ROBOTIC FABRICATION OF TOPOLOGY OPTIMISED CONCRETE COMPONENTS WITH REUSABLE FORMWORK

A design-to-fabrication workflow to manufacture freeform multi-branching concrete structures

YIYAO GUO[1], YANG LUO[2], SIHAN WANG[3], YING YI TAN[4] and KENNETH TRACY[5]
[1,2]Zhejiang University, [3,4,5]Singapore University of Technology and Design.
[1]guoyiyaoelina@163.com, 0000-0002-6346-6612
[2]3170105017@zju.edu.cn, 0000-0001-5449-5799
[3]sihan_wang@alumni.sutd.edu.sg, 0000-0003-1383-6790
[4]yingyi_tan@sutd.edu.sg, 0000-0003-0545-7061
[5]kenneth_tracy@sutd.edu.sg, 0000-0002-5143-6053

Abstract. In this paper, we introduce a design-to-fabrication workflow to create topology optimised concrete components by clay printing a temporary mould and simultaneously casting concrete into it. Our fabrication approach addresses the United Nation's Sustainability Development Goal (SDG) 12 of reducing waste in construction by employing the phase changing properties of clay, allowing this natural resource to be broken down and reused for subsequent projects. We implemented our workflow in the design and fabrication of a resilient infrastructure that responds to SDG 9 - an urban furniture that braces large trees during high-speed typhoon winds and serving as a bench for locals to rest under the tree. This paper documents our workflow with considerations of its overall workability, material properties and fabrication efficiency. We showcase our final prototype and discuss the feasibility and challenges of this approach in fabricating complex freeform components on a large scale.

Keywords. Robotic Fabrication; Topology Optimisation; Freeform Concrete; Reusable Formwork; SDG 9; SDG 12.

1. Introduction

Rapid urbanisation over the past few decades has led to construction waste becoming an increasingly prominent problem. In response, both practice and academia have moved towards adopting algorithmically driven modelling and robotic fabrication to design structurally efficient building components that can be manufactured with less resultant waste respectively (Hauschild & Karzel, 2011). These strategies echo United

POST-CARBON, Proceedings of the 27th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2022, Volume 2, 91-100.

Nation's Sustainability Development Goal (SDG) 12 in reducing waste in our modern-day construction industry (United Nations, 2022).

The subject of this research is the manufacture of concrete which has often been used to make building components. Although it serves as a low-cost and structurally viable building material, fabricating concrete is conventionally a high waste process. Each component requires a sacrificial mould, typically made from timber or foam, that attributes 46.7%-73% of costs of the total building project (Agustí-Juan et al., 2017). These moulds get discarded after the project ends which inevitably leads to significant wastage.

In this paper, we investigate how concrete building components, that have their geometries derived from topology optimisation, can be fabricated in a sustainable manner. This research tackles the challenge of creating geometrically complex 3D forms that are often the result of topology optimisation algorithms. It advances our previous work that has explored using clay as a temporary mould for concrete casting (Wang et al., 2016, 2019). This combination of additive and formative manufacturing capitalises on the phase changing properties of clay as a natural resource, allowing it to be: (i) robotically extruded as a viscous material; (ii) stiffen to resist lateral pressure and broken off and (iii) recycled for future prints.

This edition of our research incorporates simultaneous casting in this fabrication workflow – a technique inspired from traditional slipforming (Lachemi et al., 2007). Our new approach involves pouring wet concrete at certain periodic intervals of the mould printing process, allowing both concrete and clay to harden and gain stiffness together as the mould is being built up. This brings about various benefits such as: (a) faster manufacturing speeds; (b) reduction of moisture loss from concrete when in contact with wet clay; (c) facilitating the creation of more complex geometries such as low cantilevers and overhanging branching elements without risking concrete not entirely filling up the mould.

We test our fabrication approach on designs created as part of an undergraduate design-and-build studio, with this paper documenting a multi-branching urban furniture shaped by topology optimisation. We describe the steps taken from design to fabrication to produce this prototype on 1:1 scale and later discusses its advantages and limitations on using this method.

2. Motivation

The design of the urban furniture responds to SDG 9 (United Nations, 2022), specifically focusing on creating resilient infrastructure in regions that experience typhoons – tropical storms with wind speeds greater than or equals to 33 m/s (Neumann, 1999). These strong winds can break large branches or even uproot trees which then injure the nearby pedestrians and/or damage buildings and infrastructure. Thus, it is vital to reinforce trees in anticipation of high wind loads from all directions during a typhoon (Kamimura et al., 2016).

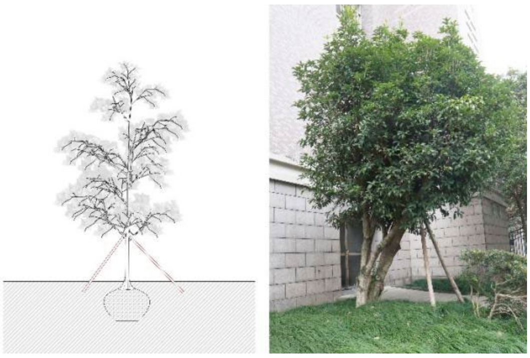

Figure 1. Traditional manual support structure made of timber poles.

Traditionally, trees are manually affixed with several timber poles at different orientations to stabilise them during the multi-directional typhoon (Figure 1). While this is a straightforward and efficient method that can be easily implemented, it faces several limitations: (I) the tree supporting structures are mostly constructed based on the workers' experience which makes the structural performance unpredictable; (II) wood poles tend to decay in high humidity in these typhoon-hit areas and require regular maintenance or replacement; (III) the supporting structure makes the area under the tree canopy inaccessible and unusable, which could have been used as a natural sunshades.

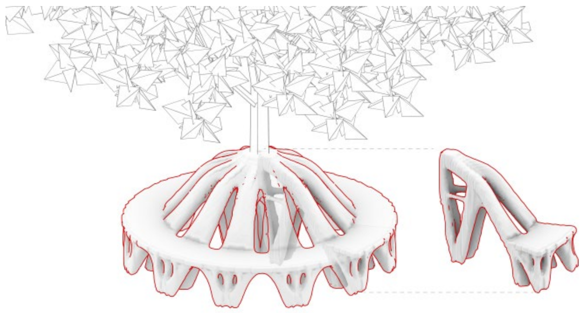

Figure 2. Conceptual design of the tree supports.

As such, our design strategy proposes a radial concrete bench positioned around the tree which can withstand multi-directional high wind loads reliably without needing constant maintenance. This also serves as a public seating area where locals can relax during regular weather conditions (Figure 2).

The support system is designed as a series of modular concrete benches that are polar arrayed around the bottom half of the tree to resist wind loads from all directions. These prefabricated benches would be assembled as a series of individual components connected to each other using concrete anchors bound by steel wires and with rubber suspensions between the trunk and the modules. Thus, this mechanism allows the individual modules to be adjusted or replaced, enabling the overall structure to adapt to different heights and girths of the tree as it grows over time, as depicted in Figure 3.

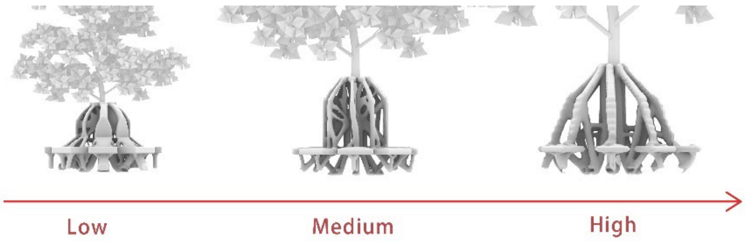

Figure 1. Supports applied on various heights and girths of the trunks.

3. Design of Components

The geometry generated by topology optimisation is dependent on the magnitudes, positions and directions of the forces that are acting on the bench. In this investigation, we defined two types of loading scenarios: (A) The load exerted by the people who sit on the flat bench surface, which is set as 2000N; (B) The wind load that the support structure can undergo to prevent breakage which should be greater than the maximum bending moment that a tree trunk can withstand:

$$M_{sb} = \frac{\pi}{32} \times MOR \times B^3 \times K_{not}$$

Equation 1. The equation of wind load on surface.

In the above equation, Msb refers to the critical bending moment for trunk breakage. This is derived from the multiplication of the modulus of rupture (MOR), trunk diameter (B) and knot factor (Knot) to account for reductions in the capacity due to imperfections and defects in the wood (Mohamed et al., 2020). Here, the tree used was Wutong, a common species in East Asia and considered as medium to tall tree standing at a height of 8-12 meters. Using equation 1, the load applied was approximately 3600 N.

The supports were designed as 12 polar arrayed individual components around the tree that each occupied a 30-degrees circular sector. As the wind loads would be applied from all directions, every component would have an identical structure and is able to withstand a wind load of approximately 2000 N.

Topology optimisation was executed in tOpos - a Grasshopper plugin which uses GPU to accelerate the iterative algorithm. The optimisation boundary was set as two adjacent volumetric blocks as seen in the grey zone of Figure 4a. The loads were assigned as red surfaces which represent the (A) human sitting load and (B) wind load, while the blue indicated the boundary support area of this structure. Once the optimisation was completed, a meshed model of the ideal distribution of material was created in Figure 4b. Lastly, the mesh was smoothened for fabrication in Figure 4c.

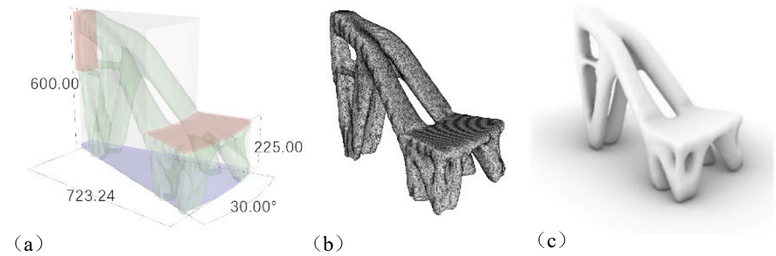

Figure 2. Design of the tree support component: (a) topology optimisation parameters for the support structure; (b) the meshed model generated from the optimisation; (c) the finalised model for fabrication.

4. Fabrication

4.1. HARDWARE AND SOFTWARE

Our 3D clay printing system has two sub-systems: (a) the extrusion end effector which includes a pump that feeds material into a cavity extruder; and (b) the positioning apparatus that allows precise control of location and motion of deposition. We used a Kuka KR120 R2500 six-axis industrial robot placed 1.6m apart from the centre points of the printing platform. Other parts of the work cell include a clay mixing sector, a concrete mixing sector and a reloading sector.

A customised end-effector was employed with a clay-feeding pump and a dispenser made of a cavity pump (Figure 5). This used a direct extrusion mechanism for the material feeder, utilising a plunger impulse by a step motor-driven reduction gearbox to push the clay out. A second phase extruder made of cavity pump was attached to the main body of the clay pump. This cavity pump can dispense 1.69 litres of clay per

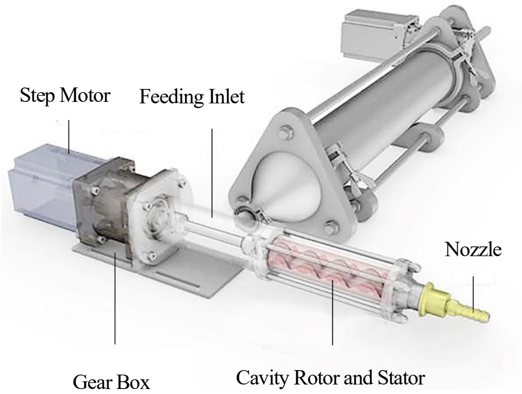

Figure 5. Schematic of the clay extrusion end effector.

minute at 300 rpm. The system also allowed the clay pump to store a large quantity of clay and generate enough torque to feed this viscous material to the extruder for precise extrusion and distribution at a rapid speed.

4.2. PRINTING WORKFLOW

The printing paths were based on the contours of global shape, sliced by the x-y plane at increments along the z-axis. We obtained these paths by offsetting the contours at half of the nozzle diameter. A double layered mould strategy was employed to create a wall thickness sufficient to resist the lateral pressure from the poured concrete and prevent leakage. Subsequently, the offset contoured paths were sorted and grouped in ascending order to assign transitions between the paths.

The planning of our approach had to consider not only the 3D printing strategy but also the casting processes, with special care to prevent the printing nozzle from colliding with the mould as it was printed. This was especially challenging as sectional contours with branches were discontinuous paths and printing these contours would cause the nozzle to travel from branch to branch without depositing material, making the printing process inefficient. Our solution was to print each branch separately so that the travel distance could be reduced. Another consideration was limiting the path length of each segment so that the amount of extruded clay was within one cylinder to avoid running out of clay before the segment was completed.

Factoring all these constraints, the component was sliced horizontally into several chunks of 300mm in height as seen in Figure 6a. This slicing also considered the large overhanging seat top surface of the mould which generated large cantilever angles. Thus, this wide area had to be split into 4 separate print paths (6-1 to 6-4) to be printed successfully.

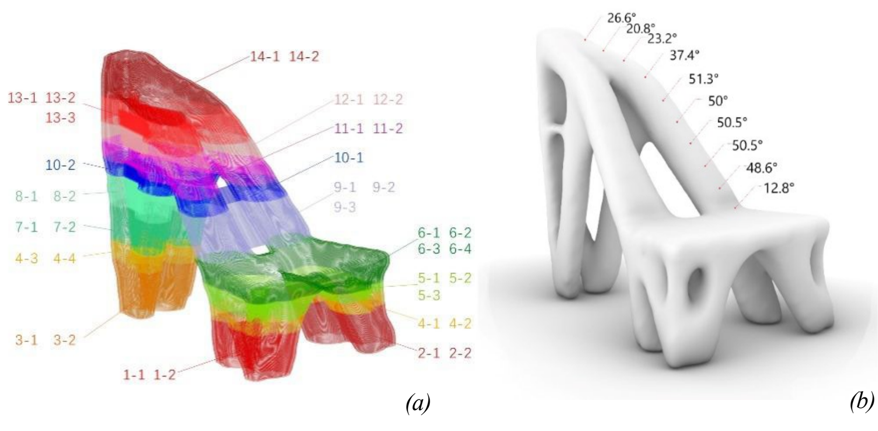

Figure 6. Fabrication challenges: (a) the segmentation of the printing paths; (b) cantilever angles along the branch.

4.3. FABRICATION METHOD & SEQUENCE

Our fabrication approach is inspired by slipforming, where a mobile formwork moves vertically upwards incrementally while concrete being poured in simultaneously. This method is useful for constructing monolithic structures and has been recently customised to fabricate geometrically complex structures (Lloret-Fitschi, et. al., 2020).

For our scenario, we print an adequately thick clay mould that resists the lateral pressure exerted by the concrete poured at specific intervals during the printing process. This gives several benefits of: (i) concurrent setting of both concrete and clay, allowing both materials to stiffen together to support the next segment, enabling larger cantilevers to be created incrementally; (ii) reducing the drying shrinkage of both materials as the concrete almost instantly fills the wet clay mould; (iii) ensure that the poured concrete entirely fills all the gaps of the mould, which is problematic for moulds with complex geometries.

The main challenge of such an approach is to identify the appropriate timing of pouring the concrete into the clay mould during the printing process. In this scenario, we consider three critical objectives: 1. The neighbouring segments of concrete must be well connected to ensure structural stability by avoiding delamination at these regions; 2. The clay printing must finish before the setting of the preceding segment of concrete; 3. The concrete has to be fast setting so that preceding segments of concrete no longer exert pressure on the clay mould and can sustain the incoming weight of the next segment of concrete. Thus, each segment of concrete must be cast before the initial setting of the former portion and must be given enough time to hydrate and solidify.

Our concrete mixture is designed to reduce its setting time and be sufficiently stiff for our application. The ingredients and their quantities are listed in Table 1, with the mix including: Calcium Sulfoaluminate (CSA), sand (S), water (W), superplasticiser (Sp), glass fibre with strands of 6 mm (GF6) and 12 mm (GF12) in length, deformer (D) and Dihydroxysuccinic acid (Da).

Table 1. Proportion of the concrete mix.

Component	CSA	S	W	Sp	GF6	GF12	D	Da
Amount(g)/Litre	812	988	295	6.5	12	12	0.9	0.5

Moreover, to guarantee the success of the print, several areas of the mould were manually supported using foam blocks that were cut to s, small clay chunks or a thin stick. These were positioned directly under the cantilevering areas with higher than 35-degree angles, such as under the seat top and at the branches at the back of the chair seat. This combination of automated and manual methods helped to reduce the chance of deformations of the clay mould when concrete was added and further sped up the overall fabrication process. In total, this combination of simultaneous robotic printing and casting allowed this urban furniture to be completed in a short duration of 5 hours.

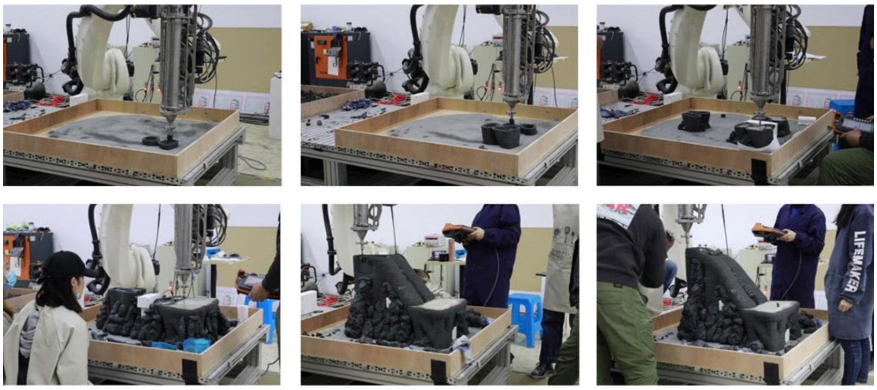

Figure 7. Fabricating the prototype

Subsequently, the concrete was left to cure within the clay mould for a total of five days before demoulding. On the first day, many cracks around the cantilever branches were observed at the regions where the segments were bonded (Figure 8a). This could be due to the smaller bonding area per layer due to the smaller sizes of the branches and larger shifts of printing paths to form the target cantilever angle. As for other areas, the cracking was distributed evenly in the cross-layer direction and along-layer direction.

On the final day, the clay mould was removed and recycled without much effort as the dried clay had already cracked and peeled off, making it easy to remove by hand. The demoulded clay was then recycled by mixing with water to filter off the concrete dust and settle as a slurry. The uncontaminated clay can be recycled for the next print job, closing the loop to this material cycle.

5. Discussion

This paper demonstrates our improved design-to-fabrication workflow to create a geometrically complex branching concrete urban furniture intended to brace trees during typhoon weathers. It showcases how our method can fabricate this topology optimised component with large cantilever angles and overhangs within a short duration. Such an approach can also facilitate the fabrication of not only structurally optimised components like our previous truss structure (Wang, et. al., 2019) or ribbed floor slabs, but also geometrically complex decorative components such as doubly curved facade panels or bifurcating non-load bearing columns.

Moreover, this approach responds to SDG 12 by considering the entire material cycle of using clay from extrusion, casting, demoulding to recycling. This closed-loop material consideration provides ecological benefits by ensuring that the clay material always returns to the first mould-making step after demoulding. This method contrasts with typical concrete formwork construction which usually ends up discarding its formwork or mould materials. Thus, this encourages a sustainable take on how a sacrificial mould material can be recycled for future prints and minimise waste.

Although this prototype uses a largely automated process in its fabrication, there still are geometric limitations where we used manual procedures. Thus, our future work aims to investigate how we can fully automate this fabrication process to minimise human intervention and make the printing and casting steps more efficient.

Figure 8. The final artifact of the tree support: (a) the clay mould a day after the final cast (before demoulding); (b) the concrete prototype (after demoulding).

Acknowledgements

This design project was one of many created during an option studio conducted in collaboration with the Zhejiang University and the Singapore University of Technology and Design. The prototyping was carried out in the Robotic and AI lab of the architectural department of Zhejiang University. The conceptual design was created by Guo Yiyao and Luo Yang with further refinements to the model and printing path generation implemented by the tutor, Wang Sihan. The fabrication sequence was planned by Guo Yiyao, Luo Yang, and Zheng Liquan. In addition to the first two authors, the fabrication process was assisted by several other students in the studio, namely Zheng Liquan, Chen Xinchang, Huang Jiale, Gu Sijia, Xu Qian, Zhu Yijiang, and Yufan.

References

Agustí-Juan, I., Müller, F., Hack, N., Wangler, T., and Habert, G. (2017) Potential benefits of digital fabrication for complex structures: Environmental assessment of a robotically fabricated concrete wall, *Journal of Cleaner Production*, vol. 154, 330-340, 06/15 2017, doi: 10.1016/j.jclepro.2017.04.002.

Akhnoukh, A. K. (2020). Advantages of Contour Crafting in Construction Applications. *Recent Patents on Engineering*, 14. https://doi.org/10.2174/1872212114666200218111631.

Gramazio, F., Kohler, M., Willmann, J., & Eidgenössische Technische Hochschule Zürich. Chair of Architecture and Digital Fabrication. (2014). *The robotic touch: how robots change architecture*. Park Books.

Hauschild, M. and Karzel, R. (2011). *Digital Processes: Planning, Designing, Production.* Birkhäuser. https://doi.org/10.11129/detail.9783034614351.

Kamimura, K., Gardiner, B., Dupont, S., Guyon, D., & Meredieu, C. (2016). Mechanistic and statistical approaches to predicting wind damage to individual maritime pine (Pinus pinaster) trees in forests. *Canadian Journal of Forest Research*, 46(1), 88-100. https://doi.org/10.1139/cjfr-2015-0237.

Lachemi, M., Hossain, K. M. A., Anagnostopoulos, C., and Sabouni, A. R. (2007) Application of maturity method to slipforming operations: Performance validation, *Cement and Concrete Composites*, vol. 29, no. 4, pp. 290-299.

Lloret-Fritschi, E., Wangler, T., Gebhard, L., Mata-Falcón, J., Mantellato, S., Scotto, F., ... & Flatt, R. (2020). From smart dynamic casting to a growing family of digital casting systems. *Cement and Concrete Research*, 134, 106071.

Mansour, M. A., Rhee, D. M., Newson, T., Peterson, C., & Lombardo, F. T. (2020). Estimating Wind Damage in Forested Areas Due to Tornadoes. *Forests*, 12(1), 17. https://doi.org/10.3390/f12010017.

Neumann, C. J., National Climatic Data Center (U.S, National Hurricane Center (1965-1995, United States. National Weather Service, & United States. National Environmental Satellite, Data, And Information Service. (1993). *Tropical cyclones of the North Atlantic Ocean, 1871-1992*. National Oceanic And Atmospheric Administration, National Weather Service, National Environmental Satellite, Data, And Information Service.

Reinhardt, D., Saunders, R., & Burry, J. (2016). *Robotic Fabrication in Architecture, Art and Design 2016*. Cham Springer International Publishing.

United Nations. (2022). *Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation,* Retrieved January 22, 2022, from https://sdgs.un.org/goals/goal9.

United Nations. (2022). *Ensure sustainable consumption and production patterns*. Retrieved January 22, 2022, from https://sdgs.un.org/goals/goal12.

Vantyghem, G., De Corte, W., Shakour, E., & Amir, O. (2020). 3D printing of a post-tensioned concrete girder designed by topology optimization. *Automation in Construction*, 112, 103084. https://doi.org/10.1016/j.autcon.2020.103084.

Wang, S.H., Morel, P., Ho, K., & Dritsas. S. (2016). Clay robotics: A hybrid 3D printing casting process, In Proceedings *of the International Conference on Sustainable Smart Manufacturing (S2M)*, Lisbon, pp. 83-88.

Wang, S.H., Huang, K.S., Huang, Z.X., Sodano, M., Xu, W.S., Raspall, F. (2019). Fabrication of Topology Optimized Concrete Components Utilizing 3D Printed Clay Mould, In Proceedings of *the International Association for Shell and Spatial Structures (IASS)*, Barcelona.