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Author(s):
Jipa, Andrei; Aghaei Meibodi, Mania; Giesecke, Rena; Shammas, Demetris; Leschok, Matthias; Bernhard, Mathias; Dillenburger, Benjamin

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3D-Printed Formwork for Prefabricated Concrete Slabs

Andrei Jipa [a] [*], Mania Aghaei Meibodi [a], Rena Giesecke [a], Demetris Shammas [a], Matthias Leschok [a], Mathias Bernhard [a], Benjamin Dillenburger [a]

[a] Digital Building Technologies, ITA, ETH Zürich, Stefano-Franscini-Platz 1, 8093 Zürich, Switzerland

[*] jipa@arch.ethz.ch, +41 (0) 44 633 2451

This research puts forward a pioneering construction method which uses 3D-printed formwork for casting or spraying concrete in any conceivable shape. 3D printing overcomes the geometric limitations of traditional methods for fabricating formwork, enabling the construction of integrative concrete elements with elaborate, free-form and highly detailed surfaces. The proposed method was used in a full-scale architectural context for the Smart Slab, a 78-m^2 prestressed concrete slab which consists of eleven 7.4-m-long prefabricated one-of-a-kind segments (Fig. 1). The Smart Slab is a fully functional structural element which showcases an exquisite digitally designed geometry, with a deeply folded surface and millimetre-precise details. Beyond the new and radically expressive aesthetic, this extensive and tolerance-free fabrication freedom for concrete enables the precise integration of the complete suite of building services and structural features necessary for a working building. Weighing over 9,000 Kg, the 3D-printed formwork for the Smart Slab relies on two different 3D printing technologies: binder jetting for the most part, as well as fused filament deposition for locally integrating building services within the slab. The formwork facilitates the accurate provision of functional voids within the slab for electrical conduits, water ducts, light fittings, fire sprinklers and rebar form ties, as well as for the accurate spatial curving of the post-tensioning ducts. The integration of building services during prefabrication streamlines assembly on site and considerably reduces construction tolerances. Furthermore, a major achievement enabled by the 3D-printed formwork was the structural optimisation of the Smart Slab and consequent weight reduction of almost 70% in comparison to a conventional solid concrete slab. The optimisation distributed the material in a hierarchical curved rib structure, which varies between 30 and 60 cm in thickness, while the interstitial surfaces are only 2 cm thick. These results have implications beyond the Smart Slab itself, showcasing how the material strength of concrete can be advantageously combined with the geometric freedom of 3D printing in a new construction method for free-form load-bearing elements.

Fig. 1. The Smart Slab – a concrete slab fabricated with 3D-printed formwork.

1. Formwork for Concrete Slabs

Morphologically, a concrete slab has two significant surfaces, the floor and the soffit or ceiling. Conventionally, these are flat, horizontal surfaces in order to keep formwork construction simple and save costs. In general, this results in oversized, monolithic concrete boxes with big carbon footprints. Furthermore, such slabs transfer big dead-loads to the vertical structure and foundations of a building, which in turn need to be oversized.

Nevertheless, non-standard, expressive slab precedents with articulated ceiling surfaces exist. The first patent for a reinforced concrete slab, filed by Hennebique in 1892 featured a trabeated system of beams; Pier Luigi Nervi introduced prefabricated ribbed slab systems using ferrocement and Hans-Dieter Hecker introduced biologically-inspired optimised designs. In these precedents, up to 80% of the resources went towards the hand-crafted timber formwork systems (Antony et al. 2014), more than reinforcement, raw materials and labour combined.

This significant challenge of formworks for complex slab constructions motivates this research. Overcoming the limitations of the flat panel formwork and increasing the geometric complexity of concrete slabs is not a goal in itself however. Complexity can significantly extend the spectrum of geometric solutions to common architectural design problems with new aesthetics, optimised topologies for material efficiency, precise enclosures for building services and smart assembly details.

2. Digital Formwork for Slabs. State of the Art

To enable complex geometric features for concrete slabs, the limitations of flat formwork panels have to be addressed. Several digital fabrication methods for formwork are already being investigated. Production of formwork for non-standard concrete elements can be done by CNC milling foam blocks (Dombernowsky and Søndergaard, 2008), actuated moulds (Oesterle et al., 2012), robotic hot-wire cutting (Rust et al., 2016), or robotic welding (Hack and Lauer, 2014). Lightweight formwork can also be produced with patterning fabrics (West et al., 2009) or knitting (Popescu et al., 2018). However, all these approaches have process and material specific limitations regarding the geometries that can be achieved.

To overcome these limitations, different 3D printing technologies have already been proposed for formwork, such as fused deposition modelling (FDM) (Jipa et al., 2017) and binder jetting sand (Jipa et al., 2016). Binder jetting is particularly interesting because of its precision, great level of geometric flexibility and availability in large scale.

3. Research Objective

This research builds up on the state-of-the-art of 3D-printed formwork with the objective of applying it to a fully-functional slab element. It focuses on the advantages of binder jetting 3D-printed formwork to fabricate intricate geometric features such as undercuts and deep folds which cannot be fabricated with any other type of formwork. The objective of the research is to define a digital workflow for integrating all the necessary details to translate a free-form slab surface into fabrication data for a formwork system. Furthermore, this research highlights how this fabrication method can be integrated within a digital ecosystem through a case study, the Smart Slab (Fig. 1).

4. The Smart Slab

The 78-m^2 Smart Slab rests on a central "S"-shaped wall. The cantilever from the wall towards the façade reaches 4.5 m. Furthermore, the slab supports a two-story timber frame structure and receives the wind loads from the 15 façade mullions on the perimeter.

The Smart Slab consists of eleven prefabricated concrete segments, mechanically assembled on-site through post-tensioning. Furthermore, it challenges the conventional flat soffit and flat floor slab by articulating both its bottom and top surfaces (Fig. 2).

Fig. 2. A section through the Smart Slab shows the variable-height post-tensioned upstand ribs, as well as the ultra-thin interstitial concrete surface.

The floor side of the slab has a simple articulation, consisting of a series of upstand ribs which contain the post-tensioning cables. These follow a hierarchical model where the principal ribs span the 7.1-metre width of the slab with gradually varying depths of 300 to 600 mm, and the secondary ribs span the 11.7-metre length of the slab with a constant depth of 300 mm. The prestressing tendon in the secondary ribs also takes the role of mechanically connecting the eleven segments once under tension.

The interstitial concrete surface between the ribs stiffens the slab and is only 20 mm in thickness. It defines the ceiling surface of the slab, which is a complex surface with a radical new aesthetic, showcasing micro-structures and deep undercuts which are computationally designed to express the flow of forces through the upstand ribs. Building services are integrated within the structural height of the slab, in the voids above the interstitial surface and between the upstand ribs.

Fig. 3. Concrete spraying (left) and the resulting articulated concrete surface (right).

4.1. Formwork Strategy

Having a flat top surface, the deep ribs were conventionally fabricated through casting concrete. Nevertheless, the thin articulated interstitial surface was not suitable for casting, and therefore concrete was sprayed instead (Fig. 3). The two concreting methods require different formwork systems. The 3D-printed formwork (Fig. 4.d) provides support for the sprayed concrete surface, while laser-cut timber panels are used to cast the upstand ribs which have a less intricate geometry (Fig. 4.a).

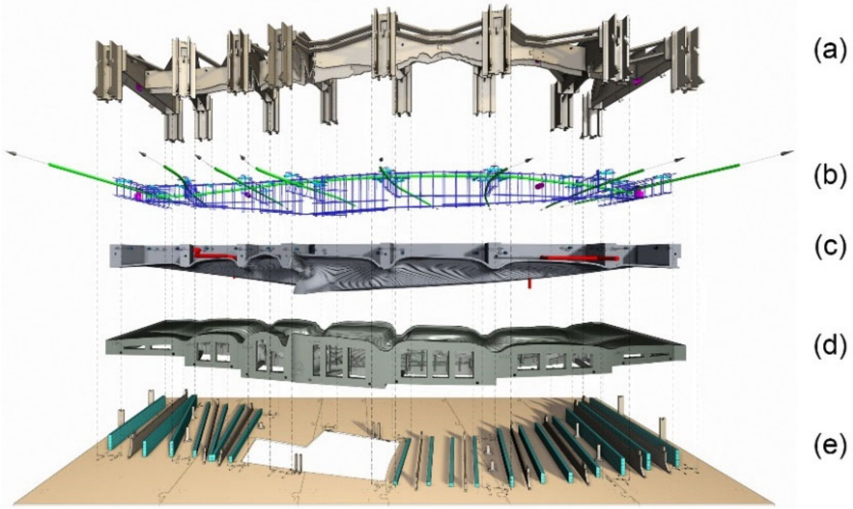

Fig. 4. Exploded diagram of the formwork system: a) CNC laser-cut formwork for the upstand ribs; b) reinforcement bars and tendons; c) the concrete segments; d) 3D-printed formwork; e) timber base and steel spacers;

The 3D-printed formwork was integrated in a wider eco-system of digital fabrication processes, such as the CNC bending of the rigid reinforcement bars and the FDM of formwork inlays (Fig. 9).

5. Digital Design of 3D-Printed Formwork

In principle, 3D-printed formwork can define any free-form shape. Given the complex Smart Slab geometry, with an articulated soffit and ribbed floor, a computational framework was developed to translate the positive concrete geometry to fabrication data for the formwork (Fig. 5).

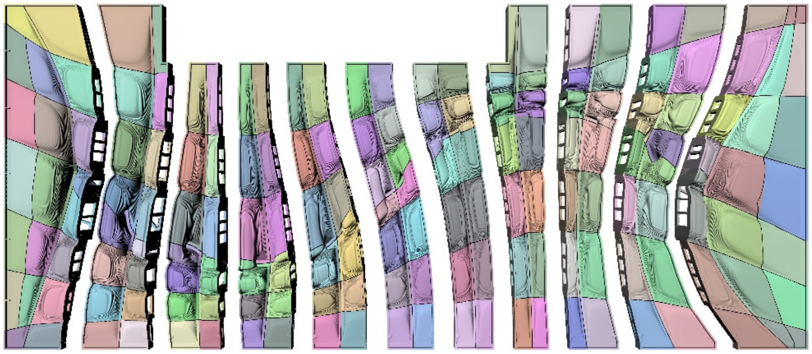

Fig. 5. The 181 3D-printed formwork parts assembled to form the 11 segments

5.1. Design Features for Fabrication

The formwork needs to meet the fabrication constraints of the 3D printers (Fig. 6, left). The limited build volume was smaller than the size of the segment and therefore the formwork had to be discretised. Furthermore, discretisation benefits transportation and manipulation during post-processing and assembly. Therefore, formwork parts were kept below 1 m in the longest dimension and between 30 to 50 Kg on average, so that two people could handle one part. The discretisation was done through seamless cuts with no gaps. These cuts were only visible in the final concrete surface as thin, precise lines 1 to 2 mm in width. Therefore, the discretisation of the formwork was done in accordance with the design of the articulated soffit. To this extent, formwork parts were always split along the centreline of the principal and secondary ribs. Due to the organic nature of the design, the discretisation resulted in 181 parts with significant morphological differences (Fig. 7).

5.2. Design Features for Assembly

Due to the significant weight of the parts, an accessible lifting system had to be provided. This consisted of two or more hollow (ø 34 mm) cross-ties for introducing lifting steel bars in each formwork part.

Fig. 6. The binder-jetting 3D printer used for the Smart Slab formwork (left) and the post-processing of one of the 3D-printed formwork parts (right).

Furthermore, the 3D formwork puzzle required a clear labelling system to identify each part and assemble it in a timely manner. Hemispherical male-female referencing pegs (ø 60 mm) with 1 mm gap in-between were used to ensure accurate assembly.

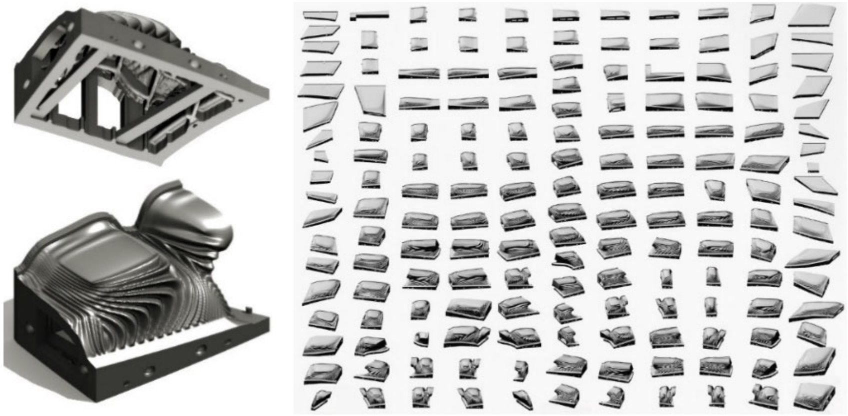

Fig. 7. The 181 3D-printed formwork parts of the Smart Slab.

Once the formwork surface was discretised, it had to be fitted with details that allowed it to be laid on a flat surface. Therefore, each discrete surface received continuous 50-mm-thick vertical supports on the perimeter. These supports stabilise the formwork pieces, but at the same time increase the weight significantly. In order to reduce the material used for these supports, rectangular openings were parametrically devised to be subtracted from these supports (Fig. 7, top left).

5.3. Design Features for Concreting and Removal

The 3D-printed formwork needs to provide a stable negative which can support the weight and hydrostatic pressure of concrete. The formwork was only 20 mm in thickness and benefited from an additional system of stiffening ribs measuring 70 mm in depth and 20 mm in thickness, positioned roughly in a 250 mm square grid (Fig. 7, top left).

Fig. 8. 3D-printed formwork for a 7.1-m concrete slab segment (left) and close-up detail (right).

While the quality and precision of the top of the sprayed concrete surface is not critical as it is hidden, the edges of each segment had to be precisely defined as they form the interface with the adjacent segments. Therefore, the formwork parts included a 20-mm-high vertical rim detail all along the perimeter of each segment. This defined a clean edge as well as a visible indicator on the height of the sprayed concrete surface (Fig. 8, left, in yellow).

The raw 3D-printed sandstone has a very porous surface and concrete binds to it, preventing removal of the formwork once concrete hardens. Therefore, a polyester coating layer, traditionally used in the boating industry is used to seal the pores and strengthen the surface. On the concreting surface, an oil-based release agent is further applied to facilitate removal.

Due to the convoluted nature of the formwork with deep folds and undercuts, entire formwork parts cannot be detached in one piece, therefore breaking lines along the inside of the formwork surface were devised. These breaking guides were essentially linear spreads along which the thickness of the formwork surface was reduced to 5mm, positioned along areas with tight curvatures in the formwork. These were independent of the stiffening ribs and allowed the formwork to be detached in smaller parts without breaking fine concrete details.

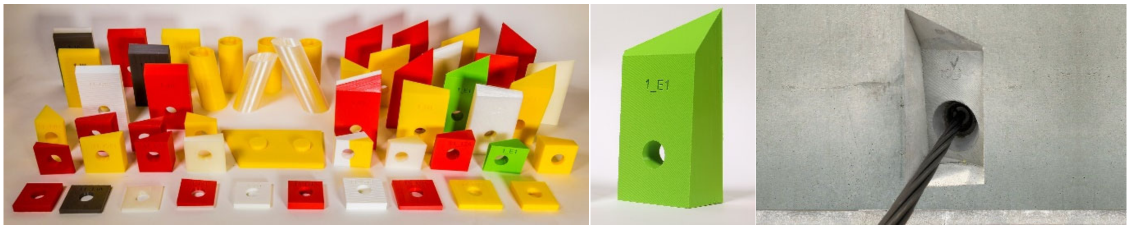

Fig. 9. 114 3D-printed plastic inlays (left) used to integrate functional voids such as the post-tensioning ducts (right)

5.4. FDM Inlays

For the integration of functional details inside the concrete ribs, FDM inlays were used (Fig. 9.). These were fabricated with a bio-based plastic which is stronger than the fragile binder jetted sandstone. FDM allowed thin shell oblique cylinders to define the sprinkler pipe voids and solid prisms to define the precise spatial curvature of post-tensioning tendons.

6. Discussion

One key achievement of this research is a major step forward in free-form shapes and high resolution geometric features achievable with structural soffits (Fig. 3, right). The Smart Slab showcases folds that are several centimetres in depth but spaced at only a few millimetres apart. This radical new aesthetic for concrete slabs is also precise enough to provide very clean functional penetrations for light fittings, fire sprinklers and connections to other building components.

6.1. Precision and Absolute Tolerances:

The construction industry tolerates relatively large margins of error. However, there are certain areas where absolute tolerances need to be kept to a minimum, especially for slabs. The planeness of the floor surface and the interfaces with other materials are critical (e.g. the steel, aluminium and glass in a curtain wall). For the Smart Slab, the interfaces with the support wall and façade mullions were critical. Furthermore, precise fabrication is especially needed to accurately define the curved interfaces between the prefabricated concrete segments. Moreover, any tolerances above 5 mm between adjacent segments would physically prevent the post-tensioning tendons from passing through.

By excellence, 3D printing processes promise tolerance-free fabrication. Nevertheless, to anticipate for any assembly margins, 4 mm gaps between the concrete segments were provided (Fig. 10, left). These tolerances were calculated to accommodate for any tolerances in the concrete segments which could occur due to accumulated errors from the assembly of discrete parts or from the autogenous shrinkage and deflection under load of the concrete.

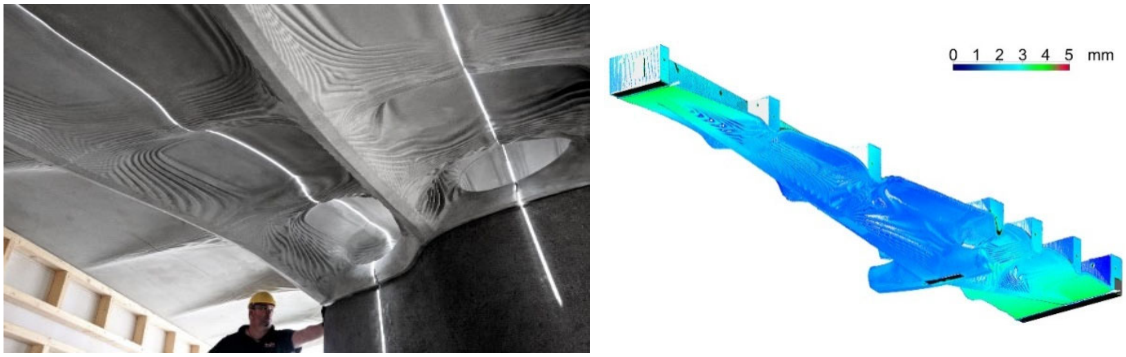

Fig. 10. The seams between the concrete segments highlighted by sunlight coming through (left). The deviations from the 3D model (right)

Once the concrete hardened, laser 3D scanning was used to determine the absolute deviations from the 3D model (Fig. 10, right). Differences were below 4 mm, mostly in the range of 1 to 2 mm. The higher deformations were only recorded in the vertical direction towards the ends of the segment and were due to the deflection of the concrete segment under its own weight before applying post-tensioning.

6.2. Weight reduction

A conventional flat concrete slab equivalent of the Smart Slab would need to be at least 37.5 cm thick (1/12 of the 4.5 m cantilever), resulting in a total volume of ~30`000 L, and a mass of 74 t. Conventionally, post-tensioning reduces the amount of concrete used by 25% (Miller et. al., 2016), and the use of lightweight high-performance concrete typically further reduces the weight of structures by 25% (Penza, 2010). Thus, a conventional lightweight concrete prestressed slab would weigh 42 t. By comparison, the Smart Slab only weighs around 15 t, which represents only 35% of the conventional benchmark.

7. Conclusion

Unlike slabs with flat soffits, where formwork is relatively minimal and can be reused and recycled easily, for the Smart Slab, the custom formwork weighing over 9.5 t, was only used once and disposed of afterwards. As a consequence, it is essential that recyclable 3D-printed formwork is developed. As building components are optimised more and more, not only the amount of formwork used increases, but generally, the processes involved become more complex.

Weight reduction in slabs clearly has considerable advantages for the structure and sustainability of a building. However, massive building components also benefit thermal insulation, thermal mass, fire retardation and acoustic insulation. To overcome these drawbacks, solutions inspired from lightweight slab constructions have to be applied.

The presented method is naturally relevant for slabs because flat soffits have a very high potential for optimisation. However, a wide variety of building elements could further benefit from this (e.g. elements which are geometrically complex intrinsically, such as stairs and transitional elements, but also elements which are conventionally flat due to material economy such as walls and facades). Optimizing and reducing the weight of building components has a significant benefit for their sustainability. Nevertheless, the fundamental benefit of 3D-printed formwork is that it expands the freedom of design with concrete, essentially enabling the design of more sustainable, high-quality spaces.

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