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Digitally fabricated ribbed concrete floor slabs: a sustainable solution for construction

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Abstract

The concrete used in floor slabs accounts for large greenhouse gas emissions in building construction. Solid slabs, often used today, consume much more concrete than ribbed slabs built by pioneer structural engineers like Hennebique, Arcangeli and Nervi. The first part of this paper analyses the evolution of slab systems over the last century and their carbon footprint, highlighting that ribbed slabs have been abandoned mainly for the sake of construction time and cost efficiency. However, highly material-efficient two-way ribbed slabs are essential to reduce the environmental impact of construction. Hence, the second part of this paper discusses how digital fabrication can help to tackle this challenge and presents four concrete floor systems built with digitally fabricated formwork. The digital fabrication technologies employed to produce these slab systems are digital cutting, binder-jetting, polymer extrusion and 3D concrete printing. The presented applications showcase a reduction in concrete use of approximately 50% compared to solid slabs. However, the digitally fabricated complex formworks produced were wasteful and/or labour-intensive. Further developments are required to make the digital processes sustainable and competitive by streamlining the production, using low carbon concrete mixes as well as reusing and recycling the formwork or structurally activating stay-in-place formwork.

Keywords: Digital fabrication; Concrete structures; Digital concrete; Floor slabs; Ribbed slabs; Optimisation; Sustainability

1 Introduction

Reinforced concrete is by far the most used construction material worldwide [1], and most concrete volume is employed in building construction (e.g. 75% in Switzerland [2]). Floor slabs constitute 40%...60% of the concrete volume within typical three to eight-storey buildings, while the foundations account for 20%...30% [3]. With increasing building height, the share of floor slabs increases compared to that of the foundations. Accordingly, the structural optimisation of reinforced concrete floor slabs is a powerful lever for the concrete construction industry to tackle climate neutrality [4].

Despite its relevance, environmental sustainability is not the only requirement floor slabs need to fulfil. Bischof et al. [3] suggested six main criteria that buildings and infrastructure need to comply with today: (i) structural safety, (ii) durability, (iii) serviceability, (iv) aesthetics and integration, (v) environmental sustainability and (vi) construction efficiency. *Table 1* elaborates on these criteria with corresponding descriptions.

Design codes define structural safety, durability, and serviceability to a certain extent. Durability requirements are minimal for most slabs, given their exposure to a dry indoor environment. In contrast, aesthetics and integration, construction efficiency (i.e. direct and indirect costs) and environmental sustainability depend on client preferences, material availability, or political and societal tendencies. Analysing (i) the evolution of these tendencies in the past and (ii) how they forged current building systems is an essential step towards identifying opportunities for reinforced concrete buildings that adapt better to new societal requirements (e.g. the importance of environmental sustainability requirements is expected to grow).

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Table 1. Description of relevant criteria holding for reinforced concrete structures and their construction.

Criteria	Description
Structural safety	Overall stability, ultimate resistance, fatigue resistance and robustness for transient, persistent and accidental limit states.
Durability	Resistance against corrosion due to carbonation and/or chloride ingress, against chemical attack and against freeze-thaw cycles.
Serviceability	Functionality, appearance (prevention of excessive deflections), and comfort (temperature, moisture, noise, vibrations, etc.).
Aesthetics and integration	Integration in landscape or urban context, logic of form, elegance.
Environmental sustainability	Recyclability, reusability, resource consumption, greenhouse gas emissions and negative impact on flora, fauna and landscape.
Construction efficiency	Construction time efficiency (indirect cost) and economy (direct cost).

Table 2. Overview of reinforced concrete floor systems.

Cross-section	Support	Load transfer	Typical floor system denomination	Traditional construction process
Ribbed	Linear (walls or beams)	One-way	Ribbed slab, T-beams	On-site, partial prefabrication, complete prefabrication
		Two-way	Waffle slab (straight ribs)	On-site
	Point (columns)	Two-way	Ribbed slab (curved ribs)	On-site
Solid*	Linear (walls or beams)	One-way	Solid slab, filigree slabs (partial prefabrication)	On-site, partial prefabrication, complete prefabrication
		Two-way	Solid slab	On-site
	Point (columns)	Two-way	Flat slab	On-site
	Point (columns with widened heads or drop panels)	Two-way	Mushroom slab	On-site, partial prefabrication
Hollow (extruded)	Linear (walls or beams)	One-way	Hollow-core-slab (extruded)	Complete prefabrication

* voids may be used to reduce the concrete volume

** "One-way" describes the load transfer in one direction to the supports, while "two-way" describes the load transfer in two directions to the supports.

Table 3. Characteristics of reinforced concrete floor systems.

Cross-section	Characteristics
Ribbed	− Ribbed cross-section allows considerable material savings and self-weight reduction. − Ribbed slabs are stiffer than solid slabs with equivalent bending resistance (e.g. implies lower deflections or a superior acoustic performance), but require higher structural depths. − Ribs require shear reinforcement. − Ribs at the soffit (underside of slab) increase the exposed surface, which is disadvantageous under fire resistance. − Ribs require alignment of building system installations. − Two-way ribbed slabs require adaptation of the rib configuration with changing spans.
Solid	− A flat soffit allows producing time and cost-effective formwork. − Solid slabs require a low structural depth compared to other slab systems. − A flat soffit minimises the exposed surface and, accordingly, delays the temperature diffusion under fire conditions. − Building system installation may be placed flexibly inside the slab or directly below the soffit. − The design of the plan layout is flexible.
Hollow	− Extruded hollow cores allow for considerable material savings and self-weight reduction (savings beyond 50% compared to solid slabs are possible). − Pre-tensioning makes production in casting beds highly efficient while facilitating compliance with serviceability requirements and, accordingly, enabling slender slabs. − The typically unreinforced, slender webs are sensitive to shear loading and fire conditions. − An upwards camber due to strong pre-tensioning may require an on-site topping. − A flat soffit delays the temperature diffusion under fire conditions.

Section 2 of this paper presents several floor slab typologies (ribbed, solid and hollow), describes how these systems evolved during the last century and evaluates the environmental impact of ribbed and solid slabs. This analysis shows that highly material-efficient slab systems employed in the past by pioneer structural engineers have been abandoned for the sake of construction time and cost efficiency, given (i) the extensive and cheap availability of raw building materials in the last decades and (ii) the high cost of bespoke structural design solutions, non-planar formwork, and human labour.

Digital fabrication with concrete (DFC) has emerged in recent years as a set of computer-controlled fabrication methods directly following CAD data [5] for entire or parts of structures. Advantages of digital fabrication include creating freeform geometries to adjust for individual requirements in terms of spans and floor plan shape without significantly influencing the fabrication cost and time.

Hence, DFC may enable the efficient manufacturing of floor slabs with a low carbon footprint [6] while respecting today's requirements for buildings. Section 3 of this paper explores the potential and limitations of such digitally fabricated floor slab systems, and Section 4 discusses corresponding ongoing research at ETH Zurich.

2 Concrete floor systems

This section presents a critical review of floor slab typologies stating their material saving potential and different characteristics that have conditioned their use in the past. *Table 2* summarises traditional reinforced concrete floor systems to specify the terminology used in the Eurocodes [7,8] and in this paper. *Table 3* elaborates on characteristics (i) inherent to the choice concerning the cross-section of floor systems and (ii) deemed necessary to discuss the potential and challenges of ribbed floor systems. The current share of the different floor types developed through the last century depends on tradition and market-specific reasons, such as the availability of material and workforce, architectonic individualism, requirements on building systems, or the available infrastructure for on-site or prefabricated construction [3]. Flat slabs, T-beams, and hollow-core-slabs are the most frequently applied floor systems.

A ribbed slab consists of a thin slab and ribs (joists). The ribs are typically straight for one-way slabs linearly supported on walls or beams, while they are often curved or kinked for two-way slabs point-supported on columns. The French engineer and builder François Hennebique (1842–1921) [9,10] successfully introduced ribbed reinforced concrete floor slabs at the end of the 19th century. His patented ribbed slabs contained different-level orthogonal ribs with deeper primary ribs supporting the secondary ribs (*Figure 1a*). The Italian engineer Pier Luigi Nervi (1891–1979) [11,12] designed aesthetically refined slabs with orthogonal ribs using prefabricated moulds (*tavelloni*) made of ferrocement for the Manifattura Tabacchi in 1949 (*Figure 1b*). In the early 1950s, Aldo Arcangeli and Nervi determined curved ribs following the directions of the principal bending moments for the Lanificio Gatti (*Figure 1c*). While the ribbed slabs of Hennebique, Arcangeli and Nervi were cast on-site, cost-efficient prefabricated straight T-beams emerged with the development of prestressing steel and pre-tensioning beds in the 1940s and 1950s. These T-beams carry loads in one direction and are mostly produced with two parallel webs ("double-T beams") incorporating highly prestressed strands. Hollow clay or concrete bricks can be placed as a stay-in-place formwork between two prefabricated joists to cast an in-situ thin slab ("hourdis block slab").

The engineers Claude A. P. Turner (1869–1955) [13] in North America and Robert Maillart (1872–1940) [14] in Europe developed designs of solid slabs (see example in *Figure 2a*) at the very beginning of the 20th century. Their mushroom slabs were point-supported by columns with widened heads, having a constant depth otherwise. This design allows (i) introduction of the high shear loads along the circumference of the columns and (ii) a local increase of the bending moment resistance. Today, flat slabs are often built (i) with an overall constant depth to facilitate the use of formwork tables and (ii) providing shear reinforcement close to the columns to avoid punching failures. The application of voids in slabs (e.g. made of high-density polypropylene materials, see *Figure 2b*) may substantially reduce the concrete volume but is typically used only for larger spans.

Partial or complete prefabrication is applied in many countries nowadays, mainly with one-way solid slabs (filigree slabs with on-site topping), one-way hollow-core slabs or double-T beams. Hollow-core slabs contain longitudinally continuous voids (hollow cores) and are supported by beams or walls (see *Figure 2c*). The development of extruded hollow-core slabs spanned from the beginning of the 20th century to the 1960s [15], continuously optimising precast production methods for providing voids and reinforcement. Today, the production of pre-tensioned hollow-core slabs by extrusion is highly industrialised.

Figure 1. Compilation of historical ribbed floor slabs: (a) Möbelfabrik Reutlinger, Karlsruhe (1899, Photo: CNAM/SIAF), (b) Manifattura Tabacchi, Bologna (1949, [12]), (c) Lanificio Gatti, Roma (1953, [12]).

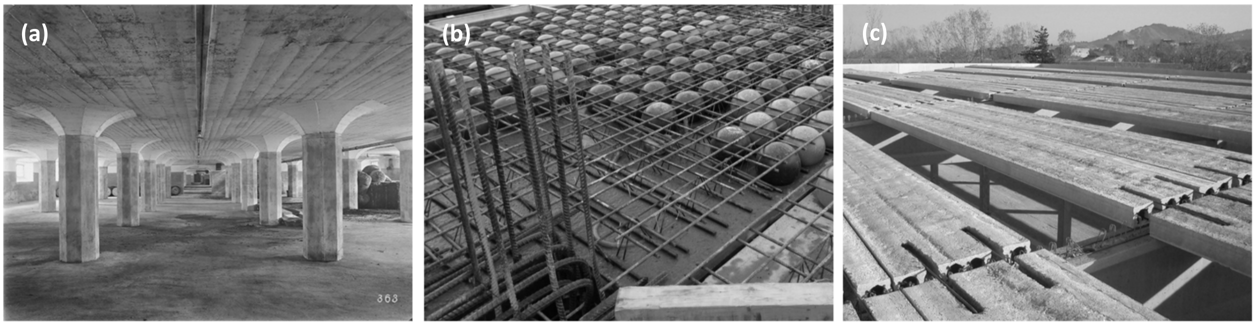

Figure 2. Examples of solid and hollow floor slabs: (a) Mushroom slab of warehouse Giesshübel, Zürich (1910, Photo: ETH-Bibliothek, Hochschularchiv, Hs 1085: 1910-3), (b) Bubble deck system (Photo: Bubbledeck North America), (c) hollow-core slab elements (Photo: Nordimpianti).

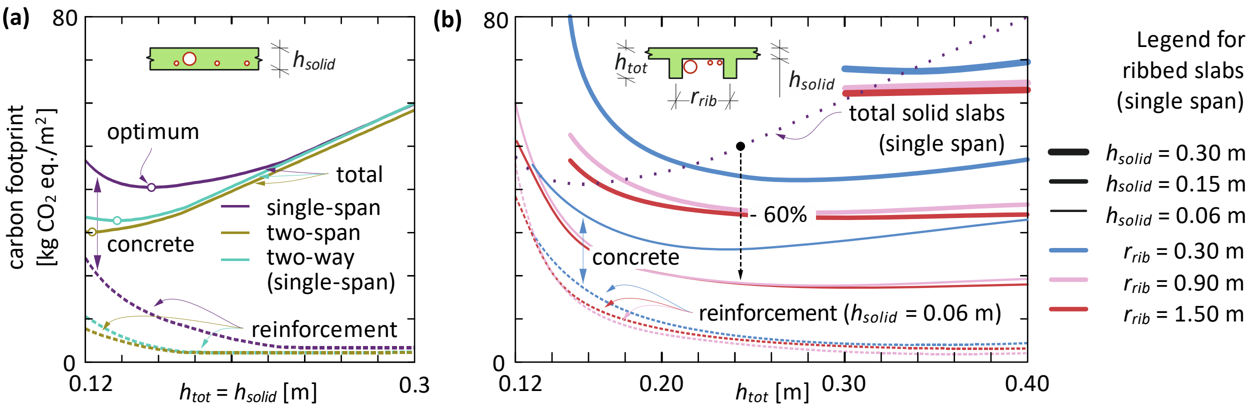

Figure 3. Carbon footprint of concrete and reinforcement (dashed lines) of (a) solid slabs (single-span, two-span, and two-way single-span) and (b) single-span ribbed slab (both spanning 6 m) as a function of its total depth

Despite being highly material-efficient floor systems, two-way ribbed slabs have been largely abandoned over the last decades due to their excessive production costs and time when built with traditional formwork, making them economically uncompetitive. However, their sustainability potential is enormous. To highlight this potential, the embodied carbon footprint of an example slab supported by columns using a ribbed or a solid typology is compared in the following.

Ribbed and solid residential slabs with 6 m spaced line supports are designed to fulfil the main structural design verifications according to EN 1992-1-1 [7] for the ultimate limit state (flexural and shear capacity) as well as for the serviceability limit state (indirect check of deflections according to Section 7.4). The fire safety requirements for 30 min resistance are fulfilled according to EN 1992-1-2 [8]. The design of all designed slabs respects a superimposed permanent load and a variable load of 2 kN/m^2 each and relies on concrete C25/30 (f_{ck}=25 MPa) and reinforcing steel B500 (f_{sk}=500 MPa). The ribbed slabs incorporate the minimum shear reinforcement according to EN 1992-1-1 [7].

Once the slab is designed, the environmental footprint is estimated by multiplying the concrete and reinforcement volumes by their global-warming potential (GWP). The GWP generally results from a life cycle assessment and may be found in the respective Environmental Product Declaration (EPD) [16] or in [17,18]. The GWP of concrete strongly depends on the amount and type of cement (particularly the clinker content), as well as the type of fuel used for clinker calcination. For reinforcing steel, it mainly depends on the manufacturing method and the amount of scrap. The chosen GWP for concrete is 190 kg CO2-eq./m^3 (representing concrete with CEM II/B produced with 70% alternative fuel [19]), while a GWP of 0.4 kg CO2-eq./kg is assumed for the reinforcement (rough average for Western European reinforcing steel [20]).

It should be noted that the environmental footprint of formwork is highly dependent on the floor system and the applied formwork technology, whose further development is the main focus of digital fabrication (see Sections 3 and 4). The comparison presented herein is intended to be technology-independent and, hence, does not include the impact of the formwork. The design includes (i) ribbed slab configurations with varying rib spacing r_{rib}, slab depth h_{solid} and total depth h_{tot} as well as (ii) solid slabs with varying depth h_{solid}. The width of the ribs was chosen to provide sufficient space to (i) include stirrups, (ii) reinforcing bars, (iii) space between reinforcing bars and (iv) a minimum concrete cover of 20 mm. Note that the calculated reinforcement volume, including stirrups in the ribs, was globally increased by 15% to account for detailing and splices.

Different static systems were considered for the solid slabs (one-way with a single span, one-way with two spans, and two-way with a single span in both directions), while the ribbed slab was modelled as one-way with a single span. It should be noted that the two-way load-carrying behaviour of the considered square slab (6 m x 6 m) was modelled in a simplified manner by halving the load and reducing the effective depth to consider both reinforcement directions.

Figure 3 shows the carbon footprint per 1 m^2 floor surface for solid (*Figure 3a)* and ribbed slabs (*Figure 3b)*. Although dependent on specific input parameters, this example assessment allows drawing the following main conclusions:

- Solid slabs used in practice are rarely optimised in terms of carbon footprint today. Typical slab depths of 0.2…0.3 m are clearly beyond the optimum (see *Figure 3a*) when considering only structural integrity requirements. Building system inserts, acoustic insulation, or architectural requirements often govern their depth (e.g. see [21]).
- Ribbed slabs with large rib spacing contain a high potential to optimise the carbon footprint, increasing with decreasing ratio of solid slab depth h_{solid} to total depth h_{tot}. For typical slab depths of 0.2…0.3 m, the footprint of a single span one-way solid slab can be reduced by 40…65% when using a rib configuration with a thin upper part of the slab (see reduction in *Figure 3b*).
- Continuous and two-way load-bearing conditions exhibit a distinctly lower carbon footprint than one-way single-span slabs. The latter requires a much higher reinforcement content at the optimal depth (see comparison of violet, brown and green solid lines in *Figure 3a)*. Two-way load-bearing conditions are not fully explored nowadays by prefabricated hollow-core and ribbed one-way solutions.

3 Digital fabrication processes for concrete floors

Various fabrication technologies are known under the umbrella of DFC. Most include additive, formative or subtractive shaping processes [22]. Commonly, these technologies share the approach to rethink, improve, and digitise traditional formwork processes and may be differentiated from traditional construction as "formworkless" technologies or technologies incorporating "non-conventional formwork" [23].

As outlined above, using ribbed slabs fosters the optimisation of construction material. Although ribbed slabs were used more often in the past, their use has diminished due to labour and formwork material costs. As outlined below, several DFC processes potentially offer efficient ways to produce two-way ribbed concrete slabs and foster the sustainability of building construction. Moreover, Lydon et al. [24] underlined the potential to combine material efficiency with functional demands such as heating, cooling and ventilation.

Additive processes such as binder jetting, extrusion and spraying can be used either to 3D print a concrete slab directly, or to print formwork for the slab. Formwork produced with DFC technologies may be stay-in-place or temporary. Stay-in-place formwork serves as mould during casting and might serve as a building system or fulfil a mechanical or aesthetic purpose in the final slab configuration, as for the example applications shown in *Sections 4.1* (CNC cutting of wood or plastics) and *4.4* (3D concrete printing). Temporary formwork might be (i) reusable as envisioned in one of the applications presented in *Section 4.2* (binder jetting) and the application shown in *Section 4.3* (polymeric extrusion), or (ii) disposable as in the Smart Slab application presented in *Section 4.2*. Beyond these applications, which will be presented in more detail in *Section 4*, several other DFC technologies using non-conventional formwork have been used or could potentially be applied to produce ribbed slabs:

- *Slipforming* is a widespread extrusion process in conventional construction of slabs, used to produce horizontally prestressed hollow-core slabs or joists. The DFC technology Smart Dynamic Casting broadens the possibilities of slipforming with variable cross-sections by adapting the slipping formwork through a robotic process and using a fast-hardening self-compacting concrete whose hydration is controlled through a digital process (known as set-on-demand or digital casting) [23,25].
- *Flexible formwork* technologies hold great potential for bespoke concrete structures [26], but their use to produce slabs is still scarce. Flexible membranes can be shaped with a wide range of systems, including cable nets [27,28] or a system of actuators [29]. A set-on-demand concrete process has been used to shorten the setting time and reduce the pressure during casting, allowing the application of minimum stiffness membranes as concrete formwork [23]. Employing fabrics made of high-strength fibres allows stay-in-place flexible formwork to be used as reinforcement after the concrete hardens (e.g. [30]). While this might be a very efficient system to reinforce optimised slabs, fire protection remains an issue to be solved.
- *Steel reinforcement meshes used as stay-in-place permeable formwork* can be activated as reinforcement in the final structure. The manual fabrication used by Nervi in the "ferrocement" system can be replaced by robotic assembly [31]. Non-conventional concrete mixes are required to avoid the material flowing out of the permeable formwork depending on the bar spacing.

4 Application of digital fabrication for concrete floors

The following sections provide an overview of ongoing research at ETH Zurich on temporary or stay-in-place formwork for ribbed slabs, involving the following digital fabrication technologies:

- CNC cutting of wood and plastics (*Section 4.1*).
- 3D printing of non-cementitious materials: binder jetting (*Section 4.2*) and polymeric extrusion (*Section 4.3*).
- 3D concrete printing (*Section 4.4*).

4.1 Funicular floors

A funicular floor is an unreinforced vaulted ribbed slab system. It is designed to have uniformly compressed concrete cross-sections under the predominant load case by following a compression-only network of forces [32]. In the case of point supports, the horizontal thrust can be resisted by tension ties exclusively along the perimeter, which require fire protection. The stiffening ribs ensure stability against concentrated loads (*Figure 4*). The system optimises material use beyond traditional ribbed systems by placing it only where it is under compression.

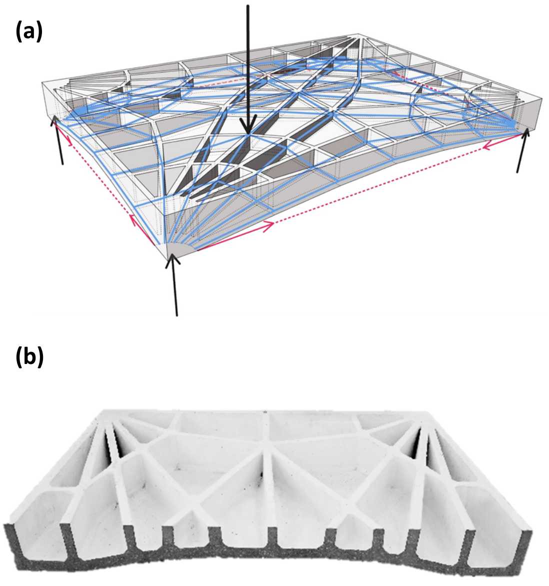

Figure 4. Funicular floors: (a) structural concept and force distribution (compression in blue, tension in red); (b) section of a funicular floor showing the rib-stiffened vaulted geometry. Diagram and photo by Block Research Group.

After a series of prototypes demonstrating the use of several fabrication techniques and materials at a small scale [33–35], two single-span funicular floors of roughly 20 m^2 with a maximum span of 5.35 m were built in the HiLo unit in Dubendorf, Switzerland [36] (Figure 5). These floors with a depth of 350 mm from the support to the top were cast in-situ, employing a self-compacting steel fibre reinforced concrete mix with more than 50% recycled aggregates and using a prefabricated double formwork. The voids between ribs were digitally cut from EPS foam. While the bottom formwork was temporary (*Figure 5a*), the upper foam formwork (*Figure 5b*) remained part of the final slab as insulating material. Ranaudo et al. [36] reported saving 50% concrete and 90% reinforcement volume (considering the post-tensioning ties but not the steel fibres) when comparing one of the two funicular floors to an assumed typical concrete flat slab of 200 mm thickness with a reinforcement ratio of 65 kg/m^3. It is also worth mentioning that the floors (i) contained the building systems (lighting, heating and cooling, and ventilation), (ii) were verified for 30 min fire exposure and (iii) complied with vibration limits [37] and acoustics standards [38]. However, the cast-in-place construction resulted in a cumbersome formwork causing considerable waste, suggesting that prefabrication might be a more suitable strategy.

4.2 Binder jet 3D-printed slab formwork

The use of binder jetted formwork was demonstrated at ETH Zurich in three different applications for ribbed slabs, as presented below. Binder jet 3D printing allows for a higher degree of customisation than cut formwork (*Section 4.1*) and higher spatial resolution than other 3D printing formwork processes (*Sections 4.3* and *4.4*). However, binder jetted formwork requires a polyester surface coating, making them difficult to recycle [39].

The *Smart Takes from the Strong* project (*Figure 6a*) showcased binder jetting for stay-in-place, non-structural formwork [40]. Two 1.8 m^2 slab prototypes with a network of topology optimised ribs were produced with ultra-high-performance fibre-reinforced concrete cast in a 9 mm thick binder jetted shell. Later, reusable binder jetted formwork was used for a modular two-way ribbed slab system dubbed the *Fast Complexity* project (*Figure 6b*) [41]. In this application, ribs were 3D printed on top of the formwork and did not incorporate any reinforcing bars.

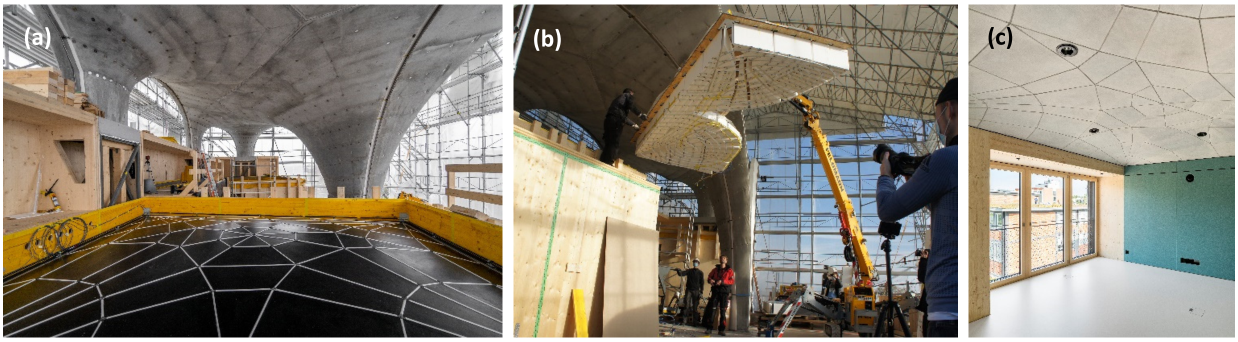

Figure 5. HiLo funicular floor: (a) bottom temporary formwork; (b) top polyurethane stay-in-place formwork; (c) bottom view of final slab. Photos by Juney Lee.

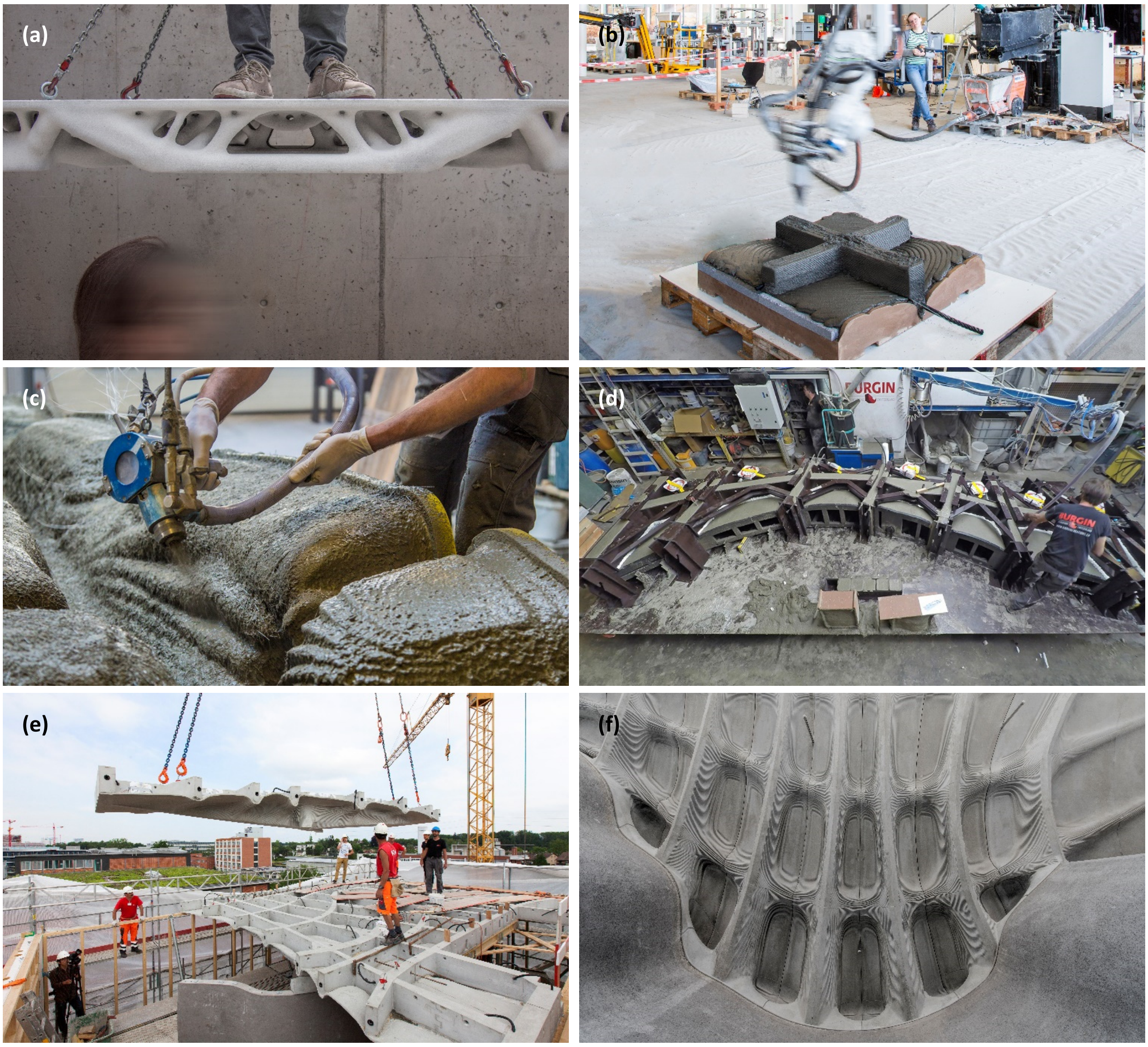

Figure 6. Ribbed slabs with binder jet 3D-printed formwork: (a) stay-in-place formwork for the Smart Takes from the Strong [40]; (b) reusable formwork for Fast Complexity [41]; and (c-f) disposable formwork for the DFAB HOUSE Smart Slab [31], illustrating (c) the spraying of the concrete cover, (d) the casting of the ribs, (e) the installation on-site, and (f) the soffit of the finished slab.

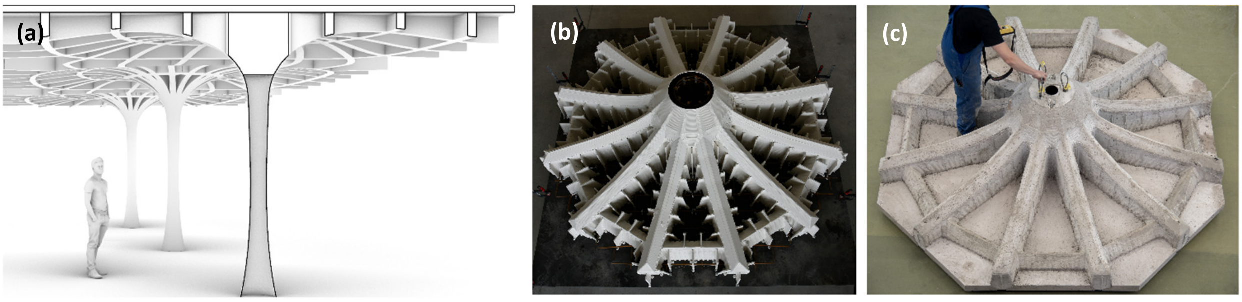

Figure 7. Ribbed slabs with thin polymeric 3D-printed formwork: (a) visualisation of the proposed slab system; (b) robotically 3D printed formwork; (c) finished optimised column-slab demonstrator.

The integration of conventional reinforcement was explored with the *Smart Slab* [42], a 78 m^2 load-bearing concrete slab in the DFAB House (*Figure 6c-f*) employing disposable binder jetted formwork. The slab cantilevers up to 4.5 m from an S-shaped concrete wall [31] and supports two timber storeys above [43]. The Smart Slab featured a non-orthogonal two-way grid of ribs (160 mm wide, varying from 300…600 mm in depth) that transitioned smoothly between the curved supporting wall and the rectangular perimeter. Given the absence of any fire resistance requirements for the slab, the interstitial surfaces of the grid could be very thin (15…20 mm), with the remaining cavities being filled with acoustic insulation from the top. The production process consisted of (i) spraying a 15…20 mm concrete cover directly on the coated bottom formwork (*Figure 6c*), followed by (ii) casting the upstand ribs using a disposable laser-cut plywood upper formwork (*Figure 6d*).

The Smart Slab was prefabricated in eleven rib segments installed on-site using a temporary timber falsework on the perimeter (*Figure 6e*) before the tendons (Ø = 15.7 mm) in the ribs were post-tensioned. The stirrups resisted the shear loads and the deviation forces resulting from the curved tendons. Thanks to the ribbed geometry and the use of lightweight aggregate concrete (bulk density = 1446 kg/m^3; mean 28-day compressive strength = 33.6 MPa), the weight of the Smart Slab was 70% lower than the considered equivalent solid concrete slab (240 mm thick; 170 kg/m^3 reinforcement).

4.3 3D printed polymeric slab formwork

The material used for the formwork for two-way ribbed slabs may mitigate the environmental benefits offered by structural optimisation [44]. The Eggshell fabrication process [45] tackles this issue by 3D printing a thin polymeric formwork. This formwork could potentially be recycled after casting and demoulding, but further studies are required to explore this potential. This type of material extrusion is also known as fused deposition modelling (FDM).

Current investigations of the Eggshell technology explore the fabrication of point-supported ribbed slabs. The corresponding design envisions a ribbed two-way slab spanning 8 m between columns with ribs following the principal directions of the bending moments (*Figure 7a*) [46,47], as proposed by Arcangeli and Nervi (see *Section 2*). The slab is designed to be 80 mm thick, complying with fire resistance requirements for 60 min, while the ribs have a varying depth. The ribbed slab is intended to be prefabricated in segments, which could be assembled on-site with construction joints or internal post-tensioning. Such a ribbed slab could reduce the use of concrete by 40% compared to the considered equivalent conventional solid slab of 220 mm thickness [46,47].

For showcasing the slab design, a full-scale column-slab segment was fabricated (*Figure 7c*) with the following steps: (i) printing of the rib formwork with FDM, including reinforcing bars crossing the formwork on the printing platform (as suggested in [3]); (ii) adding prefabricated reinforcement cages for the ribs; (iii) closing the ribs by 3D printing the ‘roof’ formwork (*Figure 7b*); (iv) casting the ribs; (v) demoulding; and (vi) complementing the interstitial surface of the slab on the printing platform serving as a formwork for the flat upper side of the slab.

With slab elements being produced upside down, this concept requires prefabrication as the slab must be turned over after production. While the flipping process might be risky, on-site connections of partially or fully prefabricated elements are essential to employ such solutions reliably [3]. At the same time, this concept benefits from the limited casting height of concrete, allowing the use of conventional concrete, albeit with stiffeners integrated into the formwork (*Figure 7b*). While these stiffeners increase the print-time and formwork material consumption, they enable using cheaper and less carbon-intensive concrete mixes than the set-on-demand mix typically needed in the Eggshell process [23,45]. It should be highlighted that applying conventional deformed steel bars enables a straightforward code-compliant design and reduces cost. However, the first results underline the necessity to streamline production, which at the moment is still time-consuming and labour-intensive concerning the reinforcement installation and formwork demoulding.

4.4 3D concrete printed slab formwork

This section explores point-supported ribbed slabs with 3D concrete printed (3DCP) elements that serve as a stay-in-place formwork. The provision of reinforcement within printing layers (see [48,49]) renders the structural activation of the printed material in the final slab possible, thus minimising the overall concrete use. After assembling the 3DCP formwork on-site, conventional reinforcing steel and concrete can be used to realise a monolithic, two-way load-bearing slab.

This approach was used to design a continuous slab supported by an orthogonal grid of columns. The directions of the principal moments served as inspiration for the design. In contrast to the example of the *Lanificio Gatti* shown in *Section 2* or the slab presented in *Section 4.3*, the primary ribs are polygonal, and the subordinate ribs are quasi-circular (see *Figure 8a*). The structure of the ribs on different levels and the concentrated kinks, with ribs balancing the deviation force under distributed loading, avoids material-inefficient lap splices and allows continuous and repetitive reinforcing bars to be placed inside the formwork. Furthermore, the radial ribs determine the printability-informed slab segmentation (see a detail of the segmentation in *Figure 8b*).

A 1:1 prototype of the column-slab connection was produced using the 3DCP process developed at ETH Zurich [50–52]. The four triangular sub-sections are envisioned to be built in a standing position and are horizontally contoured to create print paths that optimally intersect the structural ribs (see *Figure 8c*). The depth of the ribs can be varied along their length to increase their structural efficiency. The prototype demonstrates that thin (15 mm) concrete shells can be printed and assembled into complex structural slab systems. However, aspects such as the bond between the printed shell and the cast-in-situ concrete, the fire resistance of thin cross-sections, connection details or the transportability of partly unreinforced concrete elements require further attention.

5 Concluding remarks on sustainable concrete floor slabs

Floor slabs typically absorb 40%-60% of the concrete volume in building construction. Hence, the structural optimisation of reinforced concrete floor slabs is a powerful lever for the concrete construction industry to tackle carbon neutrality. Two-way ribbed slabs are highly material-efficient floor systems used by eminent structural engineers such as Hennebique, Arcangeli and Nervi more than a century ago. However, these systems have been abandoned over the past decades because their production with traditional technologies is costly and laborious, considering the dependency of the rib configuration on the spans and floor plan shape.

It is imperative to find ways to produce material-efficient slabs soon, given (i) the urgent need to reduce the environmental impact of construction and (ii) the fact that the carbon footprint of a solid slab, the most widespread concrete floor system in many countries, can be reduced by roughly 50% when introducing a ribbed configuration. To this end, this paper presents a wide range of digital fabrication processes aiming (i) at creating such efficient concrete structures and (ii) to be compliant with the constraints of individual designs. Digital technologies allow production of concrete slabs (i) without any formwork or (ii) with non-conventional temporary or stay-in-place formwork. Their potential and limitations have been presented by analysing four concrete ribbed floor slabs built with non-conventional formwork. These applications illustrate the re-adaptation of material-efficient floor systems built in the past to fulfil current building code regulations. They employ two-way ribbed and vaulted cross-sections and introduce suitable reinforcement strategies (passive reinforcing steel, post-tensioning, and steel fibres). These applications also show that further research in the following directions is required to make sustainable ribbed slabs competitive again:

- The formwork footprint may mitigate the environmental benefit of using ribbed instead of solid cross-sections. The employment of digital fabrication technologies to use recyclable formwork or thin prefabricated mechanically-engaged stay-in-place formwork, which are then filled with cast-on-site conventional or even lean concrete, is a promising strategy to build ribbed slabs sustainably. However, the formwork recyclability and the potential to combine stay-in-place formwork with cast concrete require further development.
- Not only the concrete volume but also the reinforcement dictates the efficiency and sustainability of floor systems. Studies incorporating topological optimisation should consider that straight continuous reinforcement is most efficient for environmental and construction efficiency. Strongly curved reinforcing bars require inefficient transport for site delivery and may challenge the assembly of reinforcement cages. Kinks or strong curvatures create deviation forces requiring lap splices of reinforcing bars, additional reinforcement perpendicular to the primary reinforcement, or additional ribs. Here, organising intersecting ribs on different levels of two-way ribbed slabs is very effective and ensures the continuity of the reinforcement (see example in *Figure 1a*).
- Since most digital fabrication technologies are best suited in a prefabrication environment, safe and straightforward structural connections will be essential in entirely or partially prefabricated digitally fabricated ribbed slabs.
- To penetrate the construction mass market, it is essential for digitally fabricated ribbed concrete floor systems to comply and be designed with existing building requirements, as design by testing – as currently used for many demonstrators of digital fabrication technologies (e.g. see [53]) – is not affordable for standard cases.
- The slab systems presented in Section 4 show that transporting, handling and installing digitally fabricated elements might be cumbersome and require excessive scaffolding and human labour. Hence, it is crucial to consider construction efficiency and the integration with complementary traditional construction processes when developing new ribbed floor systems.

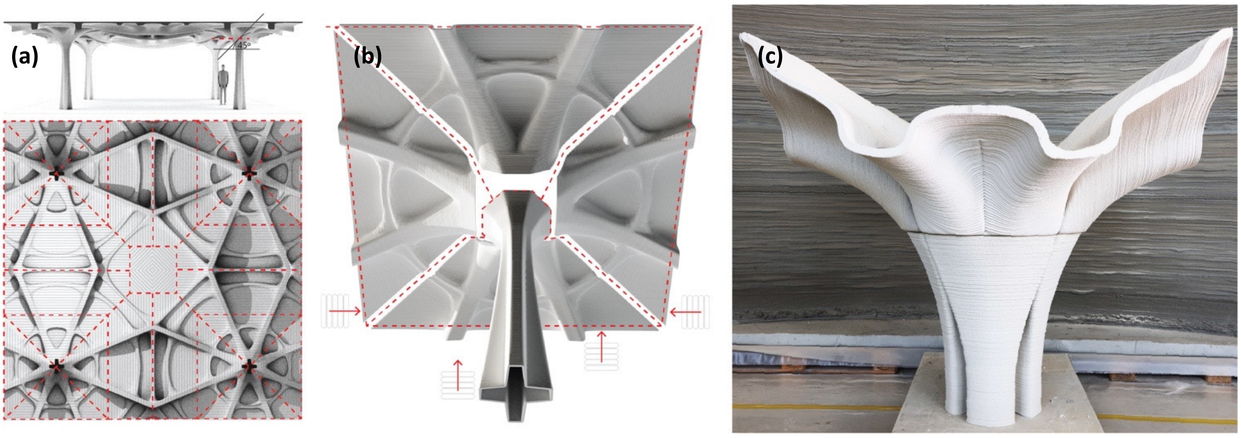

Figure 8. Ribbed slabs with 3D concrete printed formwork: (a) visualisation of the designed ribbed slab; (b) segmentation of the column to slab connection; (c) prototype of the column to slab connection.

This paper addresses the fabrication of concrete floor slabs with digital means as an exemplary application with significant environmental sustainability potential. Further work should explore how concepts presented herein can be applied in practice. Conducting these explorations holistically and collaboratively, capturing all exigencies and competencies necessary for construction, is essential to leverage the impact digital fabrication with concrete will have.

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Authorship statement (CRediT)

Jaime Mata-Falcón, Patrick Bischof (these authors contributed equally to this work): Conceptualisation, Methodology, Investigation, Writing – original draft.

Tobias Huber: Methodology (Section 2), Investigation, Writing – original draft (Sections 2 and 4), Writing – review and editing (other sections).

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Timothy Wangler: Investigation, Writing – review and editing.

Tom Van Mele, Philippe Block, Fabio Gramazio, Matthias Kohler, Benjamin Dillenburger: Writing – review and editing, Funding acquisition.

Walter Kaufmann: Conceptualisation, Methodology, Investigation, Writing – original draft.

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