3D-printed Clay Formwork for Topology-Optimized Concrete Elements

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Abstract

The use of topology-optimized precast concrete elements leads to material savings and thus to a reduction in the CO2 footprint of a building. Material is only used where it is structurally necessary. The optimum shape of a component is influenced by its structural boundary conditions. This results in a variety of bespoke shapes and geometries. Additive manufacturing techniques such as 3D printing are particularly suitable to produce such formwork. This paper examines the production of 3D-printed formwork elements made of clay using the example of an optimized concrete ribbed slab. The use of unfired clay as a formwork material is intended to enable a circular reuse of the same material for subsequent prints. For a simplified analysis of the manufacturing process, work is carried out on a reduced model scale of 1:8 or 1:16. Two manufacturing strategies will be tested. Firstly, a segmented formwork system to produce the ribs without a ceiling slab is investigated, and secondly, individual displacement bodies are produced which are then placed in a wooden formwork and with which the ribs and ceiling slab can be cast at once. In both cases, the clay is kept in a moist state until the concrete is poured. Both production strategies can achieve a dimensionally accurate result, as the clay does not deform or crack due to drying. In addition, the clay can be easily removed from the finished component after the concrete has hardened and contains only minor impurities. The production of formwork or displacement bodies for optimized concrete parts from 3D-printed clay is showing promise as an alternative to other materials such as plastic or concrete. As clay and concrete do not form a permanent bond during the curing process, the clay can be recycled. However, further investigations into the processing and cleaning of the dried clay are necessary to make precise statements about the proportion of reusable clay.

Keywords: *3D-printing, clay, precast concrete, additive manufacturing, carbon efficiency, stress-driven design*

1. Introduction

The construction sector is responsible for 38% of the world's CO2 emissions, with the production of building materials and the construction itself accounting for the majority of this figure [1]. The production and utilisation of materials such as cement and steel have a considerable carbon dioxide footprint. A significant proportion of these emissions is attributable to the dead load of structures, with slabs representing a significant contributor [2]. Therefore, the focus of this work is on optimising slab systems to reduce material consumption while maintaining structural integrity [3].

In the 1940s, engineer Pier Luigi Nervi developed innovative slab systems that used materials only where necessary to minimise material usage. He placed ribs on the underside of the slab along the principal moment lines. However, Nervi used prefabricated concrete elements for formwork. Currently, new technologies such as parametric modelling and additive manufacturing techniques (3D printing) enable the production of optimised formwork.

Additive manufacturing technology enables the creation of highly customised and complex structures, combined with much-needed process automation. For these reasons, additive manufacturing processes are developing very dynamically and finding more and more practical applications. In particular, 3D printing is gaining ground in concrete construction [4,5,6,7,8].

The authors investigate the suitability of 3D printed clay formwork elements for the production of ribbed slabs. Clay is a natural and recyclable material that is well suited to 3D printing due to its plastic properties. The potential of additive manufacturing to process clay is currently being researched in many application areas [9,10,11,12]. The authors explore the application of these modern methods to develop resource efficient and recyclable formwork systems for ribbed slabs.

As will be demonstrated below, a ribbed slab system was initially optimised in terms of material consumption without any reduction in the load-bearing capacity. This was achieved by applying a method previously used by the engineer Pier Luigi Nervi. A formwork made of clay, which is produced additively, was developed for the optimised ribbed slab system.

2. Parametric Design of Ribbed Slab

The ribbed slab model, which was optimised in this work using the programs Rhino and Grasshopper, corresponds to a parameterised version of the Gatti Woll factory designed by Pier Luigi Nervi shown in Figure 1. As illustrated in Figure 2, the initial geometry comprises a square slab section with dimensions of 8 x 8 metres. The ceiling field is represented as an integral component of a continuous ceiling system, with consideration given to the boundary conditions specified in Figure 2. The ceiling panel is supported by a central pillar. The model was loaded with its own weight and a uniformly distributed live load.

Fig. 1. Gatti Woll factory designed by Pier Luigi Nervi

The number and height of the ribs are variable, with a uniform distribution along the edges to limit the number of possible solutions in the optimisation process. The width of the ribs and the thickness of the slab are constrained by fire protection requirements. In order to prevent punching shear failure, a solid concrete area is modelled around the support. The height and number of ribs are determined by the deformation limitation of the structure. It is desirable that the deflection does not exceed 1/250 of the support span.

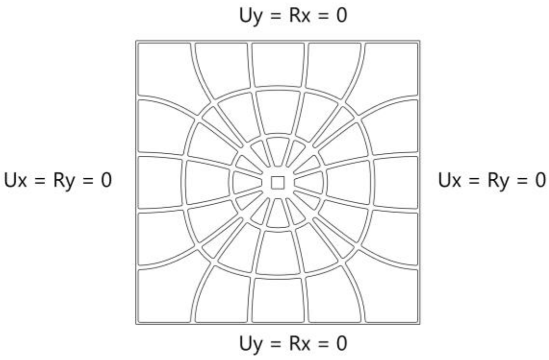


Fig 2. Square slab section with boundary conditions

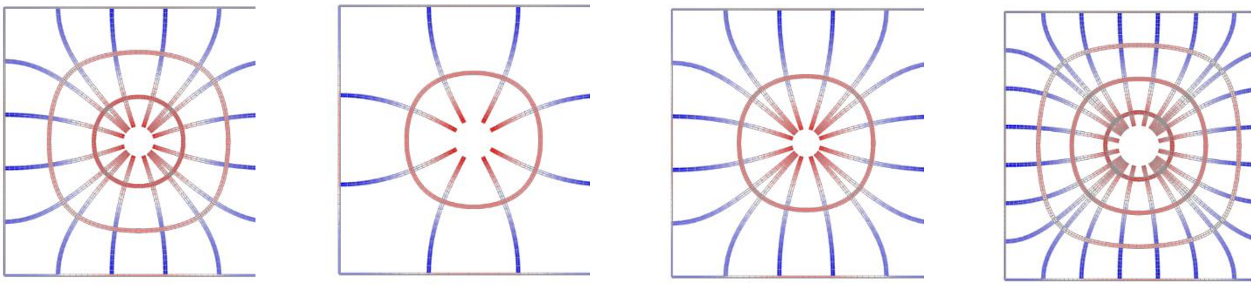
For typical slab systems, deformation can be controlled by limiting the slenderness ratio [13]. However, for more complex structures, such as the ribbed slab discussed here, a simplified approach is insufficient. Initially, the dimensioning of a flat slab was conducted by limiting the slenderness ratio. Subsequently, the ribbed slab was dimensioned to exhibit elastic deformations comparable to those of the flat slab. The model parameters were controlled and varied by an evolutionary optimisation algorithm, while the deformations of the structure are computed using the parametric finite element method (FEM) tool Karamba3d.

The main objective of the optimisation process was to determine the optimum number and height of ribs that minimise material consumption while optimising the desired deformation. It is important to note that the ceiling height should be kept as low as possible. Table 1 shows the results of the optimisation procedure for different configurations of the ribbed floor. The nomenclature used in this table is as follows: n1 stands for the number of radial ribs, n2 for the number of tangential ribs and hR for the height of the ribs. The change in mass ΔM, deformation Δw and rib height Δh are given for a range of targets achieved compared to the dimensioned flat plate.

Tab. 1. Results of the optimization process

Geometry (n1/n2/hR)	Goal	ΔM [%]	Δw [%]	Δh [%]
2/1/15	Mass reduction	-55,1	187,3	4,5
4/1/25	Deformation limitation	-42,8	1,6	50
6/3/14	Rib height reduction	-44,8	101,5	0
4/2/23	Final Geometry	-41,9	2,8	40,9

As can be observed, a material savings of between 42% and 55% can be achieved in each case. However, the objectives of limiting deformation and reducing height are in conflict with each other. It can be reasonably assumed that the overall thickness of the ribbed slab will increase by at least 40% compared to the flat slab. Figure 3 illustrates the geometry of the various solutions. With regard to the production of the system, a solution is selected that does not include an excessive number of ribs. The 4/2/23 geometry has been selected for further investigation and analysis with regard to the manufacturing processes. The selected geometry exhibits a mass reduction of 42%.



(a) (b) (c) (d)

Fig. 3. Results of the optimization process.
(a) Geometry 4/2/23 (b) Geometry 2/1/15 (c) Geometry 4/1/25 (d) Geometry 6/3/14

3. Digital Fabrication of the formwork

In order for 3D printing and traditional clay processing to be carried out effectively, it is necessary to select an appropriate type of clay according to the intended purpose. The most important properties to consider are plasticity, shrinkage, and porosity. Plasticity, which reduces the risk of cracks during drying, depends on the ratio of the basic components. For 3D printing, it is crucial to use clay with good plasticity to avoid air bubbles that can affect material flow.

A formwork system with displacement bodies was developed for the production of the ribbed slab. Two distinct manufacturing strategies were subjected to analysis. The first strategy involved investigating whether a formwork system made of clay could be realised for the production of ribs without a ceiling slab. The slab was divided into four segments with displacement bodies without top layers. The investigation was carried out on a reduced-scale model at a scale of 1:16. Figure 4 depicts the printed formwork system in its original state prior to the pouring of the concrete, followed by an illustration of the final form after the concrete has been poured. The formwork could be readily removed by breaking out the hardened clay. The results of the concreted ribbed structure are deemed satisfactory. The favourable outcomes of the initial strategy led to the development of a second approach.

(a) (b) (c)

Fig. 4. Fabrication Strategy 1; (a) formwork originally (b) formwork concreted out (c) concreted ribs

In the second fabrication strategy, individual displacement bodies were produced and subsequently placed in a wooden formwork, allowing the ribs and ceiling slab to be cast simultaneously. Each displacement body was manufactured as an individual volume element.

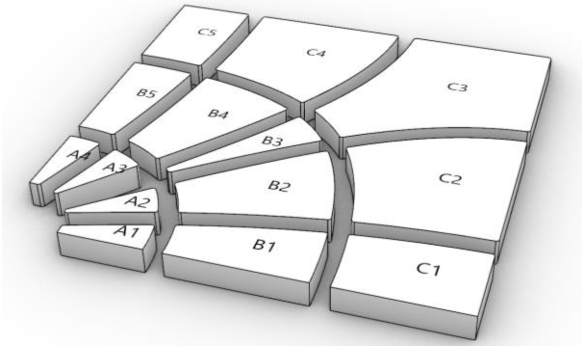


Fig. 5. Displacement bodies

The parametric model of the formwork is based on the main script of the geometric model. In order to facilitate a simplified manufacturing process, an investigation was conducted on a reduced-scale model at a scale of 1:8, with a single quadrant of the ceiling being considered. The formwork modelling process involved the creation of closed cells through offset, the exportation of the geometry in STL format, and the slicing of the geometry with Simplify3D. Subsequently, the G-code was generated, and the displacement bodies were printed in layers, as illustrated in Figure 6.

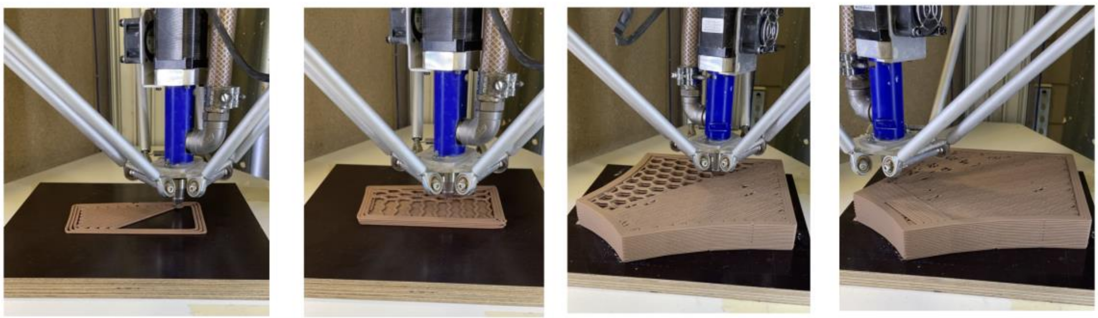


Fig. 6. Fabrication Strategy 2; printing process

Once the individual displacement bodies have been produced, it is of the utmost importance to ensure that they are kept moist in order to prevent excessive shrinkage of the clay. Excessive shrinkage may result in the deformation of displacement bodies, thereby affecting the quality of the print. Following a period of five days during which the formwork was allowed to harden, it was then removed. The printing of 14 bodies was largely successful, with the exception of two displacement bodies, which were affected by inconsistencies in the clay consistency. Figure 7 depicts the printed formwork system in its original state prior to the application of concrete. This is followed by an illustration of the final form after concreting.

(a) (b) (c)

Fig. 7. Fabrication Strategy 2; (a) formwork originally (b) formwork concreted out (c) concreted rib

The clay can be easily removed from the finished component after the concrete has hardened and can be re-used. The clay and concrete do not form a permanent bond during the curing process. The clay only contained some concrete residue. Although there was no evidence of coarse concrete residue in the clay formwork fragments, it is advisable to clean the clay before re-using it.

The results of the investigations demonstrate that the formwork for ribbed slabs can be produced from clay utilising additive technology. The utilisation of additive manufacturing allows for the fabrication of highly intricate geometrical forms. Furthermore, this process enables a swift adaptation of the formwork configuration in response to alterations in the static model. The re-use of clay as a material for formwork is unconstrained by restrictions and can be processed with minimal energy consumption. Nevertheless, further research is necessary to ascertain the precise proportion of reusable clay that can be extracted from the dried clay.

4. Conclusion

This work demonstrates how historical methods can be reinterpreted through the utilisation of digital tools and modern manufacturing techniques. While the concept of optimising slab systems by strategically placing material is not new and was developed by Italian engineer Pier Luigi Nervi in the 1960s, the approach presented here illustrates how parametrizing geometry allows for the exploration of numerous variations in a short amount of time. Different structural optimisation goals, such as limiting deformations, can be achieved through evolutionary optimisation algorithms while adhering to geometric and static constraints. It has been demonstrated that ribbed slabs optimised for force flow can require up to 40% less material than conventional flat slabs, although this is at the expense of a larger overall thickness. While Pier Luigi Nervi employed concrete as formwork in his ribbed slabs, this work demonstrates that an alternative solution is possible using 3D printers and the resource-efficient material clay. The advantages of parametric modelling are particularly evident in this instance, as the formwork is modelled based on the static model, thereby enabling the generation of new formwork for different variants in a relatively short time.

The work presented in this paper represents a preliminary investigation into the additive manufacturing of formwork made of clay. Future work could include the improvement of the material behaviour of clay in order to minimise shrinkage. Furthermore, the printing path can be optimised specifically for the application as displacement bodies, aiming for both fast printing times and a structure that minimises the risk of tearing the clay trail.

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