success rates. Upon observational archiving, a tool for predicting local print success and failures is initiated. A geometry analysis plug-in for Grasshopper is written C#. This Grasshopper plug-in is packaged for analysis of 3D geometries in Rhino.

The printability analysis plug-in works by looping through each mesh face of the geometry and assigns a printability factor and a representative coloration to it (Fig. 4). The printability factor is dependent on the *angle of the mesh face normal* and *location of mesh vertices* in relation to the print-bed. It is important to note, however, that angle and location dependent printability analysis does not encompass further influence of material rheology, prototype scale, nozzle size, and extrusion and TCP parameters. Thus within the employment of this analysis algorithm, observational data regarding the highest achievable incidence angle from the print bed, and highest achievable bridging distance must be taken into account.

2.2.2 *Print Geometry Adaptation for Increased Print Success and Efficiency*

To decrease likelihood of bridging driven print failures, a subsequent geometry adaptation algorithm is developed. This is foreseen crucial step to increase print success without excessively interfering with the lattice geometry or utilizing additional print support. In this way we aim to maintain material efficiency and fabrication sustainability inherent to generated load responsive PolyBrick lattices.

This algorithm locally addresses and manipulates areas of geometry, bridging and bridge supports. In order to increase local bridge support proximity and bridge curvature angle, the vertices that span between the central area (red) of the bridge and its respective node/branch are moved in a manner that is inversely proportional to the z-axis component of the unit normal vector (Function 1). The mesh face is then remade according to the new vertices. Thus, vertices of their concentric supporting areas are moved along their normal direction and bridge supports are enhanced and the curvature angle of the bridges are increased.

n = mesh.Normals
New Vertex = Old Vertex + n * (offset distance * (1 - n.Z)

Function 1. "n" is the unit normal vector of a given mesh face within the geometry (1). Coordinate is moved in the vertex normal direction by a distance inversely proportional to the z component of the unit normal vector

2.2.3 *Toolpath Inefficiencies and a Novel Approach Geometry Specific Toolpath Sorting*

Many AMTs utilize a standardized approach to geometry slicing and toolpathing. However standardized tools make certain assumptions regarding print material properties and print geometry characteristics which do not universally apply. In this section, a geometry-informed toolpath sequencing strategy is proposed to increase print success and efficiency in the extrusion based AM of clay lattice structures.

Standard slicers for deposition-based printing (Cura, Simplify, etc.) sequence the toolpath order such that all contours of a layer z are deposited before proceeding to the next layer z+1. When a lattice is sliced horizontally, each layer contains multiple disjoint contours. This requires retraction in traveling from one contour to the next, thereby causing an increase in print time, residual clay build up at contour end points due to delayed retraction, and nozzle-motion driven deformation and destabilization of the print prototype. Consequently, the likelihood of stability driven failures (1, section 2.2.1.) and height driven failures (2, section 2.2.1.) are increased.

In the slicing of PolyBrick lattices, as well as various other lattice typologies, one can observe several trends. Firstly, all layer contours can be understood to belong to one of two categories: strut (1) or bridge (2). A strut contour is a contour that is supported by a single contour below. A bridge contour is a contour with 2 or more supporting contours underneath. A PolyBrick lattice contains both types of contours. As opposed to printing all contours within a layer in arbitrary order, printing all contours of a strut across multiple layers is proposed to decrease unnecessary travel distances, decrease print time, and enhance geometry fidelity. For the algorithmic implementation of this, a recursive logic of contour sorting is established. If a contour has more than one curve exactly below it (determined by a layer height-informed proximity analysis), it is considered a bridge contour supported by 2 or more supporting contours. The sorting algorithm is initiated by adding the first contour of layer one to a sorted list. Then each contour above it is consecutively added to the list until a bridge contour is reached. If not all supporting strut contours have been printed, remaining support struts are identified and added to the sorted list, prior to the bridge contour. The recursive sorting is ended when all contour curves of a geometry have been added into a sorted list (Fig. 3). Digital model simulations are employed to identify potential collisions between the nozzle and printed portions of the geometry, and travel paths between struts are adjusted accordingly. The following Figure 5 depicts the deposition processes implementing geometry-aware toolpathing.

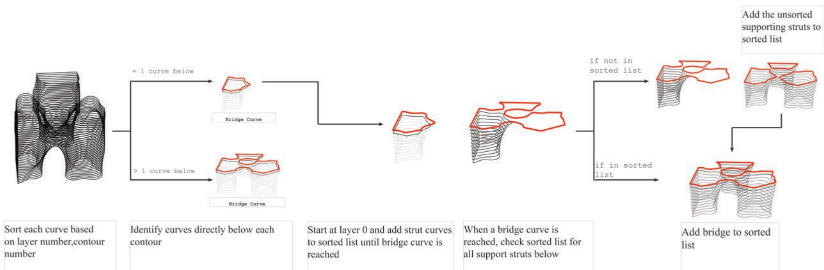

Figure 3. Workflow diagram outlining algorithmic identification and differentiation of bridge curves and strut curves.

3 RESULTS

3.1 *Print Geometry Adaptation and Geometry Aware Toolpath Sorting Results*

The developed geometry analysis and enhancement, and geometry aware toolpathing strategies are tested on introduced control modules (Section 2.2). The centrally porous control prototype is printed with and without applied geometry enhancement. It is recorded prototype prints with applied geometry enhancement algorithm show significant reduction of looping and bridge failures (Fig. 4, right).

The application of geometry aware toolpath sequencing algorithm shows significant improvement in print time and resolution from generic layer-by-layer toolpath sequencing. Residual clay accumulation at the end point of each contour is successfully mitigated (Fig. 4, left). When extrusion build up is geometry specific, in other words when each layer of a particular strut is printed consecutively, retraction is not required as frequently omitting undesired clay residue. Additionally, mitigation of long nozzle travel distances decrease prototype instability. Hence, higher print fidelity, less print deformation and decreased residual clay accumulation are recorded (Figure 4, left).

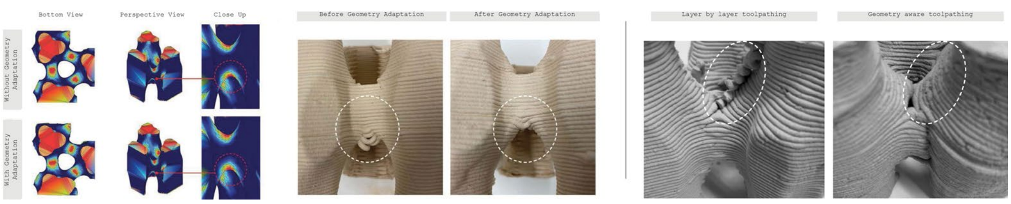

Figure 4. (Top left) Geometry analysis and (Bottom Left) applied bridge enhancement function increases support/anchor angles and areas resulting in a narrower/shorter bridge instance. (Center)The centrally porous prototype is printed using the layer by layer toolpathing and geometry specific toolpathing approach and results are compared. (Right) Clay accumulation due to imperfect retraction and its mitigation through geometry aware tool pathing.

3.2 *PolyBrick Algorithm Compilation and PolyBrick Wall Design*

Presented algorithmic workflows for lattice generation and fabrication are compiled as a series of computational tools making up the "PolyBrick" plug-in for Grasshopper. The plug-in components are utilized for the design of a load responsive *PolyBrick Wall*, thereby showcasing a potential architectural implementation. The design consists of a tessellated assembly of PolyBrick modules (Fig. 6b). The design pipeline (Fig. 5) is set up as following: an initial solid global wall geometry proposed in conjunction with its functional loading conditions. The global geometry is then analyzed under this loading scenario consisting of projected live loads (program specific user loads) and dead loads (environmental loads) using Finite Element Analysis (ANSYS). Subsequently, data regarding local principal stress magnitudes and directionalities within this global wall geometry is obtained. This informs subdivision of the wall geometry into a tessellated assembly of bricks (Lu, 2020 & Birol 2021) whereby surfaces with a perpendicular local trend to compressive stresses within the architectural body are selected as tessellation boundaries. This helps maximize the compressive forces between two brick interfaces, increasing stability between brick to brick connections. Finally, the PolyBrick packing and lattice generation plug-ins are employed to generate PolyBrick lattices within a global, tessellated wall assembly. In short, while "stress magnitudes and directions serve to inform a responsive ellipsoid packing and thickening algorithm, stress directionalities are foreseen as important drivers of tessellation" (Lu, 2020). As such, every PolyBrick module that is part of the PolyBrick wall design demonstrates geometric responsiveness to its local stress tensor data and fabrication constraints both in its overall geometry and lattice properties.

In initiating the fabrication process, each brick is analyzed using mentioned fabrication analysis plug-ins (Fig. 6a, 6b). Necessary geometry adaptations are implemented and several brick segments and bricks are comparatively fabricated via both generic and our geometry specific toolpathing methodologies (Fig. 6c, 7).

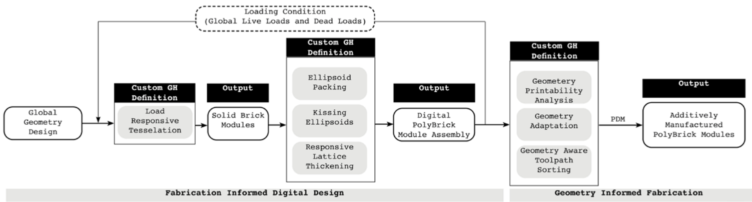

Figure 5. Workflow Diagram of generated custom scripts, inputs and outputs outlined as part of the PolyBrick 2.0 research

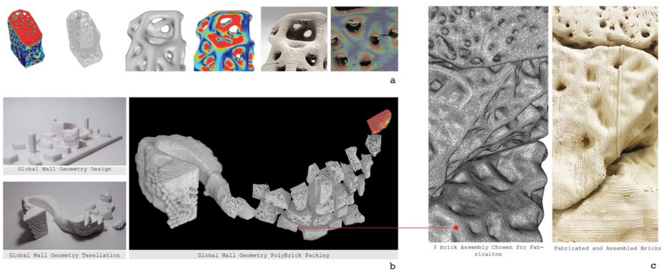

Figure 6. (a) Results of a printed portion of PolyBrick in comparison to digital models and the colored results of the analysis algorithm. An overlay of print results and the algorithmic failure prediction, indicating high correlation. (b) Outputs of the design process including a global geometry proposal, load responsive brick tessellation, and PolyBrick packing. (c) Selected brick modules for fabrication and fabrication result.

Figure 7. PDM based fabrication results of ¼ scale and full scale PolyBrick modules demonstrating the successful utilization of proposed geometry generation and adaptation algorithms contained in the PolyBrick plug-in.

4 DISCUSSION

4.1 *Results Evaluation*

Analytical findings of increased performance metrics achieved through PolyBrick lattices highlight the promise of the proposed load responsive form generation methodologies (Fig. 8). Additionally reported success with geometry analysis and geometry aware tool pathing suggest the necessity of robust AM workflows for the extrusion based deposition of clay. As such, new trajectories of designing for paste deposition modeling technologies, particularly through tools of geometry analysis and adaptation, are established, with the aim to increase prevalence of these tools in design and construction applications, particularly with clay.

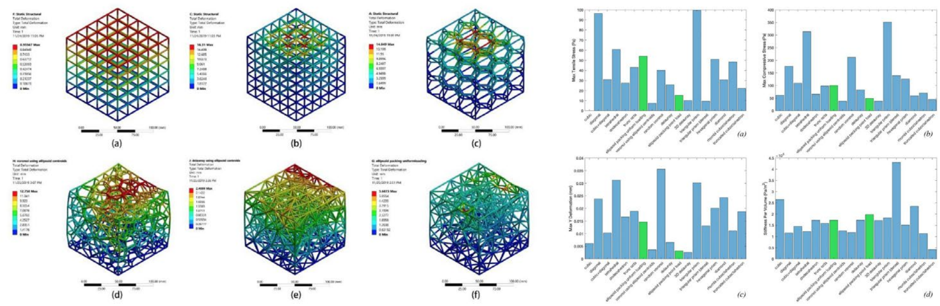

Figure 8. (1) "Part of test lattices (a) cubic (b) dodecahedron 1(c) trunc octa (d) 3D voronoi (e) 3D Delaunay (f) Kissing Ellipsoids. Blue indicates zero deformation, red indicates the maximum deformation within each lattice." (2) "Maximum Compressive Stress in one beam element. Lower stress value is more advantageous." (3) "Figure 23: Stiffness per volume for each lattice. Higher stiffness is more advantageous." Source: Lu Y., Birol E.B., Johnson C., Hernandez C., Sabin J., (2020). "A Method for Load-responsive Inhomogeneity and Anisotropy in 3D Lattice Generation Based on Ellipsoid Packing". Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA)(1): 395-404

4.2 *Limitations and Future Directions*

Several limitations and future directions are noted in the progression of this line of research. Firstly, proposed algorithms for increased fabrication success currently require user input based on empirical observation. Machine Learning processes, as well extrusion simulations based on computational fluid dynamic could serve to automate this and enhance printability analysis and bridge enhancement workflows. Furthermore, compressive testing and analysis is required to archive comparative mechanical impacts of proposed geometry enhancement and tool pathing algorithms. Increased quantitative observations regarding clay rheology in relation to print fidelity and success is an additional future direction.

Currently loading conditions and stress serve as the main input for lattice generation. However, factors such as heat transfer, water flow, air flow in relation to PolyBrick geometries can be integrated into the design process act as further inputs of geometry generation. In their comprehensive application, presented workflows hold great potential in increasing material efficiency, geometric freedom, and mechanical performance associated with building components.

5 CONCLUSION

Rapidly increasing access and techniques of AM are revolutionizing notions of manufacturability. Particularly, paste deposition modelling (PDM) exhibits extensive potential in expanding the utilization of clay and other pastes for architectural design and construction applications. Extrusion systems for PDM can be mounted onto industrial/construction gantry set-ups and 6 axis robotic arms and thereby make up for a promising additive manufacturing method to be employed at a construction scale. Additionally, due to the ability to parametrize and modularize various aspects of a clay extrusion system (Teng, Birol, Moghadasi et al, in prep.), a high range print scales and resolutions are achieved via PDM based fabrication. This showcases potential to fabricate hierarchical and multiscale structures, thereby increasing material, mechanical, and functional properties.

This paper presents a comprehensive workflow for the application of PDM based additive manufacturing in the fabrication of complex structural modules. As such, theoretical frameworks for fabrication driven design are introduced and a novel tool for the clay extrusion of lattice structures is developed. A process including algorithmically informed form finding, design speculation, and the development of necessary fabrication technologies is outlined and associated digital tools and components are presented for the potential use of the maker community. In conclusion, this paper expands on workflows for fabrication informed design, geometry adaptation, and toolpath generation, and offers tools to increase ubiquity of paste deposition modelling of clay. As such we demonstrate potential for expansive use of additively manufactured clay/ceramic components in structural and functional contexts.

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