Additive Formwork: Examining Design, Fabrication Space and Resolution for Bespoke Concrete Elements

Roberto Naboni and Luca Breseghello

Abstract

In the era when the construction industry urges a paradigm shift towards more sustainable and efficient building solutions, the paper describes the design scenarios opened by 3D printed reusable formworks in the production of bespoke building scale concrete elements as a solution to the formal and technical limitations of the conventional manufacturing processes. Combining the latest advances in computational design and Fused Deposition Modelling (FDM) 3D printing technology, the paper presents and discusses an exploration and assessment of the higher design freedom given by the use of Additive Formwork for architecture through an experimental setup, where the design and fabrication of a series of morphologically diverse concrete panels were carried out. As a method of assessing the geometric freedom enabled by the employed fabrication technology, it is presented as an explorative design strategy that translates into multiple outputs with distinct and complementary features within the manufacturing process's characteristics high-precision control over section, curvature, inclination and detailing. Through an analysis of the digital models' geometric features and an assessment of the precision of the manufactured artefacts, the results prove that combining FDM 3D Printing and concrete is a viable fabrication technique for bespoke elements, opening to unexplored aesthetics and design solutions that can potentially improve structural and material efficiency of concrete construction.

Keywords

Additive Formwork • Ultra-High-Performance Fibre Reinforced Concrete (UHPFRC) • Design for manufacturing • Geometric analysis • High-resolution

1 Introduction

The need to reduce carbon emissions and material consumption has motivated the recent focus on evolving concrete construction technology towards more flexible, material-efficient and high-performance methods of production, with environmentally and economically sustainable design solutions. As a semi-fluid material, concrete has indeed the capacity to be used for freeform, geometrically complex and high-resolution construction that can respond to the aforementioned design shift. However, technical, material and economic constraints in manufacturing formworks limit the adoption of high-resolution and non-standard architectural elements. On the one hand, in simple concrete construction, formwork materials and related labour account for over 50% of the total cost of concrete construction (Lab, 2007), which increases to over 83% for doubly-curved geometries (De Soto et al., 2018). Nonetheless, it is well-known that a gap exists between design and making as the latest advances in digital design and modelling tools do not correspond to similar growth in building and fabrication techniques (Lloret et al., 2015). The flexibility and sub-millimetre details that digital design tools enable are strongly bound by the production constraints, and a great effort in the building design processes is often put in the rationalisation of complex geometries to respond to these limitations (Naboni & Paoletti, 2015; Pottmann, 2013).

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1.1 Research Aim

While innovative processes such as Computer Numerical Control (CNC) are already employed to manufacture custom formworks, this paper focuses on using Fused Deposition Modelling (FDM) 3D printing to produce formworks for high-resolution complex concrete elements. From a theoretical point of view, Additive Manufacturing (AM) offers the potential to match contemporary modelling tools' design freedom while minimising the need for discretisation processes. Moreover, AM has the flexibility to allow for geometric features hardly achievable with alternative fabrication methods. A limit to using this technology for the production of concrete formworks at an industrial scale is the development of a consistent method for designing, analysing and manufacturing formworks with AM. The overarching goal of this research is reducing the existing geometric gap between digital modelling and manufacturing of the formworks and enabling the full morphological potential of concrete. In this context, we conduct a design-to-manufacturing experiment to realise high-resolution concrete panels with additively manufactured reusable formworks (Fig. 1). This paper: (i) tests an integrated workflow for the design and fabrication through a design experiment of eight highly unique tiles; (ii) describes and analyses the geometric freedom provided by the proposed manufacturing technique, defining a set of objective parameters and analysis tools that evaluate the complexity of the elements.

2 Background

2.1 Geometrical and Technical Limitations in Concrete Construction

To understand the potential impact of AM on the architectural design and construction industry, it is helpful to refer to the evolution of constructions in history. Architectural geometry has been closely linked to innovation in manufacturing and construction technology in a mutual problem-setting and problem-solving relation and played a fundamental role in developing the field (Fischer, 2012). In Roman and Gothic architecture, as much as in the work of Nervi, Isler and Otto, geometric constructs were exploited to conceive efficient structures. Works such as the Philips Pavilion by Xenakis and Le Corbusier and Utzon's Sydney Opera marked the role of geometry in rationalising an original design (Austern et al., 2018). With the development in digital modelling tools of the late twentieth century and the consequent emphasis on complex shapes in architectural design, rationalisation became more and more relevant over the years (Flöry & Pottmann, 2010). More than sixty years

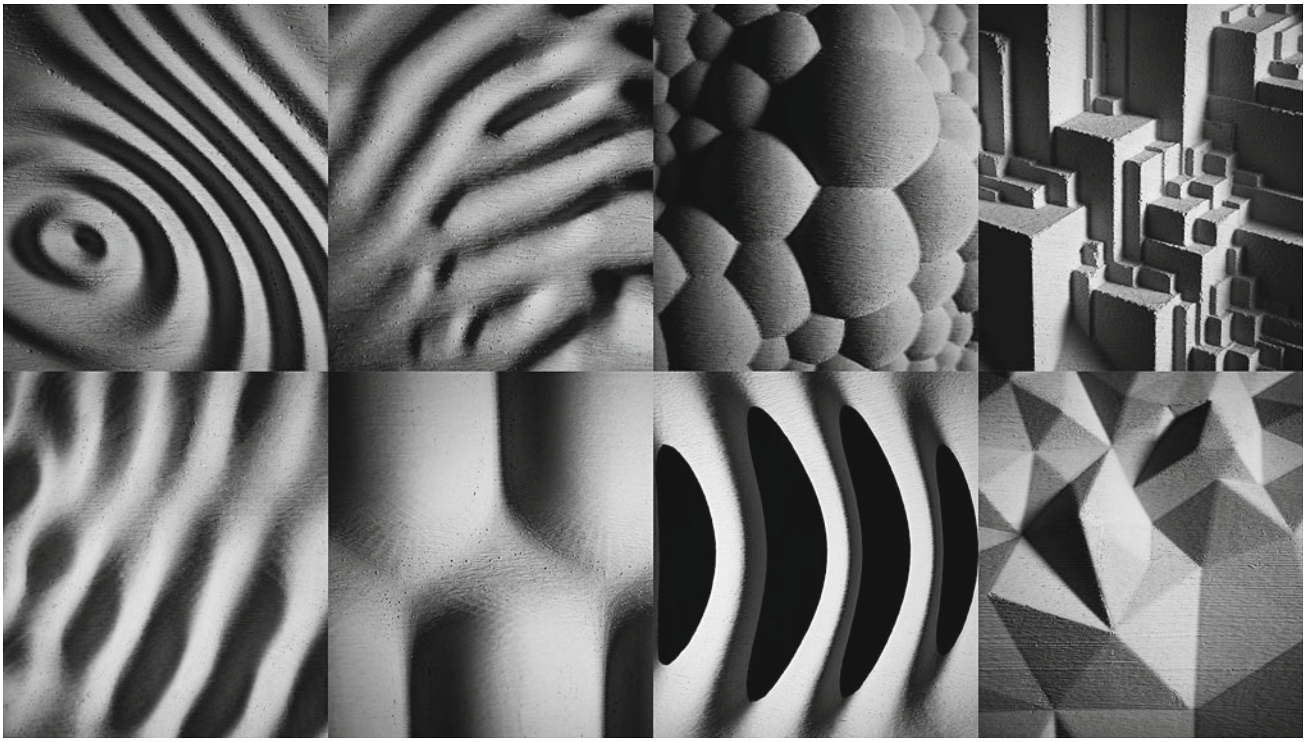


Fig. 1 Close-up views of eight experimental concrete panels designed and fabricated as a demonstration of the proposed design and manufacturing method. Image by CREATE/University of Southern Denmark

ago, Nervi observed that concrete construction was not exploited to its full potential due to technical limitations in preparing adequate formworks to contain the fluid material (Nervi, 1956). While the use of steel reinforcement is considered a milestone in the history of construction, Collins argued that the central characteristic of architectural concrete is not its plasticity but rather the way it is crafted by its mould (Collins, 1959). Still today, challenges and limitations posed by manufacturing processes are particularly relevant for constructions in concrete, still restricted by technical limitations. This paper investigates the potential of AM in expanding the design space of concrete construction, considering its level of detail and geometric flexibility.

2.2 State-of-the-Art in Digital Formwork

Due to its impact on construction management and the economy, the making of moulds for non-standard concrete elements is being increasingly explored in practice and academia (Clifford et al., 2014). CNC milling of plywood is a well-established process in the industry for bespoke formwork manufacturing, as it relies on a consolidated material and a technology that offers high design freedom and precision and consistency (Liew et al., 2017). However, inherent in the subtractive milling process are the long machining time and the waste of material, which affects both the environmental and economic sustainability of the operation. Alternatively, milled Expanded Polystyrene (EPS) is employed. Large-scale-robotic hot-wire cutting of EPS has recently gained acceptance, as it is up to 126 times faster than comparable CNC and it provides a smooth surface finishing (Brander et al., 2016). Due to the nature of the process, the design freedom is limited to ruled surfaces, demanding heavy geometric control and rationalisation. Several alternative methods are being investigated in professional practice and the academic context to reduce material waste and production time. With roots that can be traced back to the Romans, fabric formworks have a vast taxonomy of examples through history, but a small amount of scientific literature can be found (Veenendaal et al., 2011). The lightweight nature and high-quality surface finishing are the benefits of such technology; however, its implementation requires complex calculations and the formal possibilities are still limited today. Dynamic formworks such as the slipforming technology (Lloret et al., 2014) and pneumatic systems (Kromoser & Huber, 2016; Adapa, 2020), as well as reinforcement cage formworks (Hack et al., 2017) are also being investigated. In the last decade, a particular interest for AM in concrete construction arose, with most studies (Labannote et al., 2016) and industrial projects focusing on direct 3D Concrete Printing (3DCP) where the need for any mould is eliminated. To date, despite its disruptive potential, 3DCP still carries several geometric limitations and unknown performances. Alternatively, there is a growing body of research on the use of AM technologies to produce formworks to take advantage of the flexibility of the production process and rely on well-consolidated knowledge of conventional concrete (Naboni & Breseghello, 2018).

2.3 Features of Additive Formwork Manufacturing

The use of FDM technology for the fabrication of formworks presents several advantages compared to subtractive methods. Firstly, thanks to the inherent additive nature of the process, which allows depositing material only where required and to the mechanical properties of thermoplastics, the moulds can be produced as thin shell elements, saving in volume and material waste. Secondly, the programmed deposition of material guarantees high geometric freedom, with the only limitation coming from the printing overhangs and a high-resolution, dependent on the extruder dimension (Naboni & Breseghello, 2019). Furthermore, the strength of the plastic material makes the moulds suitable for reuse in multiple casts without losing their functional and mechanical attributes (Naboni & Paparella, 2020). Finally, the high degree of process automation of FDM 3D printing makes it an accessible, safe and sustainable formwork technology.

3 Methods

This research is designed to assess and quantify the geometric freedom provided by the Additive Formwork fabrication technique for concrete panels. This application is evaluated through the development and experimental testing of a workflow for the design, digital tooling and fabrication analysis of eight individual and geometrically differentiated panels. In the first phase, based on previous research by the authors (Naboni & Breseghello, 2020), this study implements an integrative design-to-manufacturing workflow (Fig. 2) for complex concrete elements realised with reusable additive formworks. The workflow encompasses four phases: (i) *Computational Modelling* of the panels, which includes geometric analysis and evaluation of their formal complexity and manufacturability; (ii) *Digital Tooling for Geometry and Process Optimization,* where digital tools are developed and employed to inform the design process with critical data regarding geometry and fabrication; (iii) *Formwork 3D Printing*, including the design and detailing of the moulds, optimisation of the machining code and production by means of FDM; (iv) *Concrete Casting,* which involves the preparation of the moulds and of an appropriate concrete

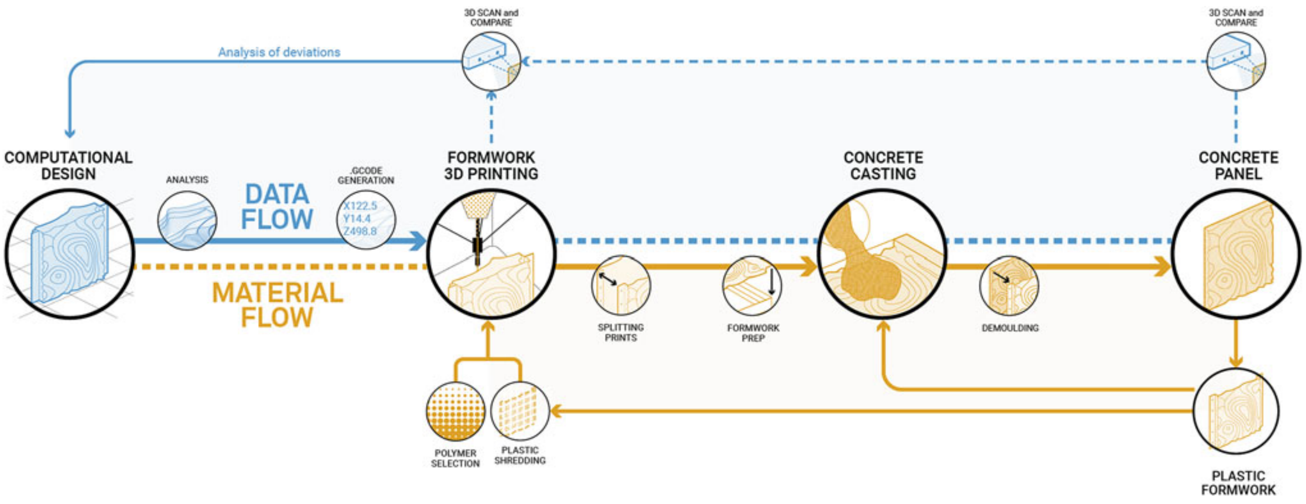


Fig. 2 Design-to-manufacturing workflow to produce concrete panels through additive formwork. Image by CREATE/University of Southern Denmark

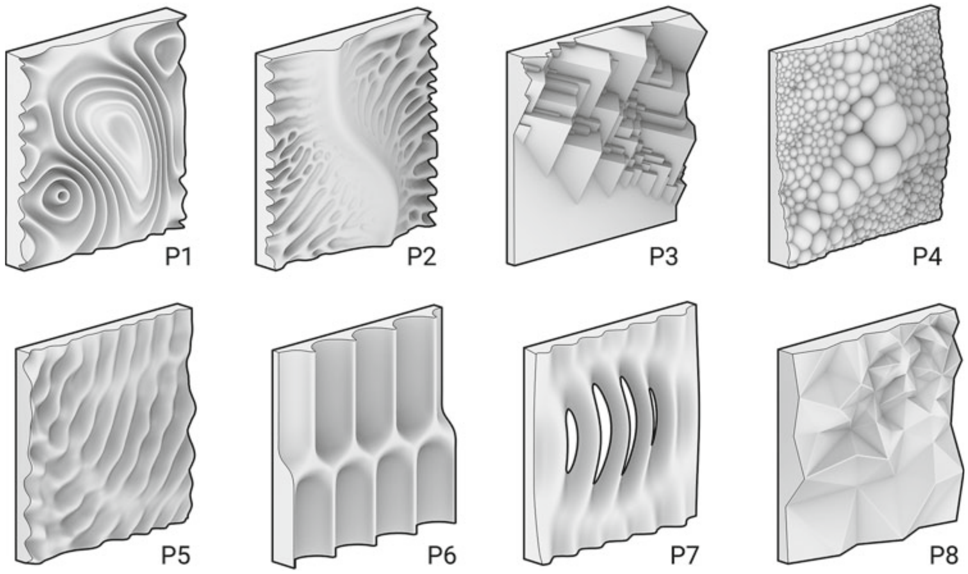
mixture, the casting process and demoulding process, where the final concrete panels are obtained and the plastic formwork is removed in a non-destructive way. In the second phase, the digital models are analysed in their geometric characteristics, i.e. mean curvature, thickness, printing angle, demoulding angle. Their geometric accuracy is evaluated with high-precision 3D scanning to evaluate the production accuracy on both the formwork and the final concrete panel.

The workflow integrates two main streams of information: on the one hand, a data flow refers to the digital information which is transferred from the digital modelling environment to the 3D printing process, consequently informing the final concrete panel and getting the feedback information from the 3D scanning process; on the other hand, a material flow informs the computational design and optimisation, where material characteristics and fabrication constraints are embedded, becoming explicit in the Formwork 3D Printing, Concrete Casting and Demoulding, where the digital geometric code (*gcode*) is translated into a machine toolpath, the concrete is poured and the panels are extracted and directly reused or shredded and recycled for the 3D printing of new formworks.

3.1 Computational Modelling

Modelled to be produced in a squared dimension of 500 × 500 mm, eight panels with highly unique designs are conceived to maximise the variation of their geometric characteristics to emphasise and test the flexibility provided

Fig. 3 The design of eight prototypical concrete panels. Image by CREATE/University of Southern Denmark



by AM (Fig. 3). All the designs were developed in the Rhinoceros environment, utilising various algorithmic processes based on Grasshopper and Python. The eight panels are modelled and described through different geometric approaches, i.e. mesh, NURBS and SubD. The first panel, *P*1, exploits a distance-based sine function to produce a corrugated mesh; *P2* is modelled as a ribbed mesh with a distance-based curve attractor onto which is applied a Reaction–Diffusion algorithm based on the Gray-Scott model (Gray & Scott, 1984); *P3* is modelled through a series of semi-randomly positioned and scaled parallelepipeds, each placed with a 45° rotation on the vertical axis and 25° rotation on the axis perpendicular to the panel; the geometry of *P4* emerges from a steered circle-packing operation, where the scale of the circles follows three curve axis; *P5* is built through a wave simulation developed with the live physics engine of Kangaroo for Grasshopper (Piker, 2013); *P6* is designed using Subdivision Surface Modelling (SubD) (Peters & Reif, 2008) to achieve a periodic smooth surface; *P7* is modelled to test topological discontinuity and the application of internal openings in the panel; *P8* presents a faceted surface through adaptive re-meshing and a controlled corrugation.

3.2 Digital Tooling for Geometry and Process Optimisation

A set of analytical tools is developed within the Grasshopper environment to test and inform the design process through visual and numerical feedback. On the one hand, the geometric features of the panels are evaluated through an analysis of intrinsic characteristics of the shapes: curvature, design resolution, local panel thickness, surface area; on the other hand, a set of computational routines is used to assess and integrate on the geometric aspects related to the fabrication processes: printing angle, toolpath optimisation, demoulding angle.

Geometry. A mapping of the mean curvature of the eight designs is performed to analyse the geometric variation and its extent along each surface and assess the geometric differences between the panels. For consistency, all the digital models are converted into triangular meshes. In the modelling phase, a live visual and numerical feedback of the thickness of the designed panels is provided. A minimum threshold is set at 25 mm as it is considered the minimum thickness that the concrete used in the experiment can be used at and a maximum thickness of 140 mm is considered.

Printing. The 3D modelled designs are then translated into *gcode* using a custom slicing tool developed through Python in Grasshopper. While different programmes to translate models into machining code are commercially available, using a tool integrated into the modelling environment brings several advantages. Firstly, it guarantees complete control over the machining toolpath, allowing for time reduction and optimisation of the travel movements and interruptions of the printing flow. This is particularly relevant in large-scale extrusion processes to prevent imprecisions due to material leakage when the print is interrupted and restarted. Secondly, within the custom toolpath, a series of geometric manipulations can be controlled parametrically: for printing purposes, the panels are joined in couples using curves boolean operations on the sliced layers; two lateral surfaces useful in the casting procedure were added with the same method; moreover, an adhesion surface, i.e. brim, of width *d2* and height *h2* of 0.3 mm is generated as a result of a series of offsets of the first printing layer. Thirdly, the custom slicing tool gives live feedback during the design phase on the printability of the digital model. The stacked layers need a good contact surface with the layer below to produce a qualitative and watertight print. For this purpose, the slicing tool calculates the horizontal deviation between corresponding points in consecutive layers to provide feedback on the printing build-up in the form of a coloured mesh with a resolution of 0.1 mm (Fig. 4). This analysis generates a seamless interaction between design and analysis of the fabrication feasibility, anticipating possible problems and optimising the design process.

Casting. To preserve the rigid formworks intact to be reused, a geometric analysis of the demoulding process was performed. The normal at every point of the panel is used to calculate the angle occurring with the vector normal to each panel's planar back face, considered as the one through which the mould is extracted from the concrete (Fig. 5). This provides feedback during the design process, where the most critical areas of the demoulding are highlighted for closer examination.

3.3 Formwork 3D Printing

The slicing procedure takes into account the different parameters of the 3D printing process. The layer height is set to 0.6 mm, balancing between the speed of the process, precision and design flexibility. The higher the layer, the coarser the resolution in the vertical dimension and the smaller the possible inclination of consecutive layers. The width of the layers is set to 4.5 mm following preliminary casting tests, as it demonstrated to be sufficient to withstand the pressure exerted by concrete

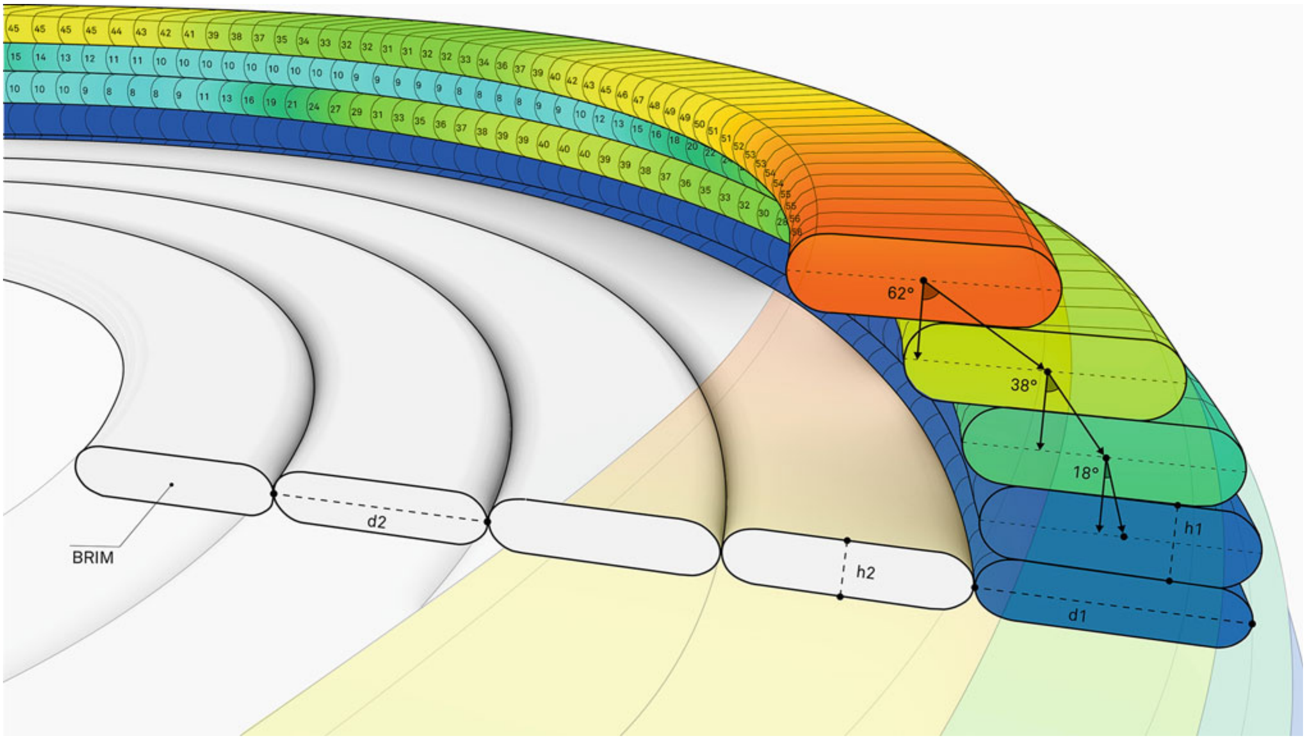
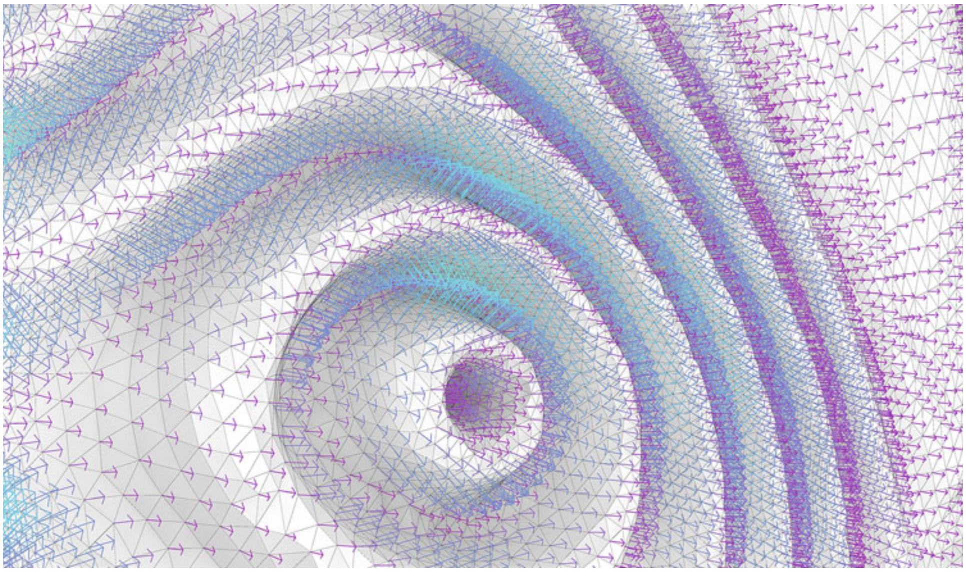


Fig. 4 Simulation and analysis of the printing process evaluate the material overhangs and possible printing angles. Image by CREATE/University of Southern Denmark

Fig. 5 Visualisation of the demoulding vectors across the formwork surface. Image by CREATE/University of Southern Denmark



with the employed formwork material. The moulds are produced using bio-polymer Polylactic Acid (PLA) pellets obtained from shredded waste from industrial production. The moulds are printed at an average speed of 80 mm/s in a delta WASP 3MT Industrial printer with a cylindrical printing volume of 1000 mm diameter and 1200 mm height (Fig. 6). The printing temperature is constantly kept at 195 C° and an overflow of the material of 30% is given to increase the extrusion pressure and the interlayer bonding strength. The 834 layers of the four prints were produced in an average of 4.5 h per panel, with an average toolpath length of 1312 m and weights ranging between 1.95 and 2.12 kg for each of the eight panels (Fig. 7).

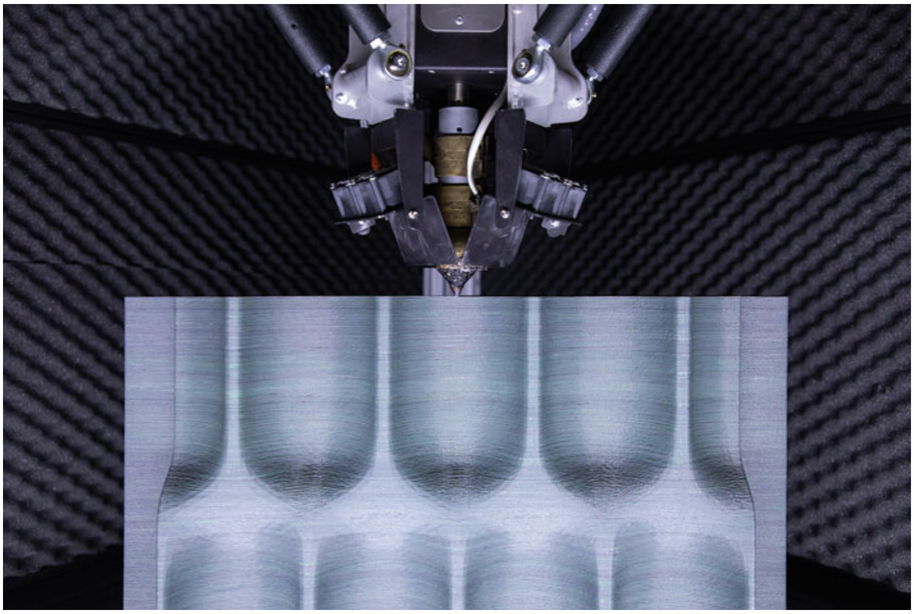


Fig. 6 FDM process of the formworks with a Delta 3 M Industrial printer. Image by CREATE/University of Southern Denmark

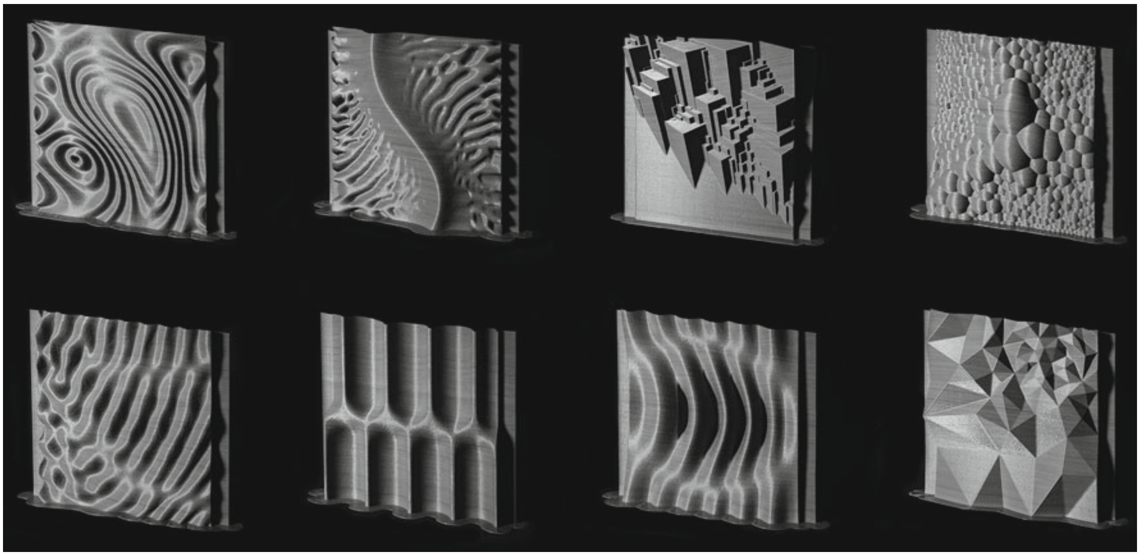


Fig. 7 Eight 3D printed moulds for concrete panels. Image by CREATE/University of Southern Denmark

3.4 Concrete Casting

The formworks are bolted to reusable modular wooden frames and oriented horizontally. This orientation of the moulds is preferred over a vertical positioning to minimise the hydrostatic pressure exerted by the fluid concrete over the mould, which is a function of the density of the fluid material and the height of the formwork. The material employed in this experiment is a Compact Reinforced Concrete (CRC) type of Ultra-High-Performance Fibre Reinforced Concrete (UHPFRC), with a self-compacting matrix suitable for the high resolution required in this application. The binder is mixed with 12% of water and 12% of short steel fibres. A release agent is applied to the moulds. The concrete is then cast and left to cure for 72 h before demoulding. The formworks are manually separated from the dry concrete. Once the mould is detached, it is washed for producing subsequent elements or eventually recycled for another cycle of 3D printing. All the concrete panels are scanned and compared to their respective digital model and the formwork point clouds, with the same procedure used for the formworks.

4 Results and Reflection

The physical output of this experiment consists of eight concrete panels with highly unique surface texture (Fig. 8). This is achieved with the use of thin reusable formworks fabricated with FDM additive manufacturing technology. The prototypes highlight the flexibility of the employed fabrication workflow.

4.1 Geometric Complexity Analysis

Mean Curvature and Thickness. The geometric analysis performed during the experiment highlighted the complexity of the design features achievable with the proposed fabrication approach. The realised panels present a mean curvature ranging from -0.59 in the designs with planar faces and sharp edges *(P3, P8)* to 0.65 in doubly-curved geometries with variable radii along their surface, with the minimum radius of curvature produced in *P1. P1, P2* and *P5* present significant variations in curvature, i.e. the rate of change of curvature per unit of area, compared to panels P4, P6 and P7, which have areas of small radius of curvature but smaller variations (Fig. 10a). All the manufactured panels have variable volume thickness, with sections ranging between 128 mm in the thickest area of *P1* and 25 mm in the shallow parts of *P2, P3, P6* and *P7* (Fig. 10b). Thanks to the adopted UHPFRC compound's tensional capacity, all the slender panels can be handled without risk of breaking (Fig. 9). The described geometric features and design resolution defined in the design are hardly compatible with any other fabrication method. In particular, the variation of the above-described parameters in the single panels and across the different panels is an unparalleled feature of AM without any additional fabrication step or cost.

Formwork 3D Printing Features. The 3D printing of the formworks proved to be consistent and met the expected design flexibility. The panels' design uses *printing angles* varying between 0° and 74°, beyond the typical limits imposed by FDM 3D printing technology. These were printed successfully as watertight geometries due to the optimisation of the height/width layer proportion, reduced from 1.0/3.0 to 0.6/4.5 and the use of cooling (Fig. 10c). The experiment shows the influence of the printing angle in the demoulding process, as more overhanging material corresponds to a rougher surface finishing, which creates additional friction between the plastic form and the concrete. From visual inspection, it is possible to assess that large overhangs towards the inner side of the mould cause irregularities and in turn, enhance the grip between the concrete and the mould. Printing angles are one of the main shortcomings of FDM 3D printing. However, the successful

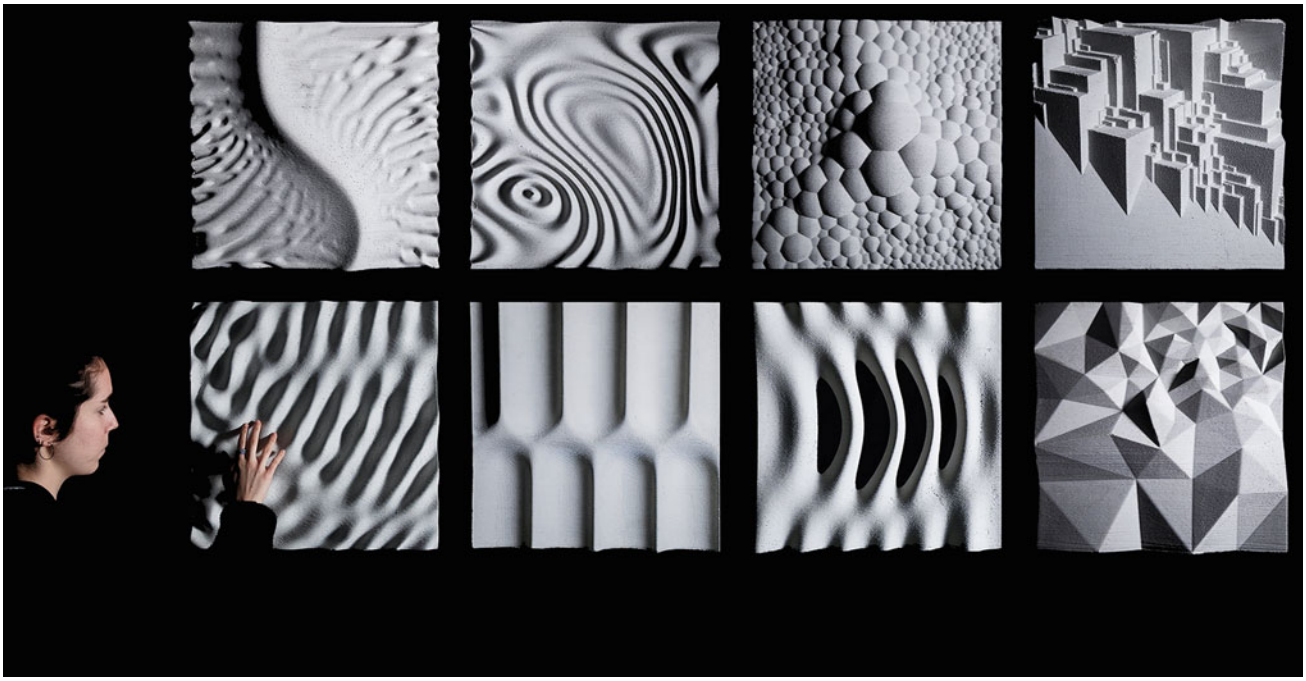


Fig. 8 The eight resulting concrete panels. Image by CREATE/University of Southern Denmark

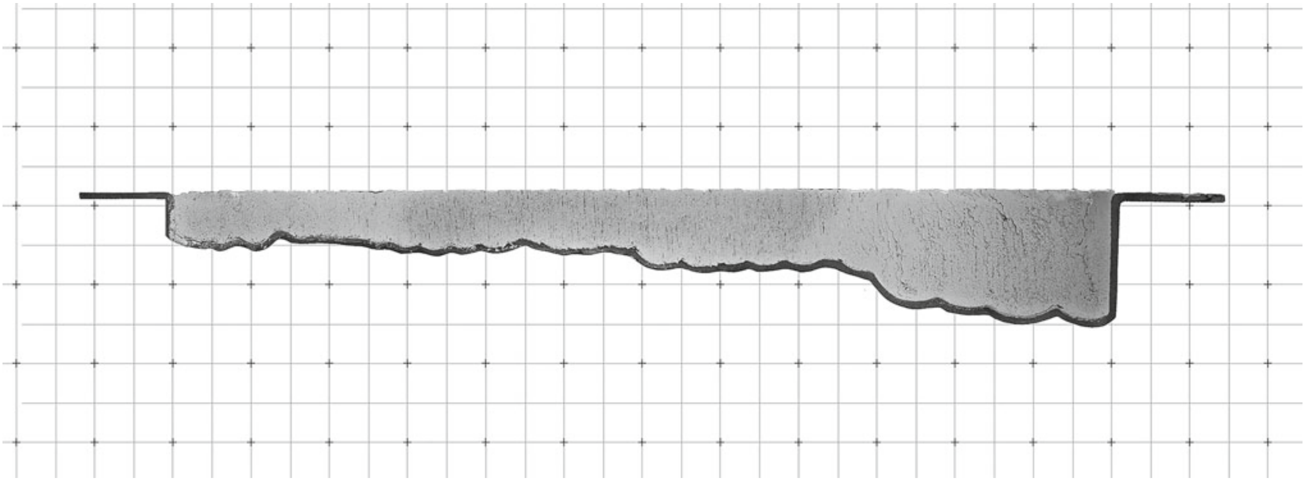


Fig. 9 Section of P4 shows the concrete element and the plastic formwork and highlights the thickness variation. Image by CREATE/University of Southern Denmark

production of these moulds and concrete elements, with an optimisation of the layer proportion, reduces the limitations.

Demoulding Features. Demoulding the panels to reuse the rigid formworks was carried out successfully for most of the elements. On a theoretical level, any angle lower than 90° between the direction of extraction of the mould and the surface should be possible. However, we observed an influence of the friction of the layered concrete on the extraction process proportional to the demoulding angle (Fig. 10d). The analysis shows the maximum and average inclination for each panel: the larger angles are registered in *P3*, which has a maximum inclination of 79° and an average of 50.9°, whereas the lowest is seen in *P8* presents a maximum angle of 61° and an average of 31.5°. While all the other panels were smoothly demoulded, *P3* and partially *P1* and *P2*, required using a heat source to deform the formwork for removal, making it not suitable for reuse. The demoulding of *P1* and *P2* was particularly difficult in the areas with higher curvature and printing angles, suggesting an interdependent relationship between these parameters and the operation of demoulding. The demoulding of the panels highlighted the importance of accounting for the demoulding angles in the design phase as it constraints the fabrication and the possibility of reusing the 3D printed formworks.

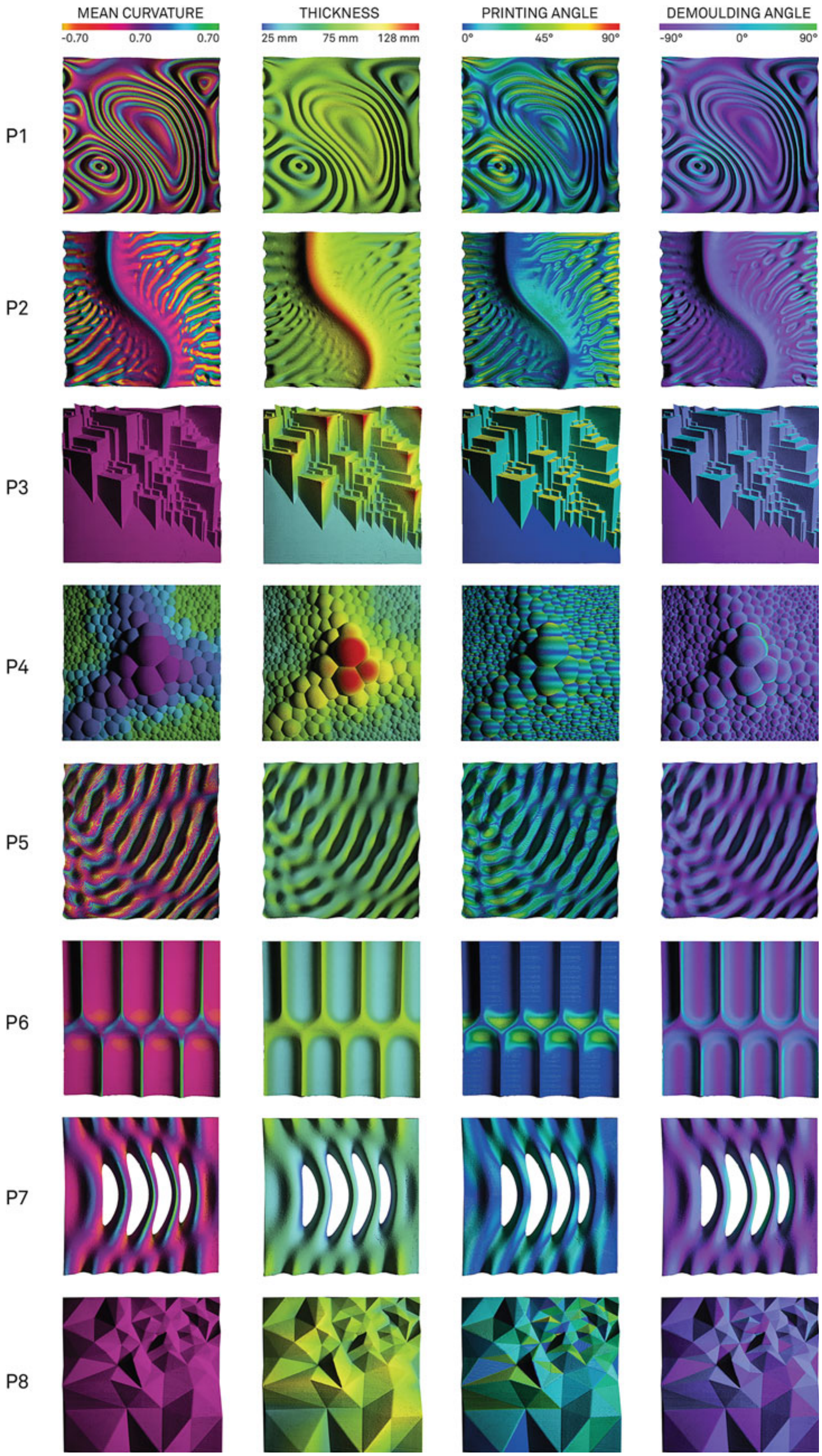
4.2 Fabrication Accuracy

All the formworks were scanned and digitised using an optical structured light GOM ATOS 3D scanner. Detailed adaptive point clouds were created, with a range of 1.5–2 million points and an accuracy of 0.06 mm. Imported in Grasshopper through Volvox (Zwierzycki et al., 2016), the deviation from the original 3D digital models was analysed for each of the forms. The use of 3D scanning to digitise the thermoplastic formworks and the concrete panels allowed to provide feedback on the relation between digital and physical prototype results and between the results of the 3D printing and casting operations. Scanning the plastic formworks before casting and testing them against the digital 3D models shows an average deviation on all the moulds of 1.07 mm. Caused by the thermoplastic shrinkage, a deformation towards their centre can be consistently observed in most of the printed moulds. From the 3D scanning of the concrete panels and analysis of the deviations from the digital 3D models (Fig. 11), a total average deviation of 1.52 mm is measured. While the printing angles have an influence at the microscale, from the scans no direct link with deviations can be outlined. This suggests that the mechanical capacity of the mould is homogeneous and there is no relation with the printing angles. The geometric differences that characterise the designs do not influence the production process and have only a minor influence on the quality of the final elements.

5 Conclusion

Overcoming the geometric limitations imposed by conventional formwork manufacturing techniques is a relevant challenge to fully unlock the potential of concrete and allow the design and production of customised, material-efficient, high-performance concrete architectural elements. Investigating and analysing the geometric freedom and fabrication precision of AM is a crucial step towards new applications in the construction industry. This study has proved the viability of the fabrication method and provided a numerical understanding of the geometric and fabrication domain it is bound to. Moreover, the design-to-manufacturing experiment has suggested the flexibility of the manufacturing method in

Fig. 10 Computational simulation and analysis of the eight panels with regard to Mean curvature, Thickness, Printing angle and Demoulding angle. Image by CREATE/University of Southern Denmark



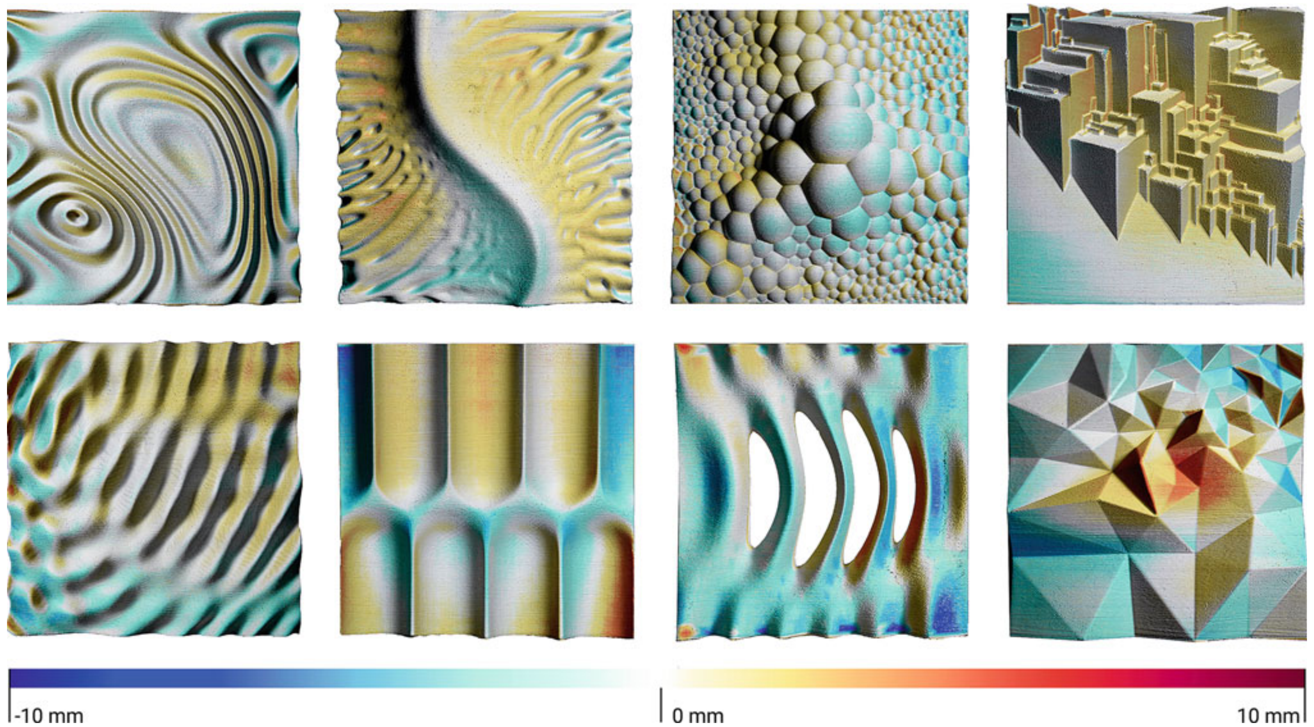


Fig. 11 Eight concrete panels with overlaid information from the 3D scanning process, showing the deviation of the resulting concrete panel compared to the digital model. Image by CREATE/University of Southern Denmark

addressing different design and geometric scales. While other techniques might achieve comparable results in some instances, our fabrication approach has revealed versatility in manufacturing a wide range of design outputs. Such a geometric resolution and production flexibility can open prospective applications for indoor surfaces and facade elements with bespoke textural and ornamental effects. Future works will engage with: the development of automated processes of optimisation of the design and formwork geometry for consistent, precise and accurate results; the application and testing of the proposed methods against larger-scale concrete elements; a systematic study on the deformations caused by the hydrostatic pressure exerted by the semi-fluid concrete.

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