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Concrete domes supported by external tendons: a novel concept for sustainable and efficient construction of concrete floor slabs

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Abstract

This paper presents a new concept for a materially optimised floor slab construction system. It addresses the current environmental challenges by reducing material consumption and construction waste. The novel floor slab approach takes advantage of a funicular shape to separate concrete and steel. The concrete works mainly in compression, and the reinforcement is composed of external tendons carrying tensile forces. The structural concept is inspired by a specific type of Fink Truss, with several external tendons that support the intermediate vertical elements and adopt a funicular shape in tension. In this approach, the horizontal top chord and vertical members are replaced by concrete domes working in compression, i.e. adopting a form-found funicular shape, with supports at the bottom chord and a flat upper surface at the top of the slab. The system takes advantage of digital fabrication technologies and conventional construction processes to allow an efficient and waste-free production of the concrete domes. Furthermore, the proposed concrete floor slab concept reduces construction material through a shape optimisation process and features separated compression- and tension-resistant construction materials, which allows for easier recyclability.

Keywords: sustainable structures, continuous shells, digital fabrication, optimisation.

1. Introduction

The current environmental crisis urges the construction of more sustainable structures, which requires a radical change in the way we design and build nowadays [1]. Although changes in the construction and buildings sectors are traditionally slow compared to other industries, such as the automotive or computer industry, there is already (at least) a general agreement in academia about the urge to reduce, reuse, recycle and recover construction materials and structures in order to achieve a radical drop in the CO_2 emissions from an industry responsible of 38% of the global greenhouse gas emissions [2], [3].

Research groups are making considerable efforts to efficiently produce materially optimised concrete floor slabs, as these elements generally consume between 40% and 60% of the total concrete in conventional building structures [4]. Furthermore, lighter slabs reduce the loads on the vertical structure resulting in smaller dimensions of columns, walls and foundations.

This paper presents ECONSLAB, a material-optimised concrete floor slab concept that aims at contributing to a more efficient and sustainable construction of our buildings and cities. The combination of digital fabrication with conventional building methods allows an efficient and waste-free production of the new sustainable construction system.

2. Concrete floor slabs

Improving building structures in terms of efficiency, economy and sustainability is a common topic of research in the field of civil engineering and architecture. Among those structures, concrete floor slabs represent an important part, as one of the most utilised building elements [5], [6]. Current cutting-edge methods and software allow concrete floor designs with a high degree of structural optimisation. Although innovative uses of digital fabrication are being used, the construction of these usually complex shapes still presents several difficulties regarding sustainability and economy [5], [6]. While the sustainability requirement is usually self-imposed as no specific regulations have been established to date, the crude reality of the construction industry reminds researchers wanting to disseminate their innovations that a system which is not economically profitable has very few chances to enter the building market. Finding the balance between sustainability and economy in the fabrication of optimised floor slabs has revealed itself as a difficult task to achieve. On the one hand, researchers need to address sustainability focused on material and waste reduction, the use of materials with less carbon footprint, circular construction and recycling and reusability possibilities. On the other hand, economical systems should be created to allow the developed ideas, concepts and patents to enter the mass-market to represent a fundamental change in the construction industry [5], [6].

A type of floor slab studied in many research institutions is one that combines compression and tension stresses in a unitary volume, i.e. one that uses bending action to resist applied loads and has the reinforcement embedded in the concrete mass, as typically done in conventional construction (Figure 1). Many researchers working on this structural system take Pier Luigi Nervi's pioneering work on the optimisation of concrete ribbed floor slabs as a reference and inspiration. The Italian engineer (1891-1979) made big efforts to achieve economic construction techniques through appropriate formwork systems. Seeking to avoid the massive timber formwork that he used in some of his first hangars for the Italian Air Force, his search led him to the use of, among other techniques, reusable *ferrocement* formworks on moveable scaffoldings [7].

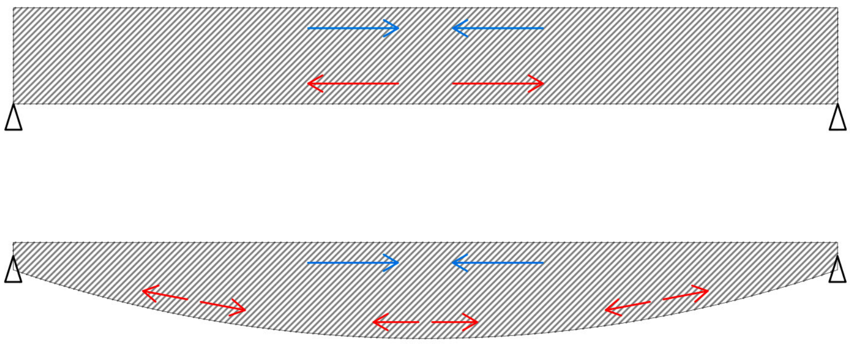

Figure 1: 2D scheme of two one-way slabs including the compression (blue) and tension (red) force resultants in a unitary volume: top) constant cross-section; bottom) ribs with variable depth.

Current research on concrete ribbed floor slabs works on topology- and shape-optimised structures [6], [8], [9], [10], [11] (Figure 2) and the way to use digital fabrication to achieve a fast and easy way to build complex slab shapes [5], [6], [12]. However, the construction process of these prototypes results expensive and complicated (being the reinforcement placement one of the main challenges), especially compared to well-established building systems like hollow-core or two-way ribbed slabs like waffle slabs, Holedeck ® or Bubble deck ® systems.

Figure 2: Optimised concrete floor slabs built by: left) Graz University of Technology [2]; middle) Digital Building Technologies, ETHZ [10]; right) Digital Building Technologies, ETHZ [11].

Another approach to the optimisation of concrete floor slabs is using the concrete as a compression-only structure and placing the tension-resistant material outside the concrete's mass (Figure 3). Examples of this approach are thin-shell flooring systems resolving the horizontal thrust with steel tension ties [13], [14], [15], [16]. Form-finding and topology optimisation procedures are utilised in some of the floor prototypes of this kind to obtain the funicular shape and the ribs positions [17], [18] (Figure 4). It is worth highlighting the implementation by the Block Research Group at ETH Zurich of an unreinforced, rib-stiffened, concrete, funicular floor prototype called the Rippmann Floor System (RFS) in the HiLo research & innovation unit, built on the NEST platform in Dübendorf, Switzerland [19]. Although this was a remarkable success in the research of concrete floor slabs, the fabrication of these specimens was still difficult and expensive compared to those previously mentioned well-established building systems due to the need for complex and double-sided formworks. Ongoing efforts to address these challenges are being carried out by the spin-off company VAULTED AG [20], with the goal of integrating the RFS into contemporary construction practices.

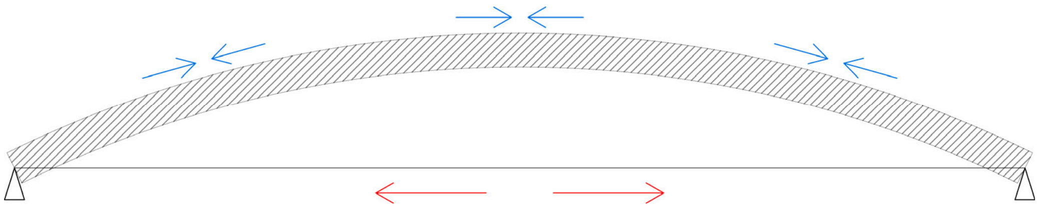

Figure 3: 2D scheme of a compression-only structure and a tension tie.

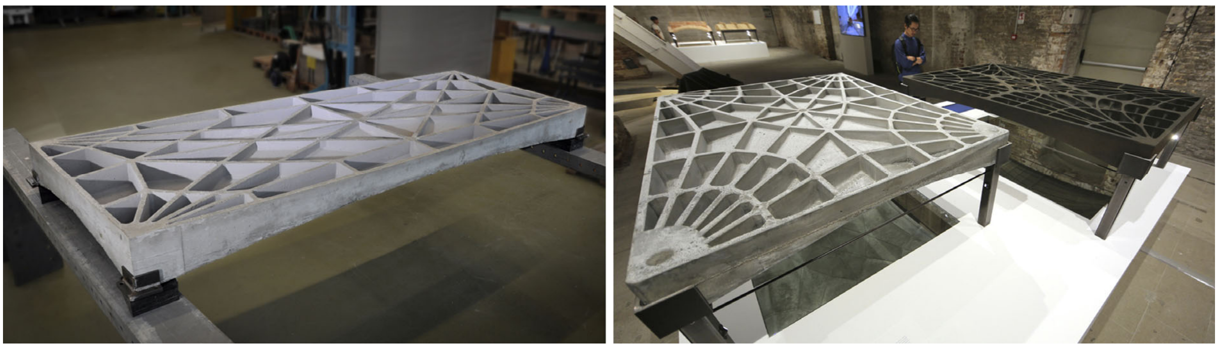

Figure 4: Prototypes of unreinforced, funicular floor slabs by the Block Research Group, ETHZ: left) first prototype [17]; right) further prototypes of the floor system during the Venice Architecture Biennale 2016 [19].

While these structures feature a compression-only concrete funicular shape and straight tension ties at the level of the springing line, a different approach features a flat upper concrete surface and a funicular-shaped tendon (or a set of tendons) as a continuous bottom chord from one end to the opposite one. Recent research on these configurations has provided interesting beam or footbridge systems, such as

"Minimass" (Figure 5, left) by Net Zero Projects and the Technical University of Denmark [21], or an ultra-high-performance fibre-reinforced concrete (UHPFRC) bending-active footbridge (Figure 5, right) by Universitat Politècnica de València [22].

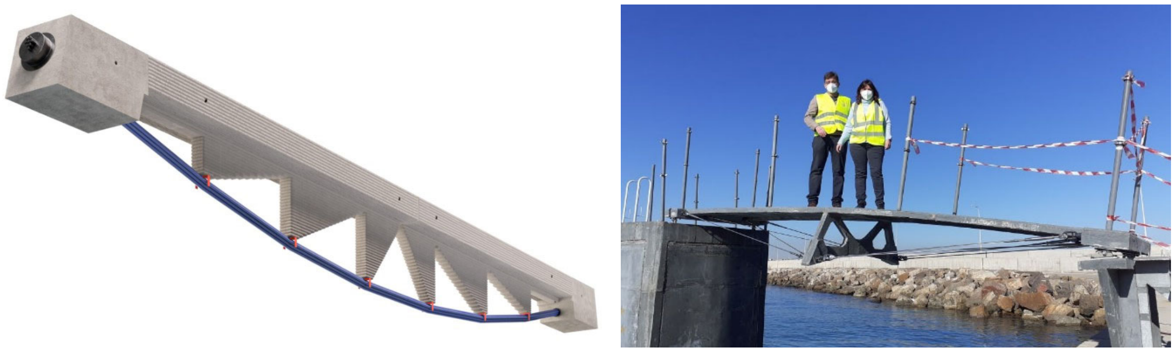

Figure 5: Left) "Minimass" beam [21], [23]; right) experimental UHPFRC bending-active footbridge [22].

Research at Tongji University and RMIT University focusing on this kind of structures has produced multi-material topologically optimised beam and floor systems: the so-called "FloatArch" and "FloatSlab" (Figure 6) [24]. These concrete elements were printed with a 6-axis robot that allowed producing accurate dry connections oriented along the principal compression trajectories.

Figure 6: Beam and floor prototypes by Tongji University and RMIT University: top) "FloatArch"; bottom) "FloatSlab" [24].

3. ECONSLAB

The system proposed in this paper is inspired by a specific type of Fink Truss, and also takes advantage of the tendon's funicular shape to separate concrete and steel, the former working only in compression and the latter working only in tension. The bottom chords, made of steel tendons, support the intermediate vertical members and adopt a funicular shape in tension.

In the ECONSLAB Fink Truss analogy, the horizontal top chord and vertical members are replaced by unreinforced concrete working only in compression, i.e. adopting also a form-found funicular shape, with supports at the bottom chord and with a flat upper surface as the top of the slab (Figure 7).

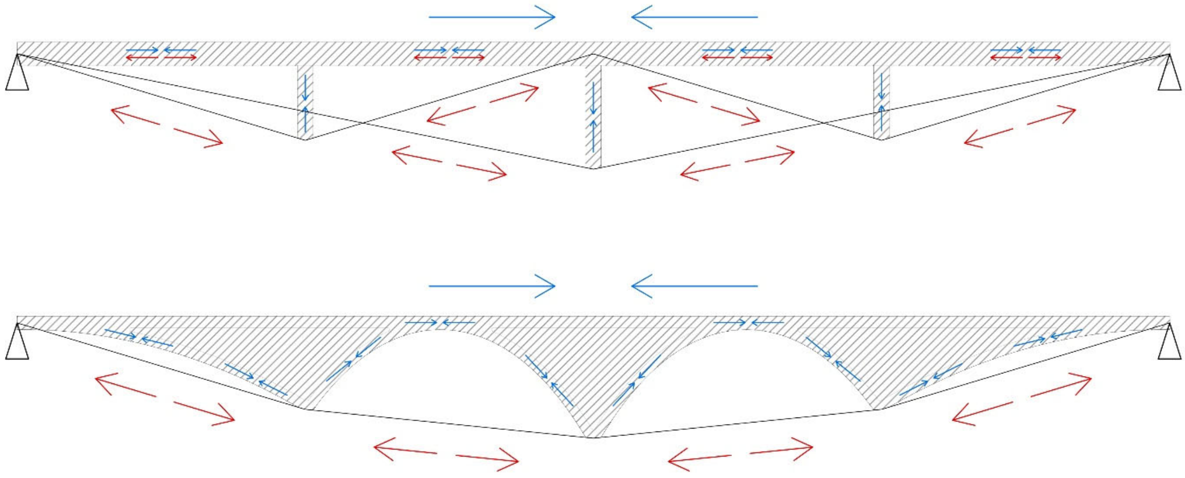

Figure 7: Top) Fink Truss; bottom) 2D scheme of the proposed floor slab.

In contrast to the projects shown in the previous section, ECONSLAB has the shape of an arcade in a 2D scheme (as if it was a beam) (Figure 7, bottom). In the 3D scheme, the concrete is shaped as a group of form-found, optimised domes with supports at different heights and the highest point of their intrados tangent to a common horizontal plane. The distance of that horizontal plane to the top flat surface of the slab is the thickness of what is called the compression layer (Figure 8).

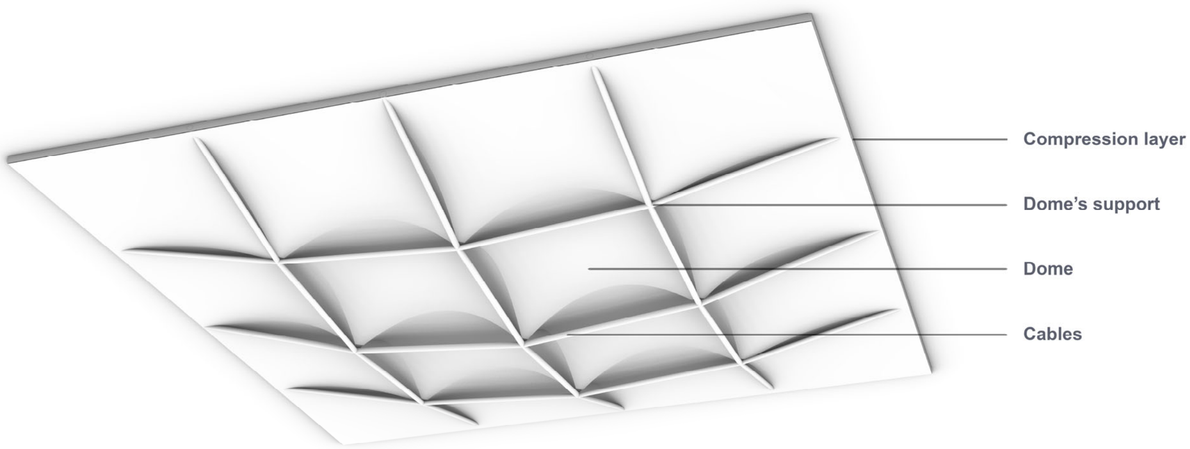

Figure 8: 3D scheme of the proposed floor slab.

4. Construction of ECONSLAB

The fabrication is carefully thought to be as efficient as possible in terms of sustainability and economy. It takes advantage of having a flat upper surface for an easy and fast upside-down fabrication, avoiding a complex lower formwork. While the compression layer is built using four simple straight planks to build a conventional formwork, the more complex funicular shape is built using a 3D concrete printer, also upside-down, for an easy manufacturing of a cone-like shape (Figure 9).

The fabrication process can be tailored to the characteristics of the desired floor slab and the context of each specific situation. The following manufacturing aspects may vary in each case:

- the 3D-printing of the cone-like supports of the domes. They can be fabricated separately or in groups. The 3D-printing possibilities also depend on the form-found geometry and the surface's slopes, which are decisive to fabricate them as a solid structure, or lighter (with interior voids), or printing only the contour to serve as (lost) formwork.
- the pouring of the concrete, which can be in one step using both the conventional and the 3D-printed formworks, or in phases, in which case, the bonding of the different casts should be guaranteed by rough surfaces or connectors.
- the type of insulation for the steel tendons to comply with specific context-dependent fire resistance requirements.
- the entire prefabrication in the factory or laboratory or a combined strategy in which the 3D-printed elements are built in the laboratory and the slab is cast onsite.

This project conceives structural design and fabrication as one integrated process, in which design solutions are constrained by fabrication requirements. ECONSLAB uses the advantages of digital fabrication in combination with conventional construction processes when required for economic or sustainable reasons.

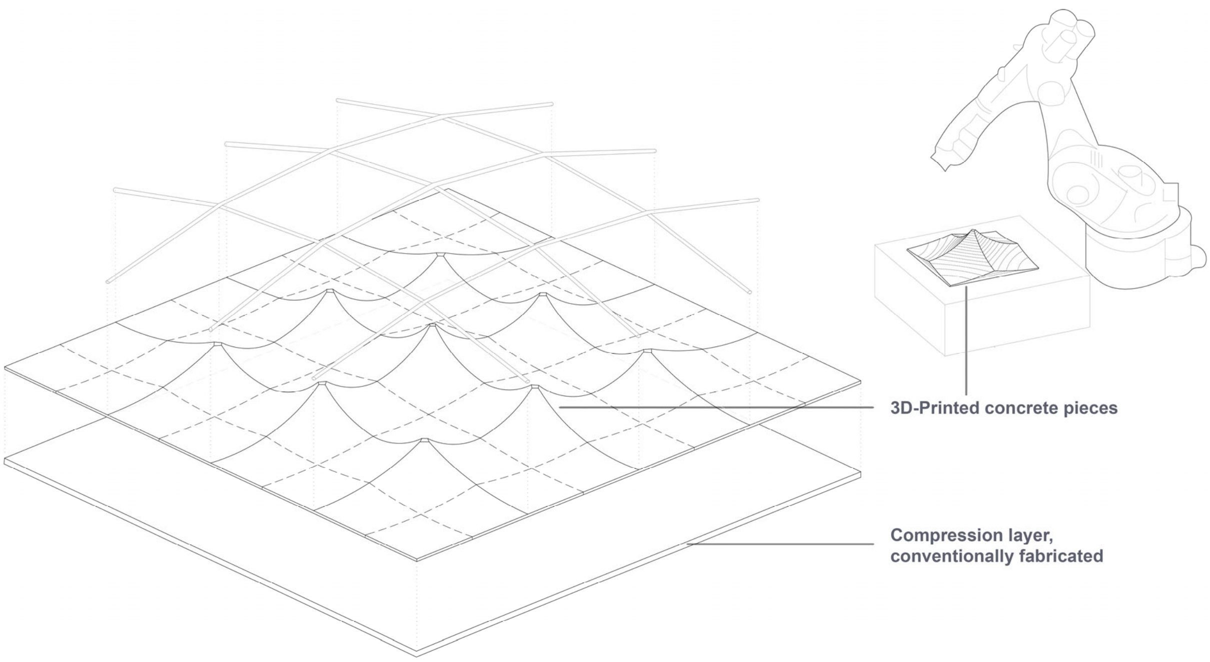

Figure 9: Scheme of the ECONSLAB floor, shown upside-down, as it is fabricated.

4. Conclusion

ECONSLAB is conceived as a material-efficient, environmental-aware slab, contributing to the creation of sustainable buildings and cities. This project understands the structural design integrating:

a) material behaviour, including topology optimisation and form-finding methods.

b) fabrication, combining digital and conventional methods and the awareness of the need of economic solutions to generate a real impact.

c) sustainability, tackling the aspects of material reduction, construction waste minimisation and recycling possibilities. Considering the sustainability of the material itself, although out of the scope of this research, it is worth highlighting the importance of the funicular shapes used in the proposed prototype to create structures with lower, distributed stresses and hence reduce the required compressive strength, enabling the use of low-cement concrete or even facilitating the use of other, less resistant but more sustainable materials.

ECONSLAB thus contributes to digital and ecological transformation by providing an innovative building system rooted in the ideas of sustainable and circular construction.

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