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Design, fabrication and testing of a prototype, thin-vaulted, unreinforced concrete floor

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ABSTRACT

This paper describes the concept, form finding, fabrication and experimental testing of a prototype floor system, derived from principles of shallow arching action, to initiate internal compressive stresses rather than exclusively flexural stresses. This vaulting in a floor system leads to a lightweight structural element, with significant weight savings compared to traditional concrete floor slabs. The form finding process to generate the floor geometry is presented, with a description of the fabrication process, the concrete mix design, material testing and experimental testing. The results from the serviceability and ultimate load testing of the prototype floor are documented in detail. The data showed that the floor unit was both stiff under service load, with maximum vertical deflections less than span/2500, as well as possessing sufficient strength for ultimate loading, carrying 2.5 times the factored design load in a more critical asymmetric loading scenario. A camera setup was used to measure displacements in-line with traditional displacement transducers, to give contour plots of vertical deflections.

1. Introduction

This research describes a prototype of a pre-fabricated modular floor, which will be utilised at the NEST-HiLo research and innovation unit [1] for the Swiss Federal Laboratories for Materials Science and Technology (Empa), Dübendorf, Switzerland (Fig. 1). The NEST-HiLo unit is a collaboration between the Institute of Technology in Architecture, represented by the Professorships of Architecture and Structure (Block Research Group) and Architecture and Building Systems, architectural office Supermanoeuvre, and engineering firm Bollinger + Grohmann. HiLo (High performance, Low energy) demonstrates innovations in the domains of lightweight construction as well as smart, integrated and adaptive building systems. HiLo is planned as a duplex penthouse apartment for visiting faculty. Four innovations are introduced: (1) an integrated, thin-shell roof [2], constructed with a lightweight, flexible formwork system, (2) an adaptive solar facade [3], (3) an automated, occupant-centred control system, and (4) the integrated, lightweight, funicular floor system as presented in this paper. Four floor units of unique geometry, with average dimensions of 5 m by 5 m (Fig. 2), will be placed above the main bedrooms and bathrooms. The construction works are due to be completed in 2018. The vaulted floor system will be a thermally active building element. The system contains an integrated hydronic pipe network within the depth, which provides heating and cooling to the bedrooms through the thin (20 mm) concrete radiant panel at ceiling level [4]. The internal voids in-between ribs can be used for services integration.

The floor system's structural principle, as shown in the geometry of the reduced-scale prototype in Fig. 3, is based on shallow arching action to initiate internal compressive stresses rather than exclusively flexural normal stresses, leading to a lightweight and stiff structure.

The concept stems from thin-tile compression vaults stiffened by diaphragms or ribs, a technique that has a long tradition in the Mediterranean and in the United States in the nineteenth century when Rafael Guastavino exported the technique and developed many patents [5] (Fig. 5). The ribs allow a floor to be supported at the topside by transmitting the loads to the vault, as well as stiffening the structure, the latter of which is important for resisting asymmetric loading. In order to carry the loads efficiently in compression, ties or horizontal restraints are needed to absorb the thrust (Fig. 4). Investigations by the Block Research Group into this concept can be found in the SUDU (Sustainable Urban Dwelling Unit) prototype in Addis Ababa, Ethiopia (Fig. 6),

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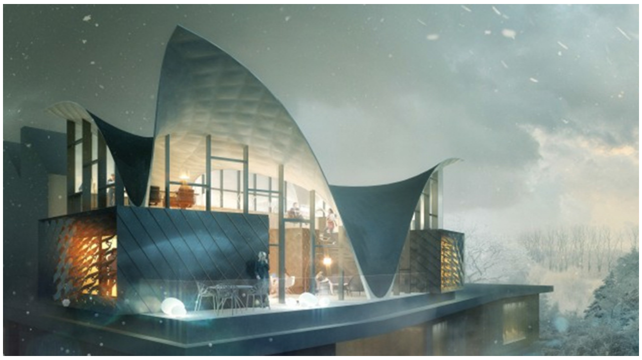

Fig. 1. The NEST-HiLo research and innovation unit at Empa, Dübendorf, Switzerland (image: Supermanoeuvre/Doug & Wolf).

which is an example of a thin, unreinforced masonry vault with ribs, supported by lightly reinforced edge beams connected by ties [6,7]. In this case, the African floor system limits the amount of material required by featuring a funicular geometry for the vault and adding structural depth using the two different strategies showed in Guastavino's patent: the construction of lightweight stiffening walls and the addition of stabilised fill. This allows the system to resist asymmetric live loading and permits thin stiffening elements that are stabilised by the compacted fill. Note that in a building with a main skeleton frame structure, the floor system could be integrated without explicit ties, relying on the frame to absorb the horizontal thrusts.

For the prototype floor presented in this paper, the ties are replaced by stiff corner elements mounted onto a stiff steel testing frame. The structure is constructed from fibre-reinforced, ultra-high strength, self-compacting concrete, with a global thickness of 20 mm. The form finding process constructs a funicular network through constrained Thrust Network Analysis [9,10], with an algorithm that generates the floor geometry. The design process includes three steps, corresponding to the typical types of structural optimisation: topology, shape and size optimisation [11]. The floor was experimentally tested to confirm the design assumptions via serviceability and ultimate load testing. This was to investigate the structural performance of the floor, and use the data and experience to quantitatively and qualitatively inform the actual floor units that will be constructed on the NEST building.

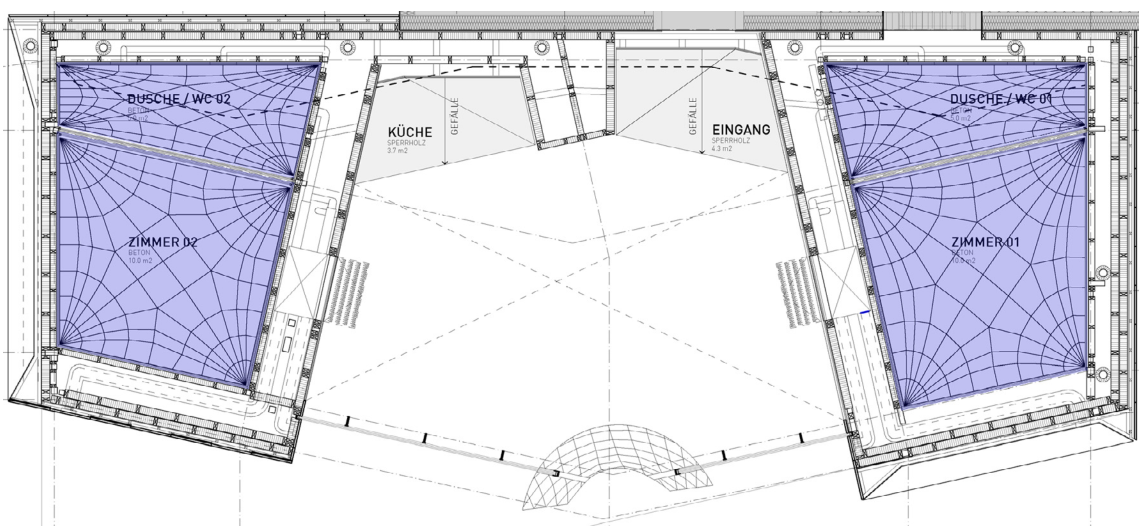

Fig. 2. Reflected ceiling plan showing the unique geometry of each of the four floor panels (blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

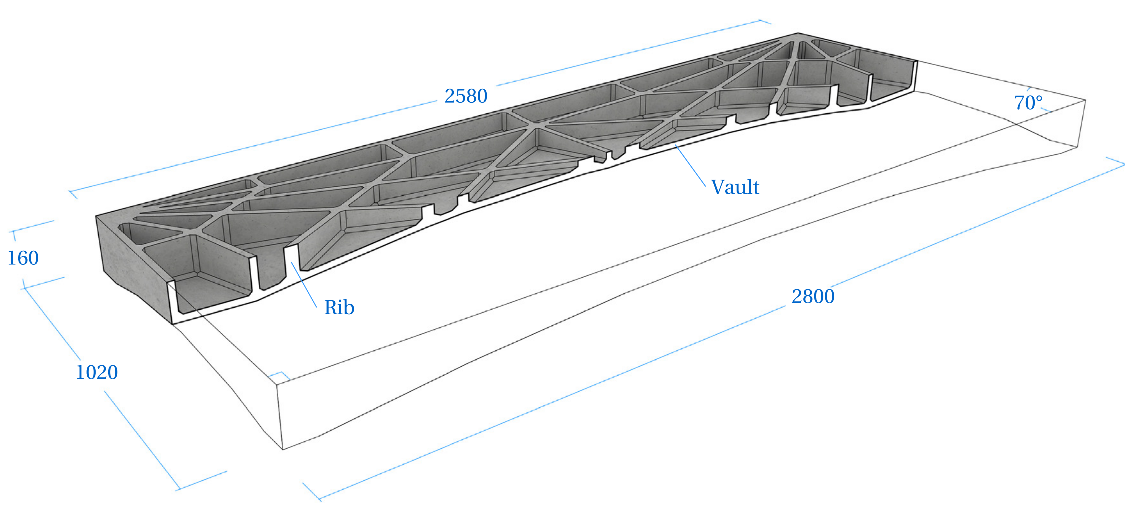

Fig. 3. Longitudinal section through the floor, which rests on its four corners. Key dimensions in mm.