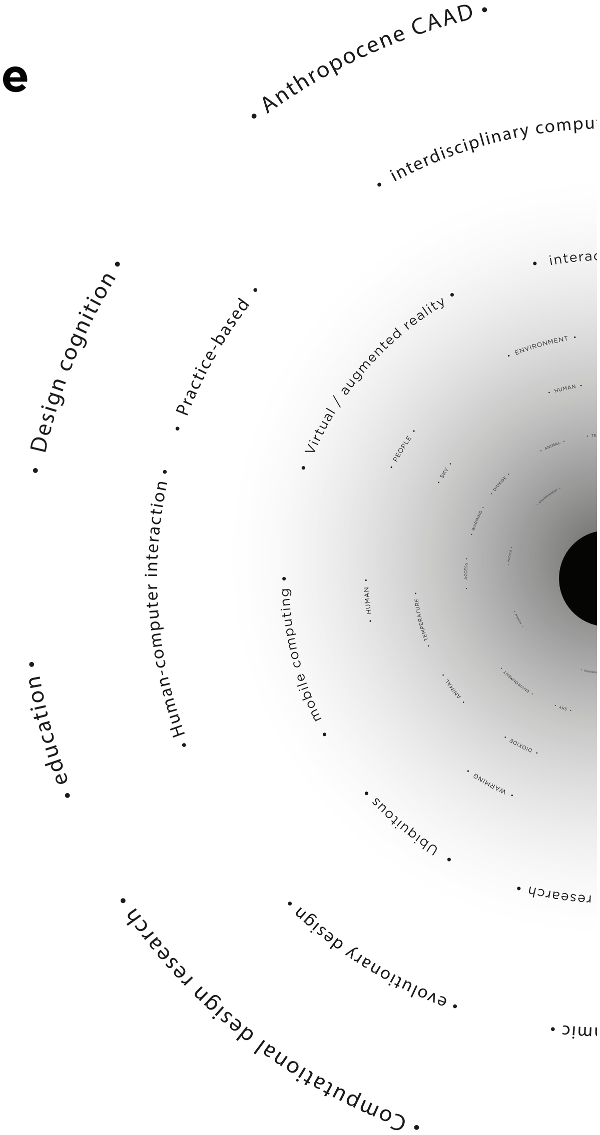
CAADRIA2020

RE: ANTHROPOCENE

Design in the Age of Humans

25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia



VOLUME 1

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Immanuel Koh

RE: Anthropocene, Design in the Age of Humans

Proceedings of the 25th International Conference on Computer-Aided
Architectural Design Research in Asia (CAADRIA 2020)

Volume 1

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RE: Anthropocene, Design in the Age of Humans

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CAADRIA 2020 Theme

RE: Anthropocene, Design in the Age of Humans

What if we are already in the Anthropocene epoch where the function of the Earth system is being impacted by human activities? What if our actions indeed are significant enough to have a critical force on the Earth as a system? The term Anthropocene (the Age of Humans) has gained increasing recognition as a description of a crucial geological stage of our planet as we face the consequences of our own events on the earth's ecosystem. While we are beginning to address the predominant challenges of sustainability and ecology, the environments we built have also shaped our behaviors.

To celebrate CAADRIA's 25th Anniversary, we challenge ourselves with these questions, asking what we want our future to look like in the next 25, 50, or even 100 years from now? If human creations are substantial enough to start a new geological epoch, what does this imply for our explorations of the realm of computational design and how will advanced technologies shape our future?

With the theme of RE: Anthropocene, we ask our contributors to REgard this new geological age as the main meaningful site for exploration into the future, REthink what our planet could become, REvisit our actions and behaviors to foster the REsponsibilities for the planet existence, and perhaps & importantly, REspond to whatever magnitudes happen to the built-environments and other planetary beings.

As the CAADRIA 2020 organizing committee, the beginning of 2020 has been quite challenging as we faced the COVID-19 pandemic in midst of conference preparations. We too, have been faced with disruptions and had to REthink, REvisit and REspond to the original format of the conference as we explored virtual possibilities. The resilience of people has never seized to surprise us and we are proud to present CAADRIA 2020 as the very first virtual conference in CAADRIA history. The essence of CAADRIA has always been and will forever be centered around the community and for that we thank all contributors for making this possible.

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Digital Fabrication & Construction

CIRCULAR CONCRETE CONSTRUCTION THROUGH ADDITIVE FDM FORMWORK

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Abstract. One of the major downsides of concrete construction is the difficulty to be adapted, modified and deconstructed. In this work, we look at the potential enabled by the use of Additive Formwork based on Fused Deposition Modelling, in order to design and manufacture structural elements which can be assembled and disassembled easily. We call this new typology of structures Circular Concrete Construction. The paper illustrates an integrated computational workflow, which encompasses design and fabrication. Technological aspects of the 3D printed formwork and its application in reversible node and strut connections are described, with reference to the material and structural aspects, as well as prototyping experiments. The work is a proof of concept that opens perspectives for a new type of reversible concrete construction.

Keywords. Circular Concrete Construction; Additive Formwork; Additive Manufacturing; Digital Fabrication.

1. Introduction

Concrete is the most used material in the world after water (Wangler et al. 2016) and by far the most used material in buildings. Concrete has good mechanical properties, is economically convenient and available in almost every country. It can be employed for a large variety of applications, across several scales, because of its capacity to adapt to any shape. Despite this intrinsic property, concrete construction is mostly limited by extrinsic factors, i.e. the employed formwork typology. Most constructions rely on reusable timber or metal formwork, to produce standard orthogonal building elements. Deviations from orthogonality in the design of concrete architecture, which is often the result of form and structural optimization, or the demand for advanced detailing are exceptions that require sophisticated approaches. The production of complex formwork is, in fact, impacting heavily on the overall construction cost (De Soto et al. 2018), and therefore largely avoided.

Advancements in digital fabrication have made it possible to develop approaches to the problem of complex concrete construction, by utilizing

RE: Anthropocene, Proceedings of the 25th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2020, Volume 1, 233-242. © 2020 and published by the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong.

subtractive techniques at a larger scale with the use of industrial robots. These approaches include the time-efficient but low-detail cut of foam blocks with a hot-wire or a hot blade (Søndergaard 2014; Søndergaard et al. 2016; 3XN et al. 2016; Brander et al. 2016), and the high-resolution but time-consuming process of milling.

In parallel to increasing ecological awareness, a recent wave of research has focused on the implementation of Additive Manufacturing (AM) to challenge the existing standards in complex formwork manufacturing. Potential advantages are in the near-zero material waste and the high level of geometric freedom (Aghaei-Meibodi et al. 2017). Moreover, AM allows for the easy integration of different functionalities within the formwork (Jipa et al. 2018). Fused Deposition Modelling (FDM) in particular offers specific advantages for construction applications, such as relatively high-resistance materials, the possibility for reuse and recycling of most plastics used for moulding, and a convenient ratio between precision and production time (Naboni and Breseghello 2018). To date, several projects have investigated FDM formwork for concrete, from early experiments (Peters 2014) to various applied work at Digital Building Technologies group at ETH Zurich (Jipa et al. 2017, Leshok and Dillenburger 2019), and at the CREATE group at the University of Southern Denmark (Naboni and Breseghello 2019), where new applications and levels of performance are targeted.

1.1. CIRCULAR CONSTRUCTION

The increased possibilities offered by FDM in forming concrete elements allow conceiving novel tectonic explorations. In this work specifically, we focus on one of the major limitations of conventional concrete buildings: the difficulty of modification and disassembly - which often leave no alternatives to demolition of buildings (Salama 2017). We introduce here the concept of Circular Concrete Construction (CCC), an approach to reversible and reusable structures which can be updated easily in time without waste generation. To achieve this, we propose an approach where the use of advanced FDM formwork if tested for the formation of reversible three-dimensional structures, made of dry-assembled struts and node joints. Specifically, we aim at proving the feasibility of using FDM to manufacture economically viable, intricate mould geometry, with sub-millimetre accuracy. In our approach, high precision moulds can be designed and produced with an automated design and fabrication process, including the detailing essential to embedding reversible features.

2. Methodology

This work involves various methods and a number of empirical experiments: it is introduced a specific material system for the formwork and the reversible node connections (i); this is initially tested and refined with a preliminary experiment (ii); subsequently, it is presented a computational workflow which automates the design and fabrication of complex concrete nodes (iii); lastly, is described a prototyping experiment in scale 1:1 which collects the previous methodological approaches into a physical artefact (iiii). The observations on this final experiment include a functional test of reversibility, the fabrication ease and accuracy through 3D scanning, and an overall quality description for future implementations in constructions.

2.1. MATERIAL SYSTEM FOR REVERSIBLE CONNECTIONS

This work is fundamentally based on the possibility of producing complex concrete elements through the use of FDM-based moulds, which can be reused multiple times. The moulds are produced with commercial machinery using thermoplastic materials that can easily withstand the hydrostatic pressure of concrete for objects up to 500 mm in height. In this experiment, we employ PLA filament because of the high geometric stability during the printing process, and its strength which allows for a reduced amount of material. The mould parts are printed separately and joined together prior to the casting. The FDM mould is instrumental to the functional combination of the two actual construction materials: concrete and steel.

The utilized concrete is a high-resistance mix fluid enough to fit into thin complex elements. After several tests, a specific type of Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) was selected. The compound is a dry mortar based on a portland/micro silica cement, mixed with fine sand aggregates (less than 3 mm in diameter), and with the addition of short steel fibres (length 12 mm, diameter 0,4 mm). This material is characterized by compressive strength of 150 MPa, and 70-90 MPa achieved after curing for 24 hours (Hi-Con 2017). The steel fibres add strength, make the material ductile to prevent cracking and provide an effective anchorage to threaded reinforcing bars, which are used to ensure the reversibility connections between various parts while serving as rebar element.

2.2. PRELIMINARY EXPERIMENT

An initial experiment was developed to understand the material behaviour for the case of a four-directions node with a 34 mm diameter. The aim was to evaluate the optimal quantity of steel fibres in the UHPFRC when casting extremely narrow geometries. A formwork consisting of several parts was utilized: the external shell was subdivided into two parts, printed with a 1,4 mm wall thickness. External caps were printed for each axis, in order to confine the concrete poured into the formwork, and guarantee the precise embedding of steel nuts and threaded bars. The PLA node weighs about 800 grams and was printed in about 3,5 hours. This experiment was iterated with various quantities of steel fibres, which indicated an ideal ratio between the binder, steel fibres, water of 1/0,085/0,085 kg. With this proportion, the node was produced and easily connected to strut elements which were fabricated in a similar manner. Minor imprecisions were found in relation to the concrete shrinkage during the curing process, mostly at the interface zones among various parts (Fig.1).

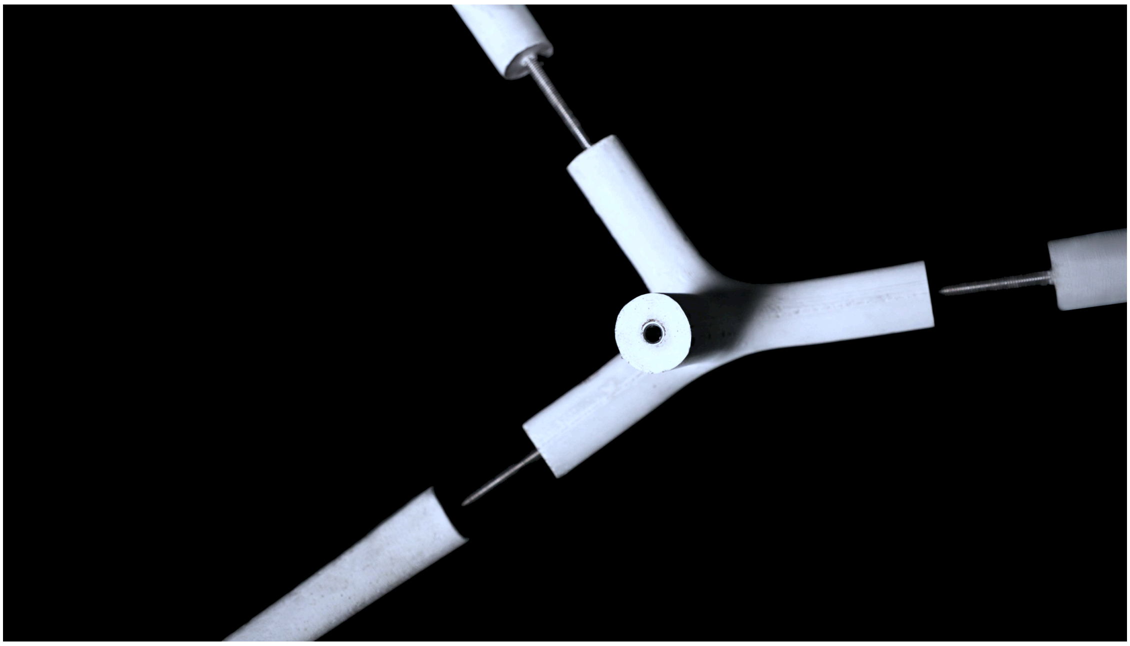

Figure 1. Preliminary experiment on node-strut reversible assembly.

2.3. INTEGRATED WORKFLOW FOR DESIGN AND FABRICATION

In order to streamline the process from design to production of the reversible concrete elements, it is developed a computational workflow which allows the automated preparation of moulding parts for nodes of any topology and complexity. In the first phase, a preliminary dimensioning of the structural elements is provided, taking into account a given geometry composed of simple intersecting segments which represent the axis of a joint connection, punctual loads applied in compression/tension, and the specific properties of the adopted structural material. With this data, a moment-resistant joint geometry is generated, with pre-dimensioned struts sections, which also takes into account the self-weight of each element.

In the second phase, the actual node design is generated utilizing tools for volumetric modelling to wrap a continuous node geometry with the determined sections and control various shape parameters. Subsequently, a refinement into a quadrilateral mesh is executed to obtain a mesh topology coherent with the overall node topology. The geometry is afterwards discretized parametrically.

The third workflow cluster focuses on the mould design for fabrication with 3D printing. An exact number of mould parts is here determined in coherence with the node topology, to allow an easy assembly and disassembly. The mould is oriented for the concrete casting process, and a supporting geometry is generated accordingly. Additional details are added to facilitate the referencing of the mould parts. An auxiliary positioner is also generated to hold the threaded rods in the correct position, both within the mould and to ensure accurate and easy welding of the steel elements. In this last phase, the G-codes for 3D printing are automatically generated taking into account the orientation of the parts for an optimal printing process (Fig.2).

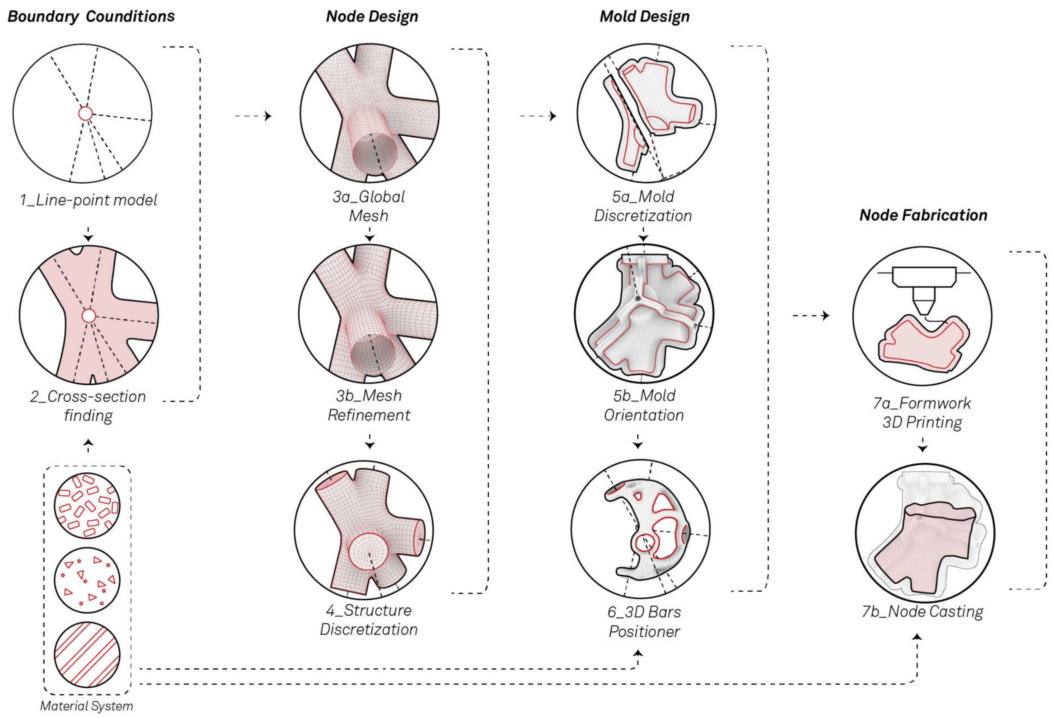

Figure 2. The scheme shows an overall design-to-fabrication workflow that has been implemented in this research.

2.4. PROTOTYPING EXPERIMENT

The above-described workflow is utilized for the design and manufacturing of an actual UHPFRC node for a lightweight concrete structure, prototyped in scale 1:1. The aim is testing the workflow, run assembly-disassembly tests in order to verify the initial hypothesis, and assessing the production accuracy. The node is a 6-axis connection, each with a diameter of 100 mm (Fig.3).

The overall node geometry is inscribed in a bounding box of approximately 350 mm by 300 mm by 300 mm for a total weight of 16,8 kg. Its formwork is characterized by a 5-piece moulding with a shell thickness of 4,9 mm. These parts have a 35 mm wide contact surface kept together by bolted connections.

Within the formwork, a welded piece with six threaded M8 struts is placed into position - this is previously welded with the use of a 3D printed positioner (Fig.4a). Threaded bars are connected to long nuts which will allow external parts to be connected afterwards.

The fabrication of the node required 2,2 kg of PLA and a printing time of 36 hours in total, using a nozzle diameter of 0,7 mm and a layer resolution of 0,2 mm (Fig.4b). The concrete mix was applied after a layer of releasing agent and exposed for a couple of minutes on a vibration table. After 48 hours, the mould parts are easily removed and cleaned for reuse - a total of three times in this experiment, without an observable reduction in functionality.

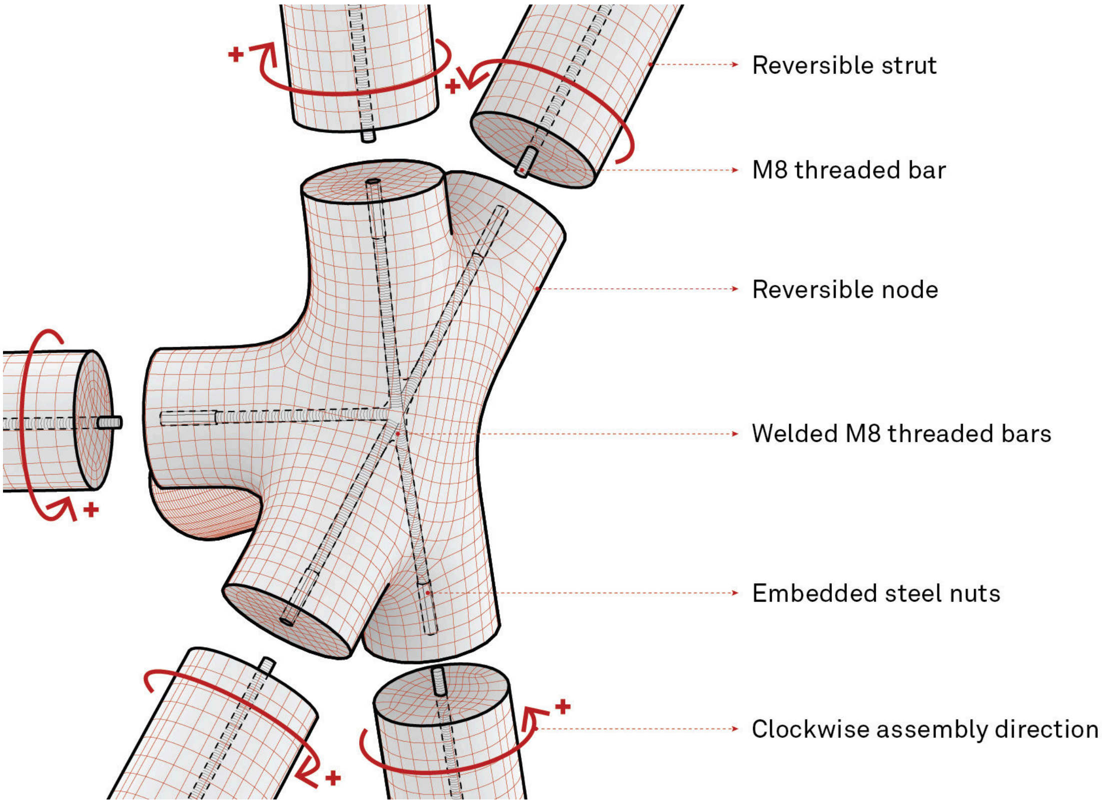

Figure 3. Schematic representation of a node-strut connection.

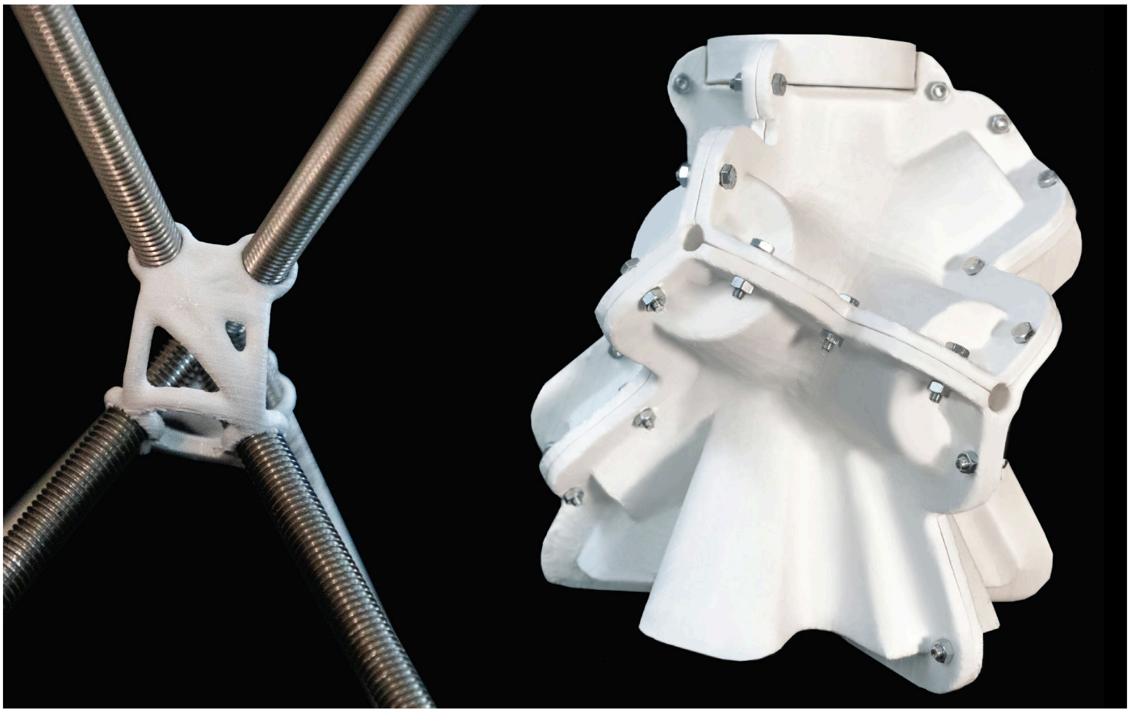

Figure 4. a) 3D printed fixture for an accurate welding process of the threaded rods which are placed within the node; b) 3D printed mould for a 6-axis node consisting of five assembled sub-parts which assure ease in demoulding process.

3. Results & Discussion

The experiment was successfully implementing a functional real scale prototype where the struts can be easily assembled and disassembled without the aid of complex machinery (Fig.5).

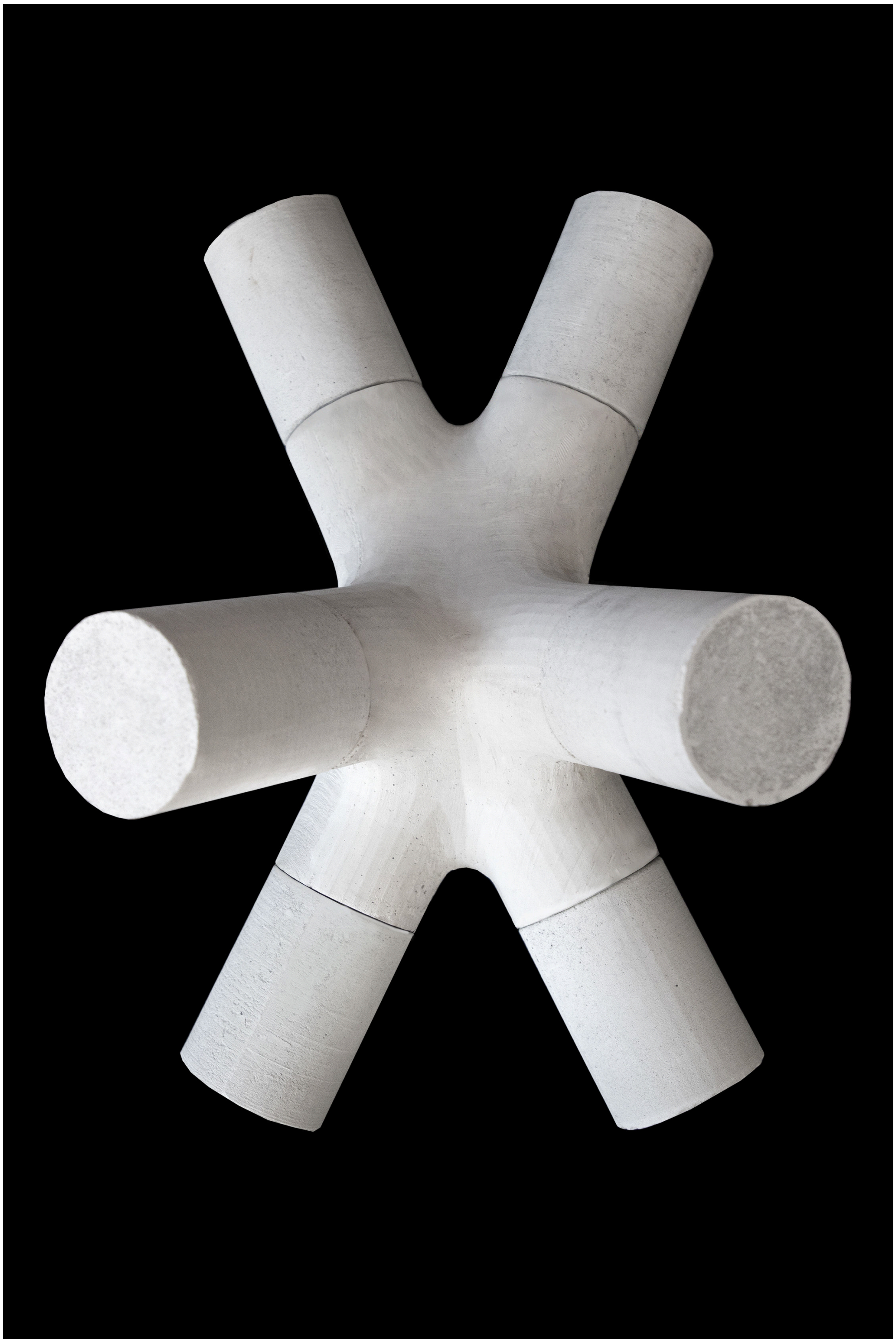

Figure 5. An assembly of a 6-axis node and the complementary struts.

In order to assess the precision of the prototyped node, we utilized an industrial metrology 3D scanner, from which we obtained a high-resolution point cloud. In the first analysis, we have compared the obtained point cloud data with the original geometry. This representation allows us to observe fine defects emerging from the fabrication process, such as the seams among assembled mould sub-parts, and local defects due to the evacuation of air embedded in the concrete mix, trapped within the non-transpirant mould - which accumulates on the top surfaces of the volume (Fig.6a). An observation of the mesh model favours an intuitive understanding of the differential displacements within the node shape (Fig.6b). The areas with larger deviations from the original (max 6,7 mm) are localized in the top areas with horizontal orientation, due to volume reduction of concrete, as the air loss occurs during the curing period. 88,5% of the points are included in the deviation range of ± 1 mm.

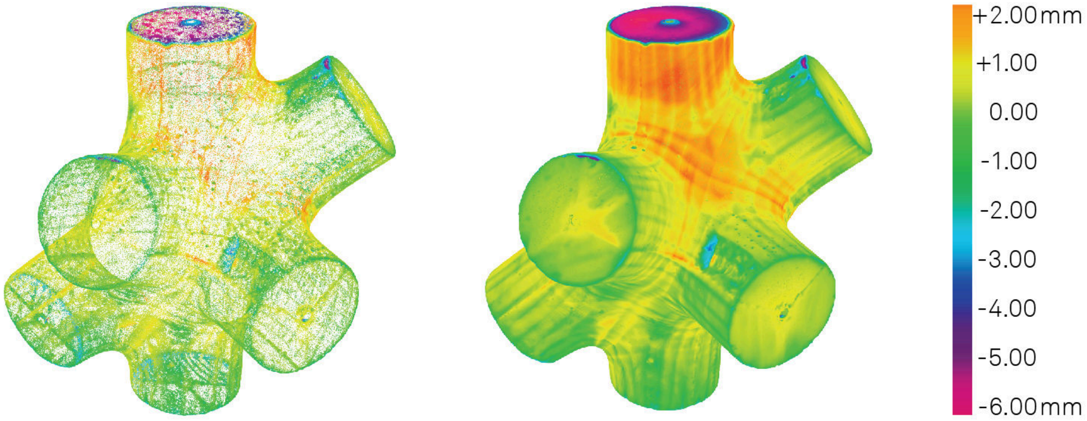

Figure 6. Points deviation analysis from the digital model to the 3D scanned one: a) points visualisation; b) mesh visualisation.

Furthermore, with an aim to provide the basis for a mechanical assessment of the node, one of the prototypes was oriented in the casting position and cut with a vertical plane, in order to investigate the internal organization of the steel fibres. We could observe an uneven distribution, with most of the fibres accumulated at the bottom areas of the geometry, in respect to the orientation adopted during the concrete pouring. This phenomenon requires further investigation in relation to the pouring process (Fig.7).

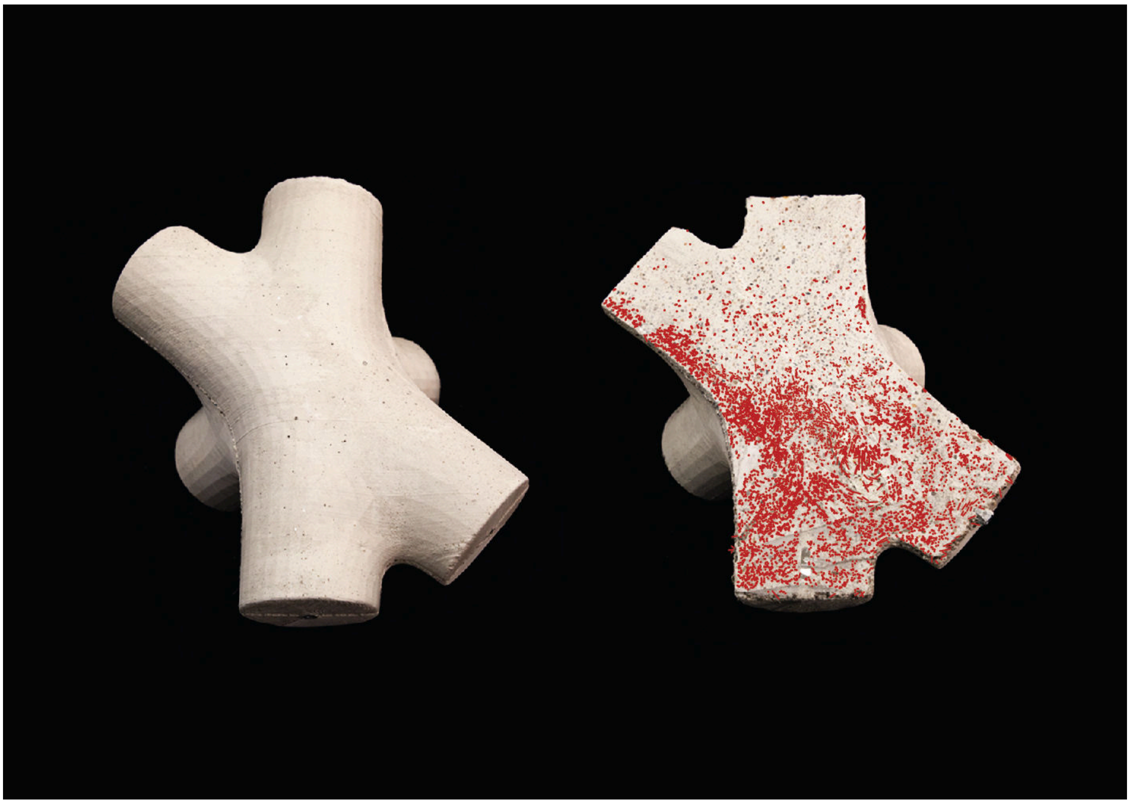

Figure 7. Analysis of the steel fibres distribution occurring through a vertical section of the node.

4. Conclusions

This paper introduces and proves the feasibility of a novel approach to reversible concrete construction, enabled by the use of additive FDM formwork. The complexity enabled by this approach allows adding innovative formwork features, such as the use of advanced detailing for reversible connections. In parallel to the tectonic and manufacturing investigation, it is adopted a computational workflow for an easy and straightforward mould production starting from a simple line model, which can be easily utilized by non-expert designers. Next developments will look at controlling the reduction in the volume of concrete, and the fibre distribution in the volume, to ensure a superior production and mechanical quality. Future work will be directed at the implementation of such a system for large reversible concrete structures, segmented in modular components, whose formworks can be reused several times. Interesting perspective applications are in the field of temporary construction with considerable structural performances and in lightweight concrete structures which are designed to work mainly in compression.

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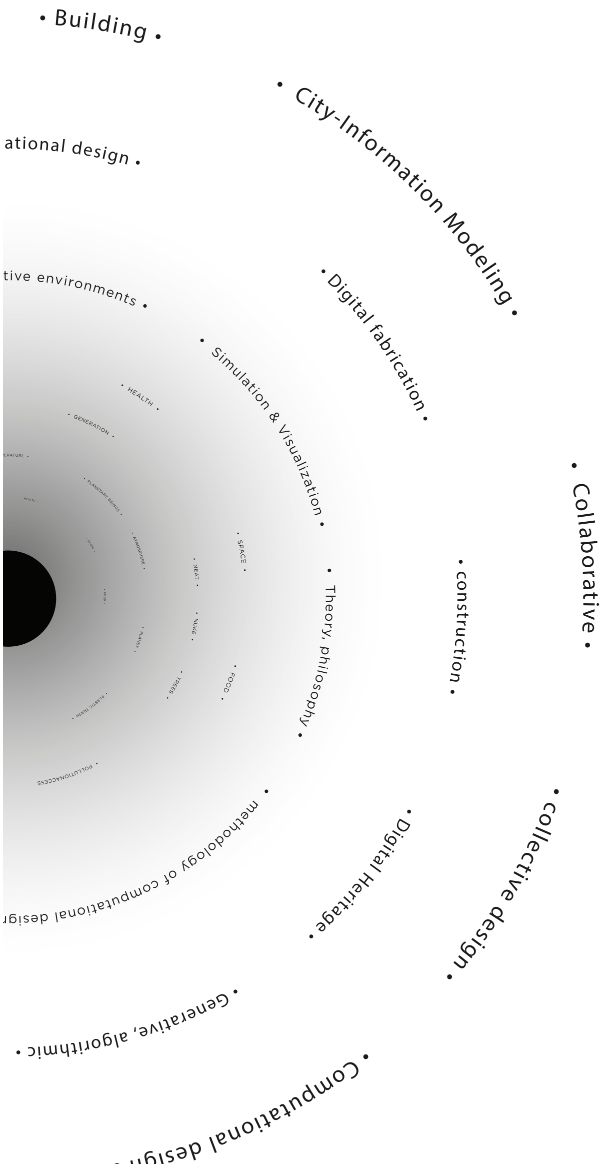

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Design in the Age of Humans

International Program in Design and Architecture (INDA)
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What if we are already in the Anthropocene epoch where the function of the Earth system is being impacted by human activities? What if our actions indeed are significant enough to have a critical force on the Earth as a system? The term Anthropocene (the Age of Humans) has gained increasing recognition as a description of a crucial geological stage of our planet as we face the consequences of our own events on the earth's ecosystem. While we are beginning to address the predominant challenges of sustainability and ecology, the environments we built have also shaped our behaviours.

To celebrate CAADRIA's 25th Anniversary, we challenge ourselves with these questions, asking what we want our future to look like, in the next 25, 50, or even 100 years? If human creations are substantial enough to start a new geological epoch, what does this imply for our explorations of the realm of computational design, and how will advanced technologies shape our futures? With the theme RE: Anthropocene, we challenge ourselves to REgard this new geological age as the main meaningful site for exploration into the future, REthink what our planet could become, REvisit our actions and behaviours to foster the REsponsibilities for the planet existence, and perhaps & importantly, REspond to whatever magnitudes happen to the built-environments and other planetary beings.

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