On-Site Fabrication and Assembly for Arid Region Settlements

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With fast growing population rates and the further desertification of the global climate, desert regions, covering one fifth of the world's surface, provide an opportunity for future habitats. However, their extreme climatic conditions and remoteness pose a planning challenge, currently addressed with prefabrication and layered design; wasteful and costly solutions. This article proposes a bespoke design, fabrication and assembly process: performed in-situ with using local resources and novel automation. The research addresses challenges in on-site robotic forming and assembly of mono-material discrete elements, made in waterless concrete of sand-Sulphur composite. The formed components are examined in formwork-free assembly of wall and arch, with Pick & Place tool-path. The component's design incorporates topological and osteomorphic interlocking, facilitating structural integrity, as well as self-shading and passive cooling, to fit with local climate. This work culminates in a design proposal for constructing desert habitats, climatically adapted for Zagora oasis in the Moroccan Sahara: a remote site of hyper-arid climate.

Keywords: *Material System, Vernacular Architecture, Digital Morphogenesis, Topological Interlocking, Robotic Fabrication, Robotic Assembly*

INTRODUCTION

Mono-Material Design

Modern-day building-industry makes use of layered, multi-material design in achieving structural integrity and climatic-adaptation. Resourcing, fabrication and transportation to site (Lucon, 2014) are major sources of world-pollution, damaging soil, water and air (United Nations Environment Programme, 2017). Addressing these issues, the use of mono-material is proposed: commonly seen in biological systems and vernacular architecture, it can potentially reduce constructions costs and pollution; especially with using local resources. Single-material biological systems gain endurance and durability with efficient use of organic matter and energy expenditure, by relaying mainly on matter's geometrical arrangement (Hensel, 2010). The study of efficient natural forms for the implementation in the field of architecture, is seen in the works of Frei Otto. Its' synthesis with multiple parameters, through digital design, is known as Digital Morphogenesis (Hensel, M., Achim Menges, A., Weinstock, M., 2012); aimed at increased designs performance and adaptation to environmental and structural factors (Hensel, M., Menges, A., Weinstock, M, 2013). Mono-material design is a characteristic of arid-region vernacular architecture, as found in the Sahara region, due to scarcity of resources available (Minke, 2013). Fabrication performed on-site with using local soils is rapid, economical and efficient; with soil-aggregates performing both as structurally-sound and insulation materials.

Digital Morphogenesis in Sand-Based Material System

System's structural integrity and thermal comfort emerge as a result of geometrical arrangements in multi-scale. The formed discrete elements are assembled into pure-compression surfaces: walls, vaults and domes; coinciding with composite's compressive-strength (Minke, 2013). Their Joining, without adhesives or locks, is enabled with Topological Interlocking: kinematic constrains achieved with elaborate geometric-design of the connecting faces (Weizmann, M., Amir, O., Grobman, J.Y, 2015). Advntages of such systems include reduced sensitivity to crack-failure, element-failure or even elements missing; vibrations and displacement resistance (Estrin, Y., Dyskin, A.V., Kanel-Belov, A.J , 2001). Thermal comfort is attained through passive cooling, self-shading and thermal mass (Hakim, 2007). Cooling towers, courtyards promote indoor ventilation with minimal fenestration (Fathy, 1986), (Khoukhi, M., Fezzioui, N, 2012), (Mohamed, 2010). Shading strategies include facade-texture and self-shading in surface and section level, reducing heat intake (Fathy, 1986). Increased heat absorption and its slow release is a factor of section thickness and material-properties (Meir, I. E., Road, S. C, 2002).Synthesis of parameters relating to material, form, fabrication and assembly for increased efficiency and performance is a feature of both biological and man-made designs (Minke, 2013, pp. 11-15) (Kershaw, P.G., Scott, P. A., Welch, H. E, December 1996); guiding the modus operandi of this of research. Material parameters are coupled with environmental performance and robotic kinematic and load-bearing abilities. They are tested for their potential in in-situ architectural-scale fabrication.

BACKGROUND
Material System

The proposed mono-material system uses aggregate found on site, Sahara sand of sieve size 0.05 [FM] (Anthony, J.W, Bideux, R. A., Bladh, K.W., Nichols, M.C, 2003) (Duran, 2000), as volumizer. The small, rounded, even-sized grains are bound with world-available Sulphur (Anthony, J.W„ Bideux, R. A., Bladh, K.W., Nichols, M.C, 2015), a bi-product of local gas refineries, found in surplus in North-Africa . Sulphur was chosen as binding agent due to its low-cost, strength in binding aggregates of varies size and compositions (Darnell, 1992) ; (Samarai, M. A., Laquerbe, M., Al-Haditi, A. , 1985); without water (Toutanji, H.A., Grugel, N. A, 2009); (Wan, L., Roman Wendner, R., Cusatis, G., 2016) recycling Sulphur dioxide for construction purposes has positive environmental effect (Scott, K., Taama, W., Cheng, H., 1999); (Viltard, 1996). Previous research in sand-Sulphur composite shows its advantages over Portland cement concrete (Yuan, 1993): In resistance to basic and acidic environment; higher tensile, compressive and flexural strengths (Tawfiq, 1982), (Samarai, M. A., Laquerbe, M., Al-Haditi, A. , 1985); high fatigue resistance and hydrophobicity; recyclable potential. in rapid curing, reaching top-mechanical properties in 3 days (Lee, S.H., Hong, K.N., Park, J.K., Kond, J., 2014). Sand-Sulphur availability and rapid curing is viewed of potential for construction (Rybczynski, W., Wajid, A. Ortega, A., 1974) (Samarai, M. A., Laquerbe, M., Al-Haditi, A. , 1985), (Tawfiq, 1982). Previous studies explored composite's performance in small-quantities and in-vitro conditions. It is yet to be tested in fabrication and assembly of architectural scale, with on-site prospects.

Sand-Based Forming

Sand-based forming is a low-cost technique used in shaping hot liquids, with clay and metal-made patterns (Groover, 1996, 2015). The method drastically reduces forming-related waste, as both soil and metal patterns allow multiple uses (Thiel, 2017). It is advantageous in quick-damping and forming of large quantities allowing uniform solidification. Sand-base forming utilizes clay similar to alluvial deposits found on-site (Skiba, 2008).

Robotic Fabrication

Studies in robotic fabrication mark its performance as a prominent tool of the future work-site; with increased process control, speed, precision of execution and load-bearing capacities (KUKA Roboter GmbH, 2018) (Bonwetsch, F. Gramazio, M. Kohler, 2012). Automation enables continuous work in environments of extreme climate (KUKA Roboter GmbH, 2018) as well as an increase in workers' safety (Bonwetsch, F. Gramazio, M. Kohler, 2012). On-site automated fabrication with using robotic-arms has been studied for its potential as a multi-robotic kinematic-system in the work-site (Bonwetsch, F. Gramazio, M. Kohler, 2012) , (Keating, S.J., Leland, J.C., Levi C., Oxman, N., 2017) and in combined fabrication with several agents (Parascho, S., Gandia, A., Mirjan, A., Gramazio, F., Kohler, M., 2017).

On-site robotic assembly has evolved from vertical-stacking of even-sized small-scale component (Helm, 2014) into small-scale component with geometric joints (Retsin. G., Jiménez García, M., Soler, V., 2017), assembly of complex surfaces (Ariza, I., Gazit, M., 2015) and assembly with using minimal support (Deuss, M. Panozzo, M., Whiting, E., Liu, Y., Block, P., Sorkine-Hornung, O., Pauly, M., 2014).

While the aforementioned examples pushed further climate-resilient design, locally resourced forming and robotic-assembly separately, a synthesis with the aim of architectural-scale fabrication performed on-site, remains challenging. As most assembly projects are performed in either small-scale models or with using representative-materials, parameters and constraints relating to material, fabrication tools and methods, tool-path design, gripping instruments and assembly accuracy remain unanswered. Block Research Group at ETH Zurich has developed design and fabrication sequence for discrete elements of low-grade material in the assembly of architectural-scale double-curved surface (Block, P., Van Mele, T., Rippmann, M., 2015), yet its assembly performed manually and relied on elaborate formwork.

AMBITION

Design and fabrication of Sand-Sulphur discrete components of architectural scale; allowing self-shading, passive cooling and interlocking. Robotic Pick & Place assembly, forming wall and arch, without formwork.

METHODOLOGY

To develop a climate-aware system of architectural scale, suited with in-situ fabrication and robotic kinematic abilities, a series of physical and digital tests were designed.

1. On-Site Forming

1.1 Material composition. Taking cue from previous research in sand-Sulphur composite, performed in-vitro in small quantities, the composite was tested in fabrication of architectural-scale components. Playsand, simulant for Sahara-sand of equivalent grain-size, was mixed with binder, 99% pure powder-form Sulphur. To delay Sulphur's rapid phase change (King, 2005-2018) , increase composite's workability in a wider range of temperatures and prolonging settling-time, several modifiers were added to the composite. The following composition was used in casting 1:4 scale components, of 30x30x30 [cm]: PlaySand (volumizer)- 3 [kg] = 62.5%; Sulphur (binding agent)- 1 [Kg] = 20.8%; Talc (silicate of magnesium)- 400 [g] = 8.3%; Calcium Sulphate (Gypsum)- 400 [g] = 8.3%; Silicone oil- 40 [ml].

1.2 Material Fabrication. Preparation, mixing and casting took place in an open terrace in 25-27°[c], simulating in-situ conditions. The ingredients were heated and mixed on an electrical stove, in an open pan. Sand was added first: pre-heated for 165°[c] for 10 minutes. While maintaining constant mixing, the following additives were added: TALC, Calcium-

Figure 1
Sand-based forming of sand-Sulphur composite into 1:4 scale blocks. Method adapted from trditional metal-casting. Pictures taken from AA SChool Northen Terrace

Sulfate, Silicone-oil. The mix was heated for another 10 minutes, then Pan's temperature was lowered to 120°c. Sulphur is added last, to avoid evaporation and mixed for 3 minutes.

1.3 Composite Forming. Casting and forming were tested in fabricating 1:4 scale components (Fig. 1) of interlocking and self-shading design. The clay-sand mixture used for patterning, contains 4-11% clay, serving as binder. The mix is moistened for strength and plasticity, shaped with CNC machined patterns, and torched; to maintain its form and refrain from the composite sipping through soil-cavities. To form joinery design and façade details, patterns are used twice: for bottom detail (shaping sand-clay cavity) and top detail (shaping the heated composite). Patterns were covered in aluminum foil, for increased resolutions of detail execution; as well as to avert damage to the patterns or fire.

1.4 Results. Casting preparation and manual execution of a single component required 60 minutes, with much time spent in mixing. Material-mixing in an open-pan promotes evaporation and Sulphur-fires, compromising composite's binding. Additives improved composite's workability; its liquid-behavior allows for easy-forming. Material's sensitivity to temperature-changes and increased performance in homogenous mixing justifies fabrication in controlled environment, achieved with automation; also vital in reducing fabrication-time.

2. Thermal mass

Specific heat-capacity of both composite main components, sand and Sulphur, is relatively high. Sulphur: 700 [J/KgoC]; Sand, Quartz: 830 [J/KgoC].

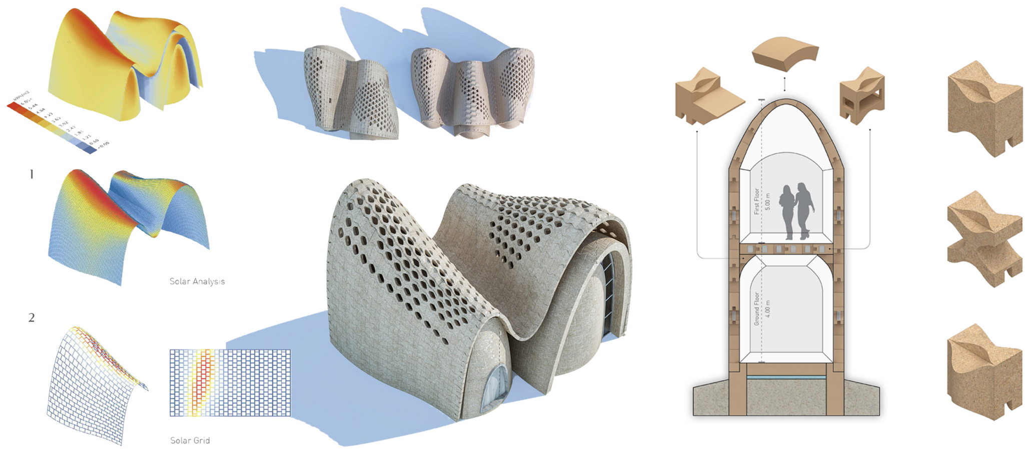

Figure 2
Left: solar analysis in Ladybug plugin for Grasshopper3D, informing roof openings and curvature. Middle: building proposal . Right: catenary curve section; building-details; building-components design of self-shading, passive cooling and topological interlocking.

Or: Sulphur: 0.17 [cal/gramoC]; sand: [0.19 cal/-gramoC] (www.nuclear-power.net, 2018). Thermal-conductivity test was performed using 4 casted samples, electric stove and 2 electronic thermometers. The stove was heated until maintained a steady temperature of 100°[c]. The casted components, fitting in size with stove shape and of 1 [cm] thickness, were placed on the stove and measured for temperature change. Heating duration, from the moment the samples were set on the stove and until reached a temperature of 100°[c], informed calculation performed in Strand7.

2.2 Results. Transmittance value was found to have [K] value of 0.3 [Kwh/mˆ2]. Composite's high-rate of specific heat-capacity and low heat-transfer are beneficial for insulation. Accumulated radiation is stored and slowly released over time, coinciding with diurnal temperature-change on site. Results influenced wall-section design of 30 [cm], for thermal mass.

3. Self Shading and Passive Cooling

Building envelope was designed in pure compression, fitting with composites compressive-strength. For increased self-shading, the envelope-surface is mathematically defined by two opposing catenary curves of different heights and two floor curves (Fig. 2: middle). Increased thermal mass achieved with second layer of envelope. Solar Access Analysis guided the forming curves height/span, as well as location of mass openings, for increased air circulation (Fig. 2: left). Calculation of surface accumulated radiation in [Kwh2/mˆ2] performed with Grasshopper3D plugin Ladybug. Thermal analysis used to guide locations of venting openings in mass.

4. Brick Morphology: Digital and Physical Experiments.

A series of discrete elements was modelled in Rhino 3D modelling tool and Grasshopper3D plugin, to comply with structural and environmental parameters: allowing passive cooling, self-shading; differing in dimensions in accordance with forces experienced (Fig. 2: right). Following studies of geometrical joineries, two evolved versions were developed:

4.1 Linear Assembly. Wall components' joining faces are formed into male-female topological interlocking, of ruled surfaces (Fig. 3). Components aggregation pattern follows traditional brick-laying principal: each vertically laid brick requires the support of the two bricks underneath it (Fig. 3: middle). Joinery design combined with aggregation pattern form kinematic constraints in X, Y, Z axes. Forces

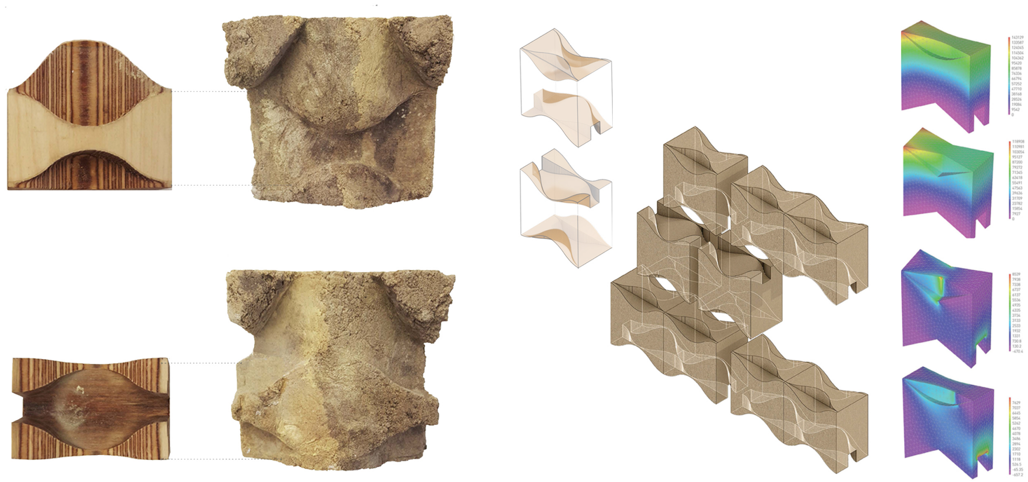

Figure 3
Design and Fabrication of sand-Sulphur wall-components. Left: topological interlocking formed with CNC milled patterns. Middle: joinery detail and aggregation pattern. Right: Autodesk Fusion 360 pressure analysis.

acting on the assembled wall are spread non-linearly along the mass, reducing failure chances. Considering composite properties and the average (1:4) brick size of 30 x 30 x 30 [cm], stress concentration values were calculated under static load and self-weight using Autodesk 360 Fusion, a structural analysis application for mechanical design. A mechanical load of 2000 (lbf) in different directions. For increased casting detail resolution, as well as to avoid breakage, joinery details was defined with curved lines (Fig. 3: right).

4.2 Arched Assembly. Arch-components were readdressed to prove potential of automated construction, solely relying on component-geometry. Here, arch's catenary curve is favorable in averting components from collapsing during assembly. The arch is discretized into non-uniform elements, increasing in size towards its base; resisting torsion through self-weight. Arch's key-stone is enlarged, "swallowing" its proximate components that may experience collapse, due to acute angle. Osteomorphic joinery was introduced to comply placing angles and robotic kinematic limitation. For speeded process, arch discretization was limited to 15 components: saving time in code-writing cycles.

5. Robotic Assembly

Assembly incorporates robotic location and movement, components dimensions and assembly logic (F. Gramazio, M. Kohler and J. Willmann, 2014). Efficient performance is defined as one of minimal errors in gripping and placing, collapse resistance during assembly and reduced cycle times. Gripper's friction-based, open-close design is so to fit with varied components geometry (Fig. 4: right). Components are gripped from their top face, on its narrow side. A feeder was designed to maintain all assembled components in same gripping location and angle (Fig. 4: left). Toolpath was simulated with Robots plug-in for Grasshopper3D, to avoid collisions.

5.1 Tool-path Design. Robotic tool-path integrates the geometrical aspects of the component, the assembled structure and safety requirements. Each tool-path consists of 6 points of reference: picking point from which all components are gripped; rotation point, to fit wuth target-position; target point within the structure; and 3 safety points. Assembly is performed with using KUKA KR 60.

Figure 4
Robotic assembly. Left: arch Pick & Place tool-path. Middle: design of catenary arch with osteomorphic interlocking. Right: 3D printed, friction-based gripper

5.2 Results. Wall assembly was tested in 1:4 scale model, cast in sand-Sulphur concrete. Linear aggregation involves assembly of same-size components in X,Y,Z axes and therefore required minimal adjusments of code gripping positions. Interlocking design and aggregation pattern (Fig. 3) proved beneficial in attaining kinematic constraints, once a component was placed. It posed minimal restriction in accurate placing. Arch assembly was tested in 1:2 scale model, CNC milled in foam for speeded fabrication and comparison. 4 arch models were tested in assembly.

ARCHITECTURAL APPLICATION

Design Proposal

A small dwelling unit, fitting five people. Dwelling unit's geometry correlates with structural and environmental paramaters, as well as formwork-free assembly requirements.Catenary-curved based design leads increased self-shading, for reduced solar gain. Additional roofing layer is proposed for increased insulation. Dwelling units are assembled in close proximy, for increased mutual shading; reducing solar gains effect on built environment.

Fabrication process

Automated large-scale fabrication of sand-based forming is proposed (Fig. 5). An additional material-processing, of automated sanding, is proposed for on-site quality control. Sanding aimed at high-resolution execution of forming details was designed and tested (Fig. 6) The tool-path was written and simulated with using Robots plug-in for Grasshopper3D. Its execution performed with KUKA KR60 robotic arm, mounted with Diamond-Cut Allow drill. A sanding table, CNC cut in 6 [mm] MDF, locks the sanded component in place.

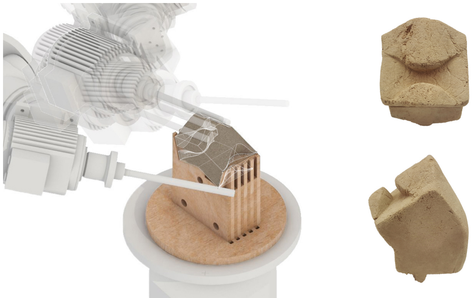
Figure 5
Sanding tool-path: a complementary processeing of fomed components, for a high-resolution execution of joinery detail.

Fabrication and assembly processes explored are proposed as construction solution fitting for remote, hot-arid regions. Zagora Oasis in the Western Sahara is characterized with hyper arid climate , and water shortage (World Meteorological Organization, 2018). Day to night temperatures vary greatly, with diurnal temperature drop of 15-20°[c] (Laity, 2008). The cho-

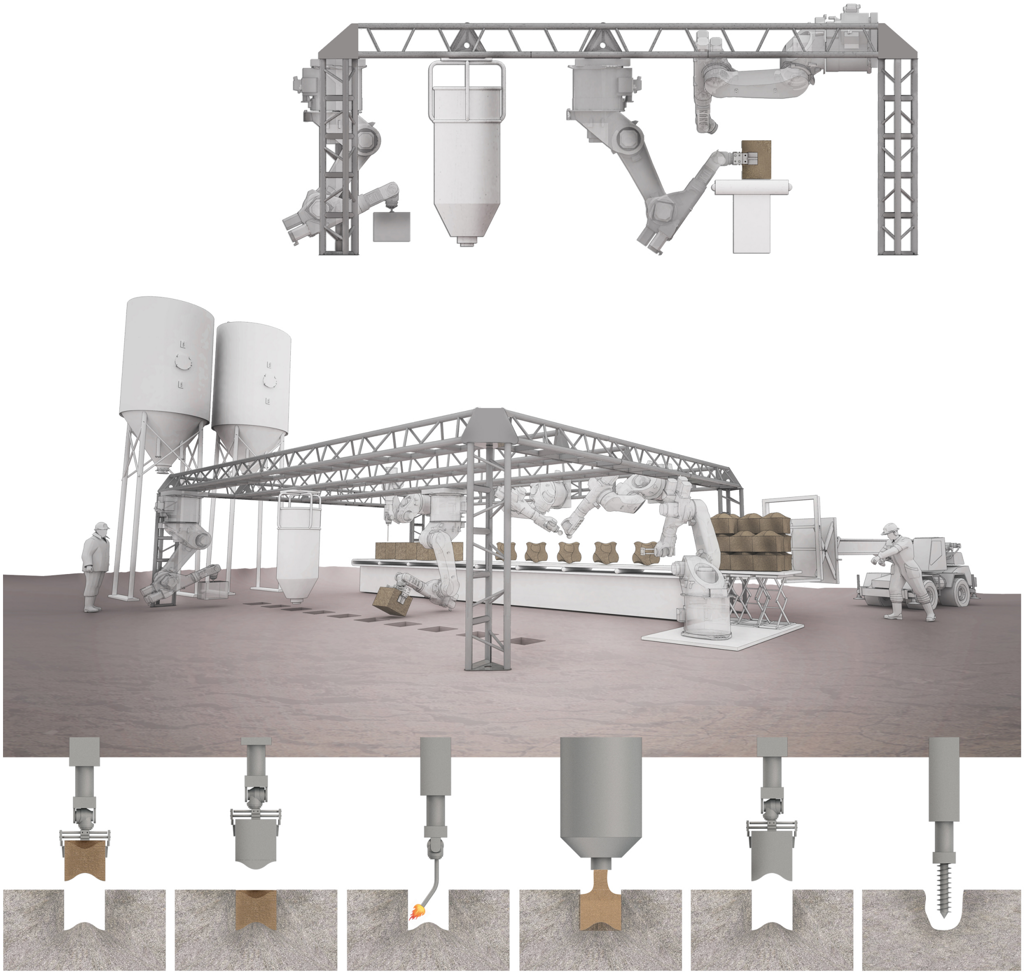

Figure 6
Proposal of on-site factory for sand-based forming

sen site is situated in a depression close to a river route, flooded in winter , while hot and arid during the rest of the year (World Meteorological Organization, 2018). Local need in affordable architecture is evident as few sources of income are at the local's disposal (Dixon, J., Gulliver, A., Gibbon, D., 2001) (Ratha, 2006).

CONCLUSION AND OUTLOOK

This paper proposed a mono-material design of discrete elements with topological interlocking, fabricated and assembled in on-site conditions, with robotic fabrication. In-depth physical analyses concluded that such a system is indeed viable. Making use of marginal, local resources is beneficial in reduced construction's cost and emission caused by transportation. Reduced amount of Sulphur in composite positively effects odor omission, a matter can be further studied for habitat applications. Process-aware design was achieved through physical models and robotic assembly experiments. Readdressing arch discretization and fitting its components with robotic limitation for assembly, combined with assembly sequence, has the potential in robotic assembly of double-curved surfaces without formwork. To further increase thermal mass with efficient use of composite, future research in employing hollow component-section with topological interlocking faces, produced in pattern-forming is proposed.

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