3D-Printed Stay-in-Place Formwork for Topologically Optimized Concrete Slabs

Abstract

Topology optimization can be used as a design method to reduce material without affecting the functionality of an object. Despite being one of the most demanding economic sectors in terms of material consumption, the construction industry has not yet adopted such design methods. This is generally because computational optimization algorithms produce solutions which are difficult to fabricate, especially at a large scale. This research investigates the feasibility of using additive manufacturing to produce large-scale building components with optimized material distribution. To evaluate this new approach, two large horizontal load-bearing slab prototypes were designed using different topology optimization algorithms and fabricated with a hybrid 3D printing and casting method.

Introduction

Material efficiency is becoming a critical design driver in the construction industry. While many strategies for improving material efficiency focus on the end of a building's lifecycle (recycling materials, reusing components, reducing waste, extending life spans, etc.), there is also great potential for reducing material use in the early design phases. This is especially significant for materials that are difficult to recycle, such as concrete (Allwood et al., 2011).

The usual means for achieving material reduction with concrete are hollow-core construction systems, pre-stressing, and the use of lightweight concrete. Computational methods, such as the optimization of size, shape, and topology, can also be used to ensure the efficient distribution of concrete for a given part. While significant material reduction can be achieved with these methods, the resulting geometries are often so intricate that fabrication becomes problematic (Dombernowsky & Søndergaard, 2011).

The designer is confronted with the compromise between optimal material distribution and fabrication constraints. Subtractive (e.g. milling) and formative (e.g. casting and moulding) fabrication processes impose significant manufacturing constraints on the optimized form and its topological features. Three-axis milling, for example, is limited by tool-head accessibility and therefore cannot be used to fabricate undercuts. Five-axis milling is more tolerant of undercuts, but often parts must be split into smaller subdivisions to prevent clashes with the larger tool heads. Formative fabrication has directional limitations determined by the rheology of the casting material and by the demoulding process (Figure 1).

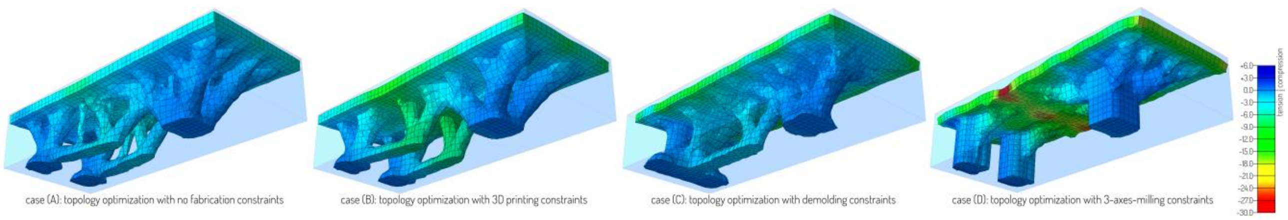

Figure 1. Topology optimization with fabrication constraints for different processes: (A) no fabrication constraints (for reference); (B) 3D printing; (C) casting and demoulding; (D) three-axis milling. Unlike the other case studies, 3D-printing constraints have a minor impact on the reference topology.

However, 3D printing, or additive manufacturing, is a process that promises almost no fabrication constraints, potentially enabling the production of topologically optimized complex geometries. The aim of this research is to demonstrate that large-scale parts can be fabricated with additive manufacturing. To investigate this hypothesis, two concrete slab components were designed with the aid of topology optimization algorithms and fabricated using 3D printing.

Topology Optimization

Designing for efficient material distribution can be achieved through size, shape, or topology optimization processes. Size optimizations are contained within a fixed shape, while shape optimizations are constrained by a fixed topology (Figure 2). Topology optimization processes will therefore be considered in this research, as they are the most versatile and most broadly applicable, being capable of improving material distribution in terms of size, shape, and topology (Mijar et al., 1998).

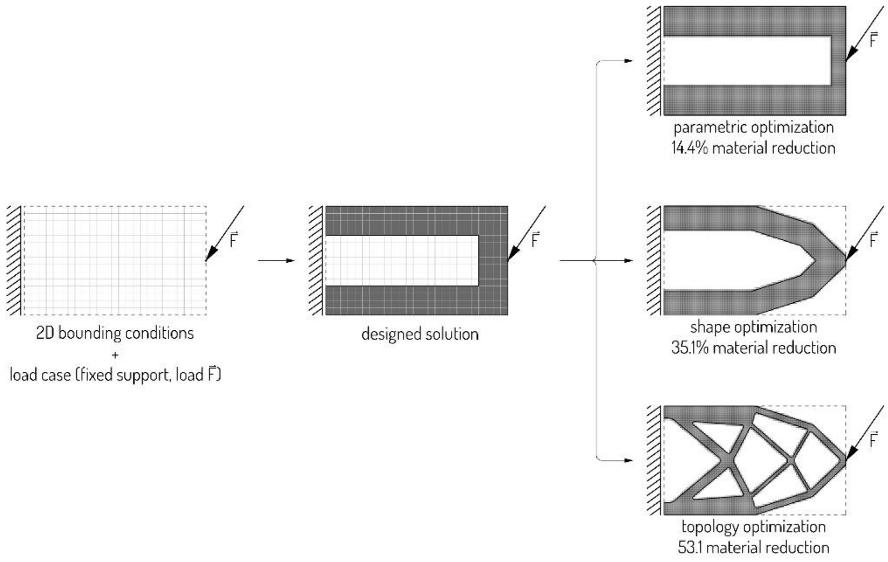

Figure 2. Different computational optimization processes: size, shape, and topology. Size optimization alters only the size of members, without changing their shape. Shape optimization alters the part with continuous deformations only, without modifying the topology. Topology optimization is the most versatile process, allowing changes in size, shape, and topology.

Topology optimization is an iterative computational process that works within a confined, discretized space. For given loads and supports, the algorithm will refine material distribution to meet a prescribed set of performance targets (Figure 3). There are a number of different topology optimization algorithms, including Solid Isotropic Microstructure with Penalization (SIMP), Evolutionary Structural Optimization (ESO), and Topological Derivatives (Rozvany, 2009; Aremu, 2010). Despite the computational differences between these algorithms, they all produce a family of typical geometric features: interconnected networks of thin ribs and narrow tubular structures with dynamic changes in porosity. The focus of this paper is on how these typical features can be fabricated.

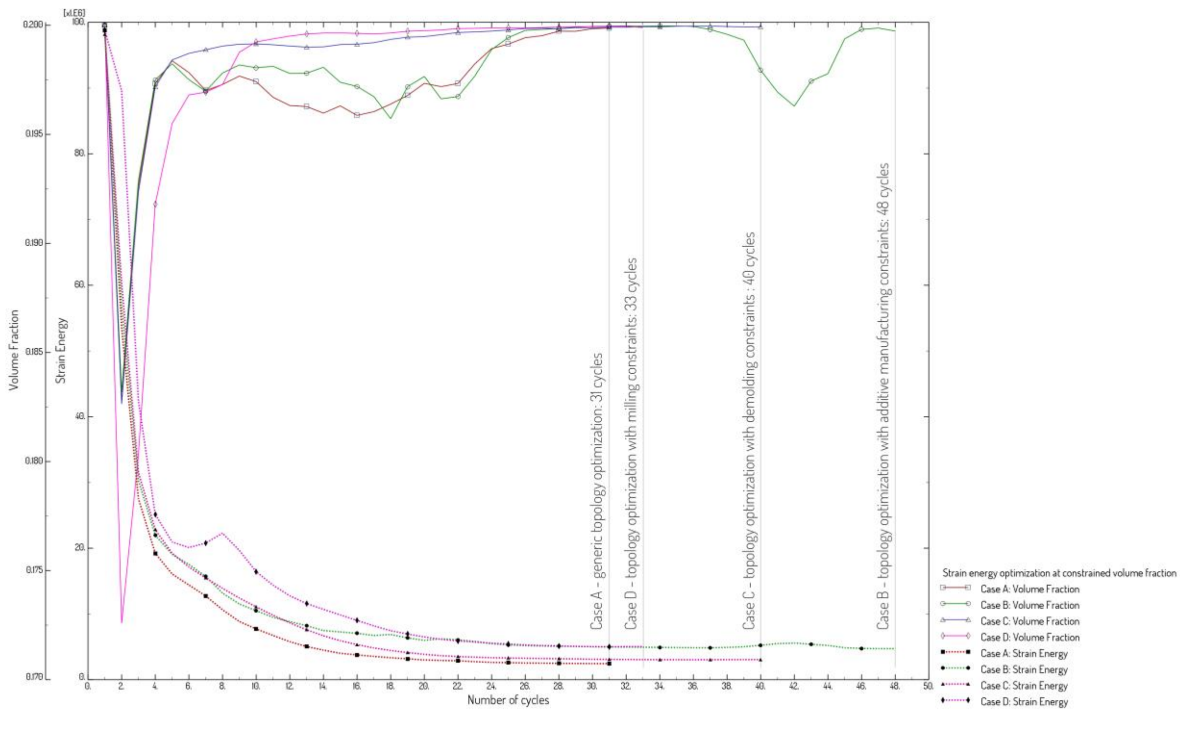

Figure 3. Convergence graph for the optimizations in Figure 1. The goal is to achieve an 80% reduction in material use while minimizing the strain energy. Convergence is achieved more slowly with additional fabrication constraints.

The greatest interest in topology optimization currently comes from the aerospace and automotive industries (Rozvany, 2009), where weight reduction is a critical design driver for improving performance, decreasing running costs, and reducing CO_2 emissions. Small-scale 3D-printed prototypes of topologically optimized connectors and hinges for planes, satellites, and Formula 1 racing cars have already been successfully created.

For large-scale construction, topology optimization frameworks do exist (Beghini et al., 2016; Tomas & Marti, 2010; Liang & Steven, 2000), but built examples are scarce. This lack of practical investigation is due in part to

- the limited availability of large-scale digital fabrication facilities;
- the limited compatibility of such facilities with materials suitable for structural applications;
- and the complexity of setting up physically accurate and reliable models for topology optimization, especially for anisotropic materials such as reinforced concrete.

3D Printing in Architecture

The issues noted above have thus far restricted the fabrication of large and topologically optimized architectural components. Nevertheless, recent developments have motivated the endeavour described in this paper:

- Large-scale 3D-printing facilities that can fabricate parts without geometric limitations at no additional cost are becoming more accessible (Dillenburger & Hansmeyer, 2013). The largest 3D-printing facility currently available commercially is VoxelJet VX4000, which uses sand to produce parts in sizes up to 4 x 2 x 1 m^3. Binder jetting, the technology used by this machine, is of particular interest to this research. Binder jetting is a type of 3D-printing technology in which layers of powder material are selectively bonded by a resin jet. This type of technology is particularly suitable for the fabrication of optimized topologies because it does not entail the use of auxiliary supports when printing geometries with undercuts and internal voids—the bed of unconsolidated powder provides this functionality by default. Binder jetting produces clean surface finishes and accurate details in the range of 0.2 mm.
- While the relatively low bending strength of 3D-printed sand (Stutz & de Taisne, 2016) makes it inadequate for large-scale structural applications, this drawback can be overcome if binder jetting is used to 3D print stay-in-place formwork (PSPF) for concrete. This fabrication method was developed recently by the authors to combine the structural properties of ultra-high-performance fibre-reinforced concrete (UHPFRC) with the fabrication freedom of binder-jet 3D printing (Aghaei-Meibodi et al., submitted).

Given the fact that with PSPF structural components can be fabricated with indefinite geometric freedom, the questions addressed in this research are these: If additive manufacturing allows the prefabrication of large, complex architectural parts with optimized topologies, what is the potential and what are the limitations of the PSPF fabrication method with regard to material optimization?

Topologically Optimized 3D-Printed Concrete Slab Elements

To explore the suitability of topology optimization algorithms for PSPF additive fabrication, two prototypes were designed and fabricated, investigating:

- design with two different topology optimization tools—a free plug-in with limited functionality and a robust commercial application;
- adaptation of the design to suit specific fabrication constraints;
- and the fabrication process using stay-in-place 3D-printed formwork for fibre-reinforced concrete;

To demonstrate the applicability of this process to architecture, the prototypes are large-scale examples of prefabricated concrete slabs measuring 1.8 x 1 m^2—the full size of the Ex-One S-MAX 3D printer bed.

Two Topology Optimization Strategies

Prototype "A" (Figures 4 and 5) was developed through a hybrid process based on topology optimization and mesh subdivision. A two-dimensional evolutionary algorithm was used: Millipede, a free add-on for McNeal Rhinoceros, and Grasshopper (Michalatos & Payne, 2014). The main goal of the optimization process was to reduce material to a 0.2 set fraction of the initial amount while minimizing deformations of the slab under uniform surface load. Boundary conditions were set to three fixed supports.

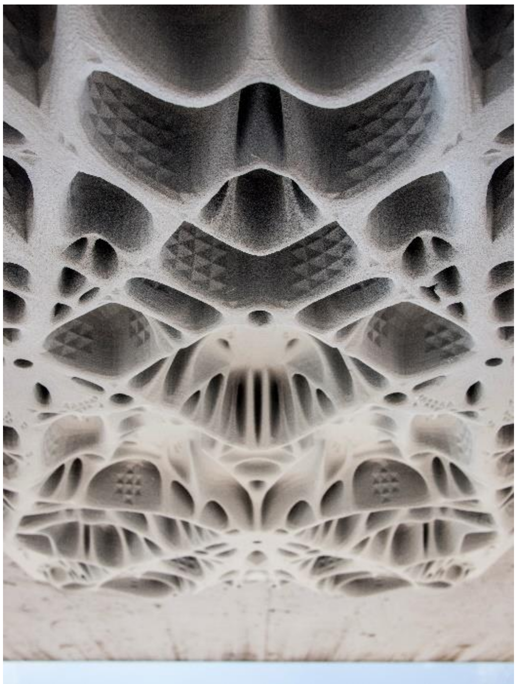

Figure 4, left. Prototype "A"; topology optimization of a slab with three supports.

Figure 5, right. Prototype "A" close-up detail.

The design space was discretized into 135,000 nodes and the algorithm was run for 500 cycles, producing a greyscale bitmap representing material distribution. This bitmap was subsequently vectorised and given a three-dimensional ribbed topology based on the grey values corresponding to the underlying nodes. Catmull-Clark and loop subdivision algorithms were finally applied to achieve a smooth surface and accommodate fabrication constraints. The subdivision algorithms were selectively applied to aesthetically differentiate the ribs and the fields (Figure 06).

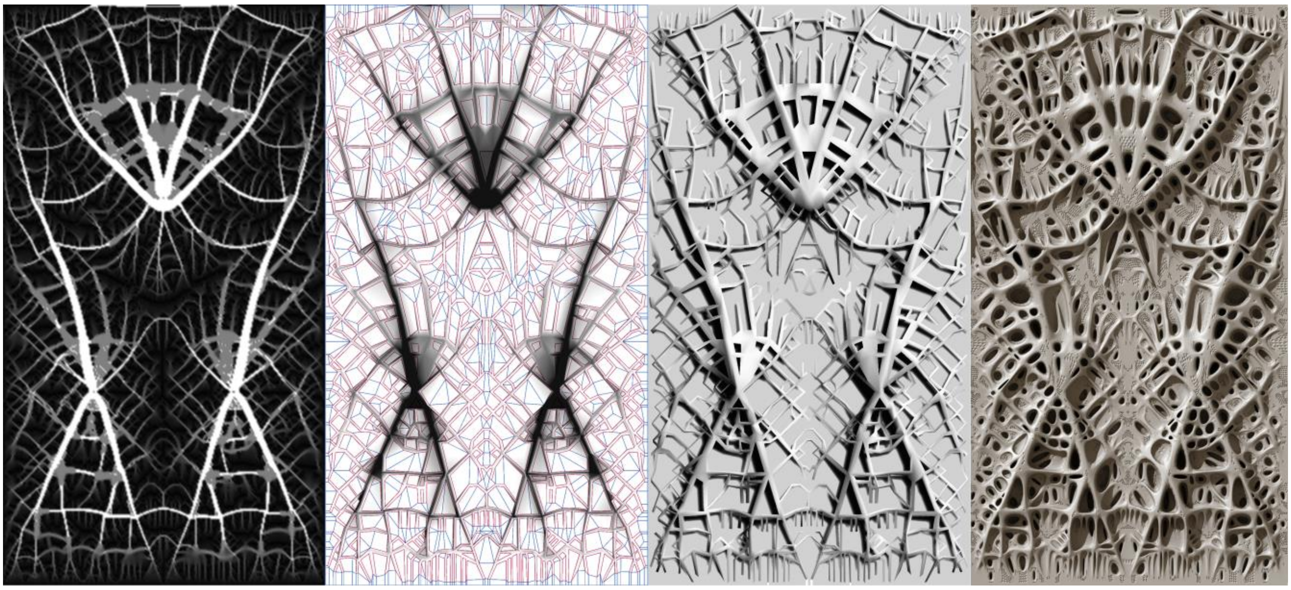

Figure 6. Design process for prototype "A": From left to right: greyscale bitmap resulting from Millipede, where each pixel represents an optimization node; vectorization with hierarchical differentiation of ribs and fields; three-dimensional mesh with depth based on greyscale values of underlying pixels; selective subdivision algorithms to achieve desired aesthetics.

<u>Prototype "B"</u> (Figure 7) was developed through the SIMP topology optimization algorithm of Simulia ABAQUS, a commercial structural analysis software package. The main goal of the optimization process was to reduce material to a 0.18 set fraction of the initial volume while minimizing the stress of the slab under uniform surface load. Boundary conditions were set to four simple supports located close to the corners.

Figure 7, left. Prototype "B"; topology optimization of a slab with four supports.

Figure 8. Prototype "B"; close-up detail

The 1.8 x 1 x 0.15 m^3 design domain was discretized into 83,072 nodes with a volume of approximately 3.4 cm^3 each. Other tests were done with 270,336 samples at 1 cm^3 and with 2,162,688 samples at 0.12 cm^3 (Figure 9). While finer discretization marginally improved the quality of the result, it also had a major impact on computation time, and therefore the coarser samples were used for designing the prototypes.

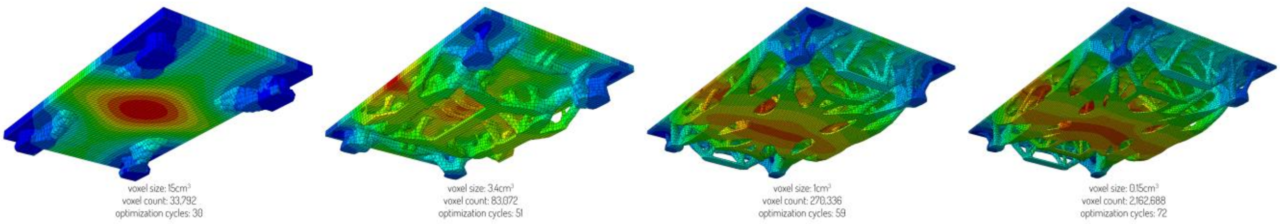

Figure 9. Topology optimization of Prototype "B" with different numbers of nodes.

From Optimized Form to Printable Geometry

To help determine the fabrication constraints specific to the PSPF fabrication method, a number of preliminary tests were performed in collaboration with the group for Physical Chemistry of Building Materials (PCBM, D-BAUG, ETH Zurich). These tests investigated (Stutz & de Taisne, 2016):

- the properties of 3D-printed formwork in relation to concrete—how the porosity, sorptivity, and capillary absorption of the sandstone influenced the setting of concrete;
- new ultra-high-performance fibre-reinforced concrete mixes with ductile behaviour;
- the rheological properties of these new mixes as a relation between fibre content and geometric features—inner radii, bending radii, and channel length to diameter ratios (Figure 10);
- the properties of the sandstone-to-concrete bond;

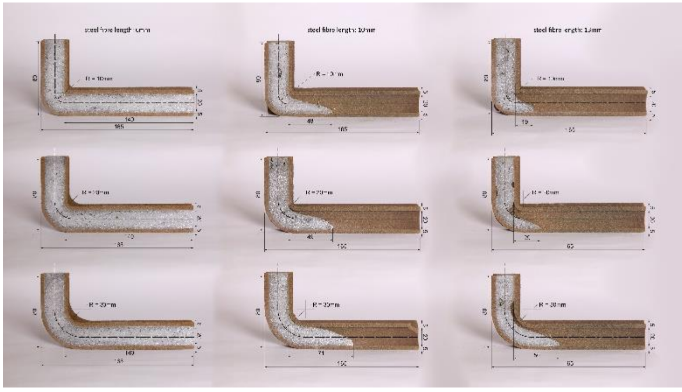

Figure 10. Rheology studies investigating the relation between fibre reinforcement and geometric features.

The preliminary tests described above were an essential step in the design process. Their role was to establish a series of formal design guidelines derived from the fabrication constraints. According to these, the geometric features of the formwork can be dimensioned in relation to both the length and volumetric content of the fibres in the concrete mixture. These guidelines informed the final design of the two prototypes with regard to the rheological constraints of the concrete-casting process.

In response to these fabrication constraints, geometric refinements had to be included in the design process in order to:

- smoothen under-sampling and correct artefacts resulting from the discretized nature of the topology optimization process;
- filter out geometric features that were too fragile to be 3D printed;
- filter out geometric features that were too narrow to permit 3D printing post-processing (unconsolidated sand removal and surface infiltration);
- filter out geometric features that were too narrow to permit the flow of concrete because of local fibre clogs;
- and accommodate the architect’s design intention regarding surface quality, ornamentation, edge details, etc.

Fabrication constraints were applied to the intricate geometry resulting from the optimization process, with tubular structures being hollow only if they were large enough to permit the flow of concrete inside.

Fabrication: Binder Jet 3D Printing and Fibre-Reinforced Concrete

For both prototypes, the fabrication process began with binder jetting the sand formwork followed by post-processing the prints (Figure 11). This involved removal of unconsolidated sand and infiltration with epoxy resin in order to increase the strength of the material. A strategy to avoid damaging the friable formwork during post-processing was tested. It involves the integration of a protective bed of unconsolidated sand contained within a closed 3D-printed box (Aghaei-Meibodi et al., submitted).

Figure 11. Post-processing of the 3D-printed formwork.

This auxiliary protective box also provides support for the formwork during the casting of the UHPFRC (fig 12.). The special concrete mix contains 2.75 vol. % steel fibres 10 mm long and 0.16 mm in diameter. The average concrete thickness achieved, 30 mm, indicates that weight reductions of up to 70% are possible. The initial structural tests performed so far by applying a 2,500 KN/m^2 distributed load on Prototype “B” empirically confirmed the validity of the topology optimization algorithm.

Figure 12. Casting UHPFRC inside the 3D-printed formwork.

Fabrication Constraints

While generic digital fabrication—including some 3D-printing technologies—will require significant design alterations to permit the fabrication of large-scale topologically optimized geometries, this paper shows that PSPF, a hybrid fabrication process, requires only minimal changes to the topological optimum.

In general, PSPF for concrete is a fabrication method which is not as permissive as pure binder-jet 3D-printing fabrication. Nevertheless, compared to the other fabrication methods discussed in the introduction, PSPF is very generous in terms of its fabrication constraints. The necessary geometric adjustments for fabrication have only a minor impact on the calculated optimal topology and are significantly less intrusive than with other processes (e.g., completely eliminating undercuts for three-axis milling, subdividing the part into multiple elements for five-axis milling tool-head access, or eliminating cantilevers for extrusion 3D printing).

For PSPF fabrication, geometric features become problematic at a scale of around 20 mm. Such fabrication constraints are close to the material limitations of concrete anyway (below 20 mm, the structural integrity of concrete begins to suffer), and such detailed features have little relevance for large-scale building components.

Outlook and Conclusion

With the two successful large-scale prototypes described above, this paper can conclude that PSPF fabrication is sufficiently tolerant of geometric complexity to enable the design of architectural components directly through topology optimization. This is possible because of some particular interrelations between the different aspects of the project:

- The use of 3D printing enables the accurate fabrication of precise topology optimization details, while concrete provides the structural strength necessary for large-scale components.
- Empirical observation suggests that UHPFRC has an isotropic behaviour which is easily modelled digitally for topology optimization algorithms; when using fibre reinforcement, anisotropic behaviour and fabrication constraints resulting from reinforcement bars do not have to be considered.
- Topology optimization and 3D printing both have potential applications in the realm of one-of-a-kind, non-standard building components rather than in mass-production.

In applications of PSPF for larger building components, such as entire concrete slabs, structures would need to be assembled from multiple prefabricated parts. In order to achieve this, further research must address the following challenges:

- Reinforcement considerations. Steel-fibre reinforcement was sufficient for the prototypes, but in order to increase the structural spanning capabilities, traditional reinforcement bars or pre-stressing strategies are considered. Again demonstrating its suitability, 3D printing can be used to fabricate guiding features for the precise integration of reinforcement. Topology optimization strategies will have to account for the anisotropy introduced by the direction of the reinforcement.
- Additional functionality. This paper highlights the significant potential of using 3D printing to fabricate large-scale parts with optimal structural performance for specific material reduction targets. Nevertheless, optimization criteria are not limited to structural performance. Acoustic performance or heat transfer, as well as any combination of two or more criteria, can constitute optimization targets. This opens up the possibility of integrative optimization strategies for the design of smart building components.

Concrete is one of the most consumed products in the world, with 10 billion tonnes being produced every year. Optimizing the use of concrete in prefabricated components can have a global impact in reducing material costs and the carbon footprint of buildings and infrastructure. This research draws attention to this major potential and proposes a fabrication method based on additive processes which is viable at a large scale. A harmonious compatibility exists between this additive fabrication process and topology optimization used for form-finding purposes. The authors regard this research as the first steps towards a new, fully integrated approach to construction driven by material economy.

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