

Smart Slab

Computational Design and Digital
Fabrication of a Lightweight Concrete Slab

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1

ABSTRACT

The optimization of slab systems can have a large impact on buildings: more compact slabs allow for more usable space within the same building volume, refined structural concepts allow for material reduction, and integrated prefabrication can reduce complexity on the construction site.

We present a novel slab system which reduces material through concentrating concrete in hierarchical ribs on a 20 mm thick concrete shell. This slab structure provides voids to integrate electrical conduits, sprinklers and lighting. It is prefabricated out of prestressed concrete elements, for which we introduce a hybrid formwork approach, combining 3D printing and CNC laser-cut timber formwork. The formwork is used with casting and spraying concrete to enable efficient fabrication of free-form geometry with highly detailed surfaces. A digital process chain connects the design of the elements, the integration of the building services and the fabrication data of the formwork.

This research is demonstrated on the project Smart Slab, the first concrete slab using 3D printed formwork. The Smart Slab is around 70% lighter than a conventional concrete slab and showcases a new radical aesthetic with three-dimensional geometric differentiation on multiple scales. The project demonstrates the potential of 3D printing for custom formwork, especially when strategically synthesized with other CNC fabrication methods. This work provides an outlook on how digital fabrication can achieve more sustainable structures and can broaden the design possibilities of concrete in architecture.

1 Interior view of the Smart Slab— ceiling.

BACKGROUND

Concrete floor slabs play an important role in building structures and represent significant material use; they can account for up to eighty-five percent of a building's total self-weight (Georgopoulos and Minson 2014). This massive use of concrete also generates critical amounts of CO₂ emissions from cement production. Reducing material usage can therefore contribute to reducing the self-weight of the structure and thus foundation costs, and to the creation of sustainable building structures. In addition, concrete floor systems which are able to embed building services like air handling can lead to a significant reduction in height, resulting in more interior space per building volume (Banham 1984).

Standardized and prefabricated systems have been developed to reduce the quantity of concrete needed for concrete floor systems, for example ribbed or waffle slabs, the BubbleDeck system which replaces concrete with plastic balls within the slab, and the Holedeck formwork system which allows for the integration of services. Element-Slabs combine prefabricated concrete elements acting as stay-in-place formwork with on-site concrete casting to reduce the work on the construction site. However, these formwork solutions are not feasible or economical for the fabrication of non-standard bespoke slab designs.

Several strategies for non-standard formwork have been developed. Fabric formworks (West and Ronnie 2009) are resource friendly and for some geometries highly efficient. CNC cutting of foam represents a fast and rational but geometrically limited way of producing formworks (Søndergaard 2016). CNC-milled formworks allow for greater geometric freedom, but achieving a detailed milled surface is time-consuming and requires significant material consumption (Dombernowsky and Søndergaard 2009), and geometries with undercuts require multi-axis CNC machinery.

Additive manufacturing such as concrete extrusion could eliminate the need for complex formwork, but while several pilot projects of extrusion-printed walls exist (Khoshnevis 2004), slabs seem to be structurally and geometrically too demanding for the current concrete printing techniques. Another printing strategy, binder jetting, has been used to prefabricate architectural elements at high resolution without formwork (Dillenburger and Hansmeyer 2014), and also for lightweight slab prototypes (Rippmann et al. 2018), but the material properties of the organic binder—such as low fire/heat resistance, weak water resistance, emissions, and especially poor structural strength—limit

its possible applications in architecture. Hybrid constructions composed of high-performance concrete and binder jet prints are promising (Aghaei-Meibodi et al. 2017), but would need better material properties to become a solution for architectural components.

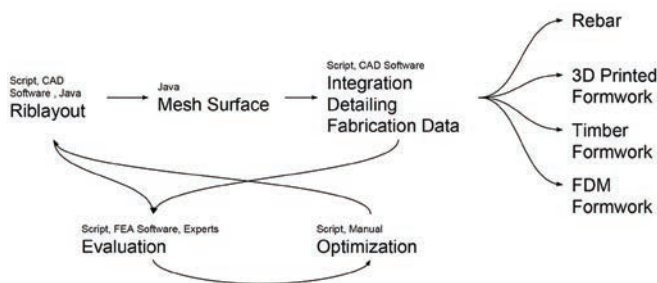
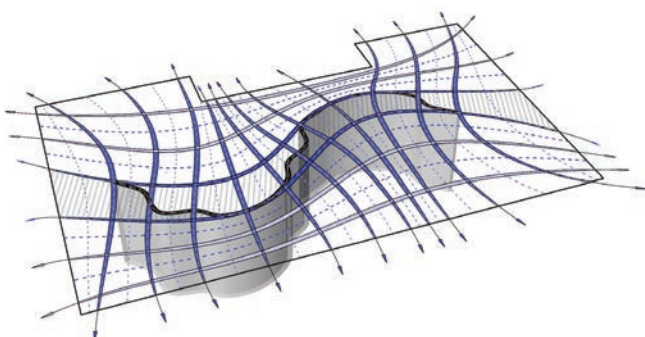
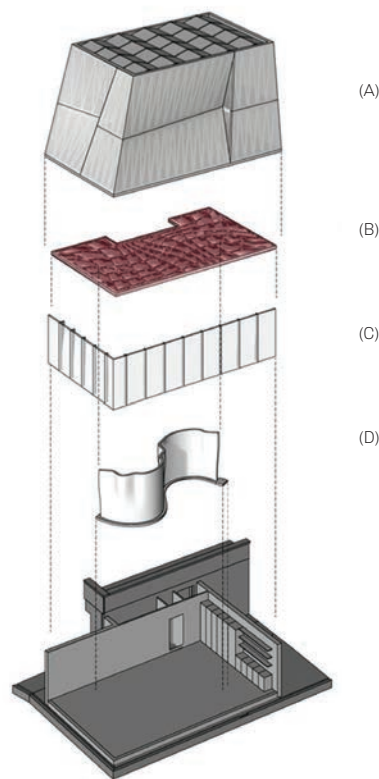
Our approach uses 3D binder jet printing to produce sandstone formworks for casting large concrete parts in any shape, regardless of geometric complexity. This strategy allows us to combine the benefits of the material properties of concrete and the geometric freedom of 3D printing. Formworks for concrete have already been 3D printed with plastic (Jipa, Dillenburger, and Bernhard 2017), and wax (Gardiner and Janssen 2014), but the use of binder jet technology to 3D print formwork has important advantages such as speed of fabrication, high resolution, geometric freedom and low cost. While the first successful experiments with this fabrication method have been conducted in the context of installations (Dillenburger 2016), the presented project demonstrates for the first time the use of a 3D-printed formwork for full-scale real-world architectural application: the Smart Slab of the DFAB HOUSE.

SMART SLAB

The 78m² Smart Slab cantilevers over an S-shaped wall and carries a two-story wood framed structure (Figure 2). The wall is the main load-bearing component; the Slab rests on it, cantilevers out to the façade, and is fixed at the L-shaped back side of this unit and the interior walls.

The Smart Slab comprises eleven 7.1-meter-long prestressed concrete segments which are prefabricated and then joined using post-tensioning cables (Figure 3). Its structural system consists of a series of hierarchical curved ribs containing the post-tensioning cables, spanning around seven meters from one end to the other, reducing in height from 600 to 300 mm. Six secondary ribs are spanning the 11.7 metre length of the slab with a shallower depth of 300 mm. The prestressing tendon in the secondary ribs also mechanically connects the eleven segments once under tension. The 20 mm thick concrete fields between these ribs are domed to maximize stability and to minimize the amount of material needed. This structural system reduces the overall weight of the slab without compromising its structural performance.

Assembling the eleven prefabricated segments onsite follows a sequential logic: one by one the segments are placed next to each other on top of the S-shaped wall and fixed to it with pin connections.



COMPUTATIONAL DESIGN

From the early design to the CNC fabrication of every part, the building information, including all information for the fabrication of formwork, rebar and integration of additional building services, stayed in a digital three-dimensional model (Figure 4). Such a fabrication-informed model can avoid geometric collisions and errors and improve precision. The digital workflow of the design strategically connects multiple software environments: custom Java applications, CAD software such as Rhinoceros extended with custom scripting, and commercial mesh-modelling applications. During the refinement, the geometric data is translated between line representation, mesh representation, and volumetric representation. The digital design model is strongly interlinked with analysis and optimization methods to help to use material more efficiently and make building elements more compact. The computational design of the slab involved two integral stages: the generation and optimisation of the rib layout that would later contain the post tensioning cables, and the generation of the freeform ornamented surface in accordance with the rib layout.

2 Generation of the Rib Layout

The layout of the ribs has to fulfill many competing criteria, like an optimal transfer of loads to the S-shaped wall while keeping the fields between the ribs equalised in size and shape. Therefore, in early design phases, various rib layouts were explored, following different generation logics and organisational hierarchies. An automated testing and evaluation procedure was developed to quickly and qualitatively compare the strategies with each other.

Instead of a fully detailed 3D model, the FEA model is generated based on a 2D sketch, a horizontal plane for the slab and vertical stripes for the ribs, both assigned the corresponding shell thickness (Figure 5).

The main focus was not on absolute stress and deformation values but rather on fast, qualitative feedback on the structural implications of design variations relative to each other. The benefit is the method's ability to test dozens of variations in minutes, rather than taking hours to thoroughly investigate one version.

4 Optimization of the Rib Position

With the principal topology of the layout fixed, the exact position of the curved grid of ribs was generated using a genetic evolutionary algorithm operating on the control points of the axes of the ribs. The fitness criteria for the optimization included the 2.5 metre minimum bending radius of the post-tensioning cables; an even distribution of the principal ribs along the S-shaped wall; a regular

- 2 Axonometric visualization of the DFAB HOUSE. (A) Spatial Timber Assemblies (B) Smart Slab (C) Smart Dynamic Casting (D) In Situ Fabricator / Mesh Mould.
- 3 Rendering of the slab highlighting structural concept and positions of the ribs with post tensioning cables.
- 4 Digital workflow, based on Java programming and customized CAD software.

distribution of the principal and secondary ribs along the facades; and an even distribution of tributary load areas for each rib.

Generation of Freeform Ornamented Surface

This ceiling surface is articulated with a differentiated ornament which creates a play of light and shadow on the ceiling, influences the acoustic properties of the space and increases the stability of the thin shell (Figure 6). This chosen design, expressed as an undulating form at multiple scales, highlights the possibilities offered by 3D printing.

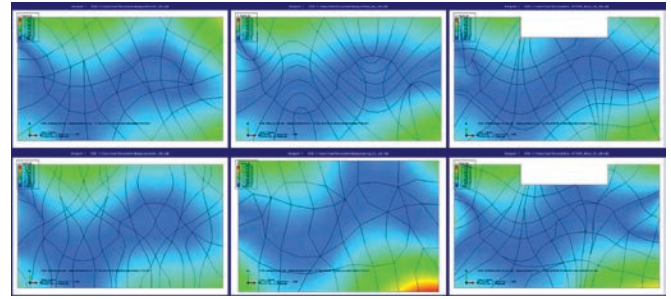
The optimized rib layout was used to build a computational model of the freeform ornamented surface of the ceiling. This surface is a high-resolution mesh, which includes all the formal articulation of the slab as well as the segmentation seams of the prefabricated parts. The generation of this surface consisted of two steps: first, the rib layout and the evaluated heights of the ribs were used as inputs to generate the approximate overall geometry. All the polygons of the mesh store certain characteristics in relation to their type (principal rib, secondary rib, field, etc.) and contain topographical and topological attributes (Hansmeyer and Dillenburger 2013) (Figures 7 and 8).

Second, the mesh is algorithmically subdivided to produce a highly ornamental surface consisting of thirteen million facets (Figure 9). The subdivision process follows the inherent characteristics of the mesh. All the above-mentioned properties of the polygons were considered in generating the final form, which could adapt to any possible changes of the initial rib layout.

Integration

By differentiating between slender ribs and shell elements with minimized thickness, the structural principle of the Smart Slab maximizes the vertical installation space available for integrating building systems. The increased construction height toward the center support offers room for trunk lines and main conduits, while smaller branches are run in the shallower areas near the slab edge. This way, the slab thickness can be reduced toward the perimeter, maximizing architectural potential and daylight penetration. All technical infrastructure is integrated into the slab, eliminating the need for suspended ceilings.

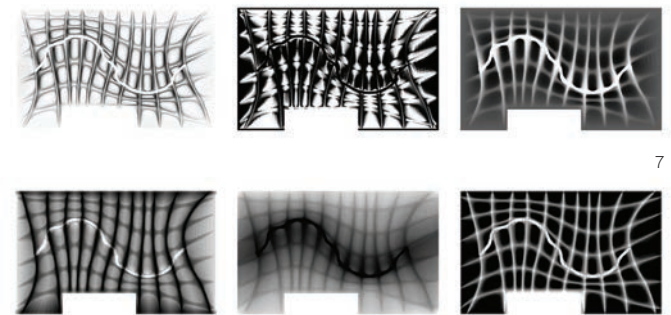
Structural connections for facade mullions, a sprinkler system, and electrical installations for lighting, fire alarm systems, and occupancy sensors were integrated. All openings for facade brackets, pipes, and cabling were coordinated in the 3D model to avoid clashes with post-tensioning and rebar, and pre-integrated in the rib formwork.



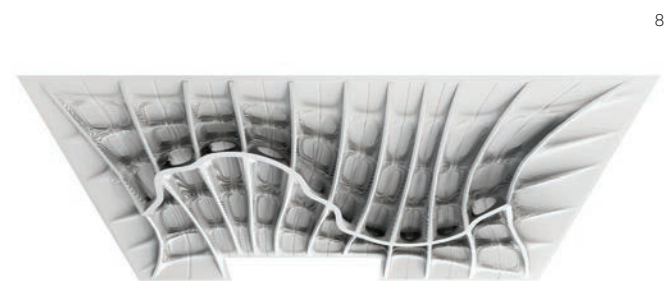
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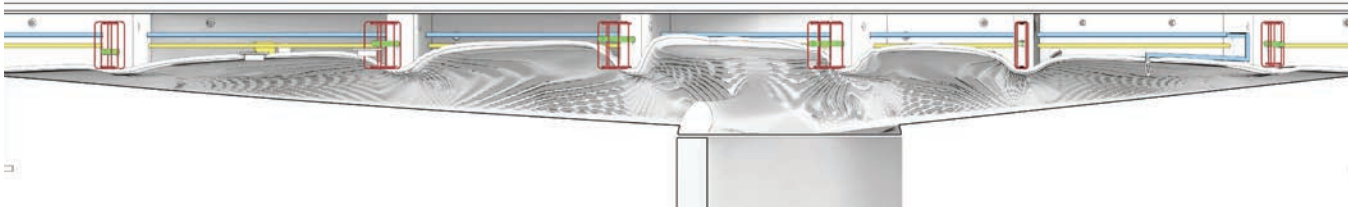
5 Maximum deformation of different rib layouts.

6 Detail of concrete surface over the support wall.

7 Topographical attributes of the mesh polygons visualized as shades of gray. From left to right: horizontality, verticality, z position

8 Topological distances within the mesh visualized as shades of gray. From left to right: distance from primary ribs, from S-shaped wall and from fields.

9 Perspective of subdivided parametric model.



10 Section of the smart slab

Sprinkler pipes and electrical conduits are installed onsite from the open tops of the segments. Depending on the requirements of future projects, air chases, and slab activation for heating and cooling could be integrated as well (Figure 10). In the realized design, acoustic structures, lighting details, facade interface, sprinklers, and electric outlets are integrated.

FABRICATION OF THE SMART SLAB

The fabrication of concrete segments involved two methods of concrete distribution, spraying and casting, and the development of a hybrid formwork system made from both 3D-printed and CNC-machined parts. The different fabrication processes involved in the prefabrication of the concrete segments can be summarized as follows (Figure 11):

- The 3D-printed parts are assembled to form the lower part of a formwork segment, then sealed and treated with paint for spraying concrete;
- A thin (20mm thick) fiber-reinforced concrete layer is sprayed on the surface;
- Pre-assembled timber formwork modules, integrating the building services voids and reinforcement bars, are installed above the sprayed layer;
- The upstand ribs are cast inside the plywood formwork.

Hybrid Method of Concrete Casting and Spraying

Fiber-reinforced concrete is sprayed to form a thin (20 mm thick) shell shaped by the sand mold, while the upstand ribs above are cast (Figure 13). While spraying is ideal for producing the thin freeform surface with a consistent thickness, casting is faster and ensures better bonding with the reinforcement bars. Furthermore, it improves concrete compactness within the structural beam.

Hybrid Formwork

The two methods are further differentiated by the use of two different formwork systems. The 3D-printed formwork provides support for the sprayed concrete surface, while laser-cut timber panels are used to cast the upstand ribs (Figure 12). While the high-resolution capabilities of binder jet printing are perfectly suited to the fabrication of the formwork for the highly articulated visible ceiling surface, the upstand concrete ribs are simple, smooth surfaces and



11

11. From top to bottom, (a) 3D printed formwork segment with release agent; (b) first concrete layer without fibers (sprayed); (c) 20mm thick concrete surface, spraying concrete on 3D-printed formwork segment; (d) Positioning pre-assembled timber formwork modules above the sprayed surface; (e) upstand beam cast inside the plywood formwork.

therefore a more efficient formwork system could be used. Moreover, the production of the ribs from timber formwork allowed easier handling for assembly and quicker removal after casting.

The design and fabrication of the hybrid formwork was mostly automated, addressing the following challenges:

- Speeding the assembly of wood formwork over the 3D-printed formwork to ensure a proper bond between the sprayed concrete and cast concrete of upstand ribs.
- Precision of interfaces between the neighboring segments after concrete is cured
- Controlling the surface quality of each concrete segment and ensuring a coherent look all over the slab
- Avoid chipping off ornamentation when removing 3D-printed formwork

Design and Fabrication of 3D-Printed Formwork

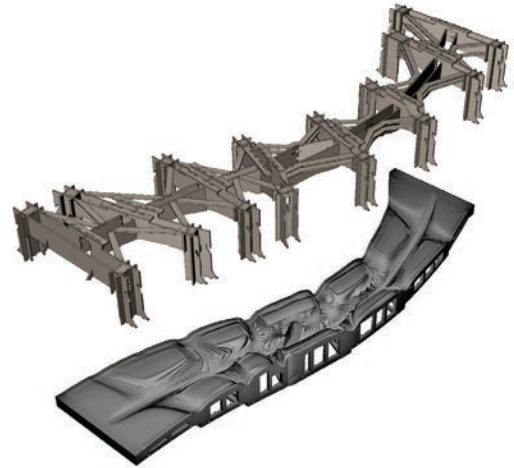
Each concrete-segment was made of multiple 3D-printed formwork parts (Figure 14). The automatically generated formwork data for the entire slab included features such as labelling, connection- and lifting-details. The formwork system consisted of 174 3D-printed parts in total. For each segment, additional Fused Deposition Modelling (FDM) parts were printed and used to generate additional cavities or act as guides for the post-tensioning system.

After the assembly of the 3D printed sand-formwork, the sand surface was infiltrated with polyester resin to harden it and to allow for the application of the release agent immediately before the concrete is sprayed (Figure 15).

Laser-Cut Flat-Panel Formwork

Laser-cut plywood panels were used to fabricate the formwork for the upstand concrete ribs. Due to the constraints of the laser-cutting process, which does not tolerate curved surfaces, a shape optimization step was introduced. This computational step approximates the single-curvature of the ribs to a minimum number of flat panels fit for fabrication.

The plywood panels were pre-assembled in discrete modules corresponding to each secondary rib (Figure 13). These modules were installed on top of the 3D-printed formwork once the sprayed concrete layer was in place (Figure 16). The pre-assembly integrated the rigid reinforcement bar baskets, the tie bolts, and the lifting anchors, as well as provisions for functional voids for the integration of fire sprinkler ducts (Figure 16). Finally, the concrete casting process continued inside the plywood formwork and on top of the sprayed concrete layer.



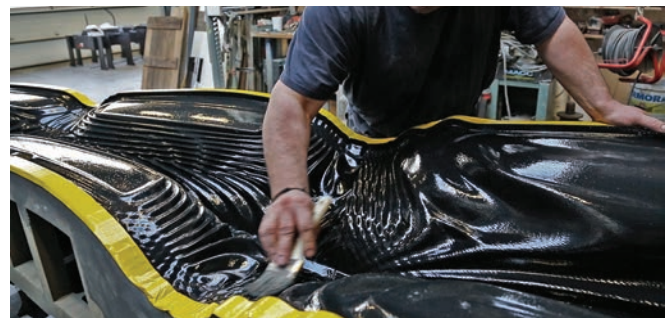
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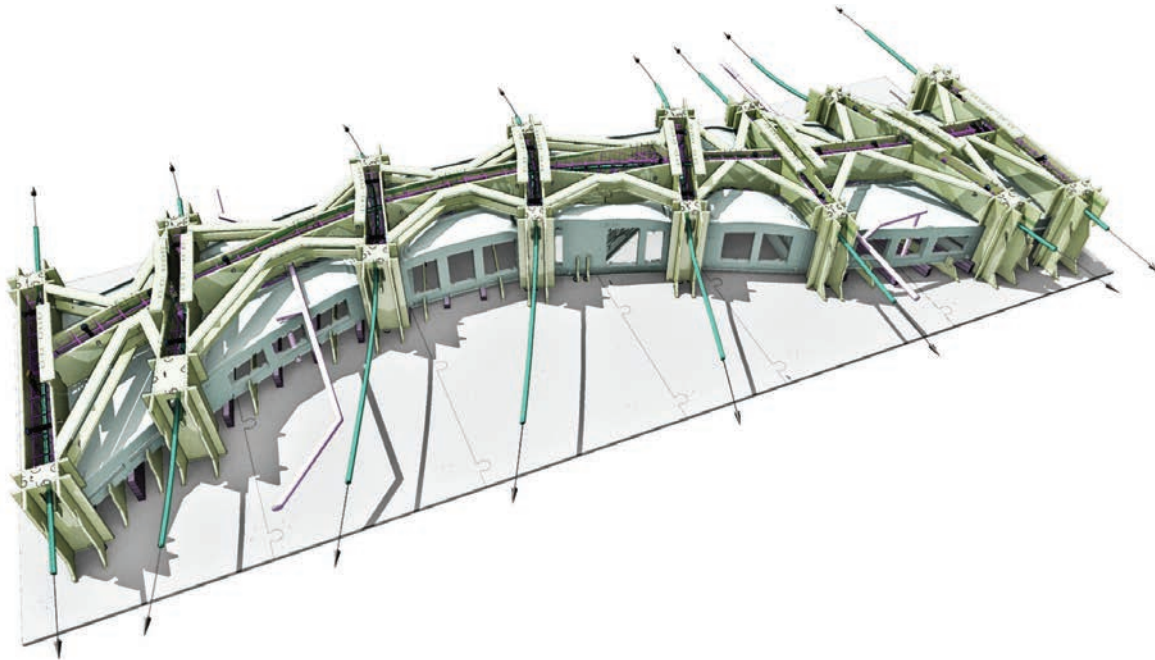
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12 CNC laser-cut timber formwork for casting the upstand ribs (top) and 3D-printed formwork for sprayed concrete surface.

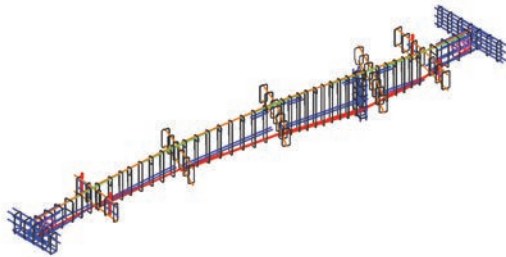
13 Spraying of fiber-reinforced concrete.

14 Multiple 3D-printed formwork parts. Scripts were developed to generate detailing and numbering of each 3D printed part.

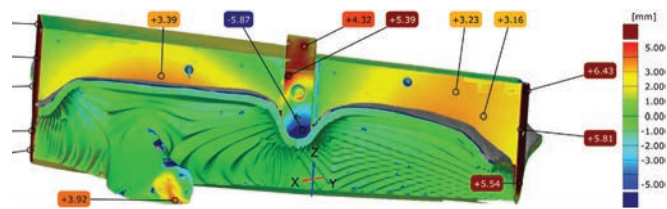
15 Application of the release agent to the 3D-printed formwork surface after assembly into a segment.



16 CNC laser-cut timber formwork with rebar integration and sprinkler plumbing over the 3D-printed formwork.



17 Rendering of stirrups (black), rebar segments (various colors), and overlap rebar (blue)



18 Measurement of deviations using 3d scanning

System of CNC Rebar, and Post-tensioning

Post-tensioning cables were added to the slab in two stages. During the prefabrication of segments, the hollow channels for post-tensioning in both slab directions were embedded in each segment. In addition, CNC-bent rebar welded together in prefabricated baskets was inserted into the curved concrete ribs (Figure 17).

RECALIBRATION

Adjustment after scanning prototypes

To improve the precision of the concrete elements, several 1:1 prototypes were built. Assembly details were adjusted after 3D scanning those initial prototypes (Figure 18) as it showed large deviations occurred at the end caps which are crucial for the joining of segments.

Adjustment After Scanning the Wall

To minimize the impact of construction tolerances at the interface between wall and slab, survey data from the built wall was fed back into the slab design before the start of formwork production. The final model was adjusted to the

as-built wall geometry using data from a 3D scan of the wall. This mitigated the effect of the greater tolerances of the cast-in-place wall on the prefabricated slab system with its very tight tolerances.

RESULTS AND DISCUSSION

The Smart Slab led to innovations in structural and material systems, computational design, and digital fabrication.

The project is exemplary in its use of a digital process-chain from design to fabrication.

Customized scripts and parametrization facilitated fast adaptation to constantly changing design constraints. A puzzle of over two thousand custom elements, including 3D-printed formwork, CNC laser-cut timber formwork, rebar, and FDM-printed alignment details could be coordinated, avoiding geometric conflicts and collisions within the minimized concrete sections.

Structural Concept and Material System

Despite the complexity of the project (cantilevering in multiple directions, a curved wall as the main support) the design of slab reduced concrete use by about 70% compared to a conventional concrete slab (Figure 20). The main reasons are the combination of a post-tensioning system and lightweight fiber-reinforced concrete and the optimized geometry adapted to the specific load case.

Digital Fabrication

Typically, organic and complex geometry resulting from the structural optimization of concrete elements generates additional costs for fabrication—it is currently cheaper to use more material than to design and fabricate an optimized slab with custom formwork. This project shows that digital fabrication, and especially 3D printing, can help to solve this dilemma: the fabrication cost of 3D-printed formwork is independent of the complexity and the customization of the geometry of the printed part.

Using 3D printing for formwork combines the geometric freedom of additive manufacturing with the optimal material properties of high-performance concrete (Figures 19–21). An important result of the research was that the approach of 3D printing formwork outperforms current strategies of direct 3D printing of concrete in terms of material properties and surface quality.

Furthermore, the strategic combination of different digital manufacturing methods can lead to a more efficient prefabrication of custom concrete elements. The presented project successfully applied binderjet printing, CNC laser cutting, and FDM 3D printing, depending on the targeted geometric features and function within the structure of the formwork. Using a hybrid strategy of spraying and casting concrete further facilitated the prefabrication (Figure 19). Compared to the fabrication and assembly of the formwork, the actual casting and spraying of the concrete was the least amount of manual labour and did not require automation.



19 A prefabricated concrete segment made of sprayed 20-mm-thick fiber-reinforced concrete shell and cast upstand ribs above.

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20 On-site assembly of concrete segments.

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21 Interior view of the slab—ceiling. The scaffolding floor at mid room height facilitates assembly and improves safety

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Future Work

This project, DFAB House, will allow us to assess the behavior and long-term performance of the Smart Slab over multiple years.

Two parts of the presented fabrication process could be improved and will be addressed with future research. The development of new materials for printed formwork such as specific dissolvable binder systems could facilitate the removal of the formwork. In addition, the bespoke rebar system required a large amount of manual labor. While some of the rebar parts could already be bent and welded robotically, further automation could avoid errors and improve precision and should be investigated. In order to foster innovation in the construction industry, further demonstration projects of digitally optimized slabs are targeted.

CONCLUSION

The research generated a deeper understanding of how digital planning and fabrication can be implemented in the building industry in the future, and how the interplay between automated manufacturing and manual work can be optimized. The power of the computer (parametric design software) works together with human experts (e.g. structural engineers), and the precision of CNC (pre) fabrication works in concert with the embodied knowledge of the skilled craftsman.

It is the nature of architectural works that they are produced not with a single material or process but through the combination of multiple materials and processes. In that spirit, this project brings together and celebrates a range of design techniques, fabrication processes and materials.

One of the most important findings of this research is the relevance of advanced computational design methods. Such fabrication-informed modelling allows us to integrate aspects that are usually addressed separately or as an afterthought from the very first design sketch. Only in combination with digital design can we get the most out of digital fabrication methods such as 3D printing. The Smart Slab project showcases how in the future, a hybrid workflow from design to fabrication can lead to better performing and more expressive design solutions without the need for standardization. This will be the key to creating a larger impact on the building industry and improving the overall quality of our built environment.

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