MATERIAL EFFICIENCY: PATTERN DESIGN TECHNIQUES FOR 3D PRINTED RIB-STIFFENED FLOOR SYSTEMS

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ABSTRACT

The rib-stiffened concrete slabs have been in development and use for over a century due to their potential to reduce material consumption. Manufacturing ribbed concrete slabs with an even greater degree of geometric complexity than before is now possible because of advances in digital fabrication, mainly 3D printing technology. The main goal of this paper is to analyse and classify rib configuration patterns used in slab design in order to determine the underlying principles of generation and the potential of their application for 3D printed slabs. The first part of this paper reviews the development of ribbed slab systems over the last century, focusing on identifying the applied pattern types. Based on the results of this analysis, the identified patterns are then systematically classified. In the second part, the paper focuses on recognizing different methods and tools of digital pattern generation to assess the potential and challenges of their application in the design process of structural slab elements. Finally, using case study methodology, selected pattern configurations are applied in the digital design and fabrication of nonstandard rib-stiffened floor systems. The pattern configurations were computationally generated and applied to create 3D digital models of rib-stiffened slabs. The scale prototypes of digital models are then fabricated using 3D printing technology. Finally, the effectiveness of the models and prototypes in relation to the applied pattern configurations is evaluated. The results of this paper are part of ongoing research into 3D printed rib-stiffened slabs and are to be used and further verified in the next stage through model tests.

KEYWORDS _ *pattern design, digital design, digital fabrication, 3D printing, rib-stiffened floor systems*

Introduction

Reinforced concrete was introduced to the building industry in the second half of the 19th century with the development of cement and steel materials (Moussard et al., 2018). Since then, reinforced concrete has been established as an indispensable material in the building industry, becoming one of the most used construction materials worldwide (Van Damme, 2018). Due to its volume of use, concrete, as cement-based material, is estimated to contribute to 5-8% of global CO2 emissions, making it a significant source of global pollution (Chau et al., 2012; Jayasinghe et al., 2022).

Out of all building elements, floor slabs use the most concrete overall. According to some studies, a typical multi-story building's slab volume can reach 50% of the concrete volume (Bischof et al., 2022; Jayasinghe et al., 2022). Previous is because most concrete floors are still made as flat solid slabs even though more material-efficient systems have existed since the mid-20th century. These systems include hollow-core, rib-stiffened slabs of different configurations and spans, slabs with void generators, and filigree slabs (Huber et al., 2023); all of them offer higher structural efficiency with the reduced use of material compared to the standard solid slabs. However, their use is often disregarded in favor of solid slabs because the complex and labor-intensive formwork needed to make nonstandard geometries render them cost-time inefficient.

Digital fabrication, mainly 3D printing (3DP) technology, offers new possibilities for producing ribbed concrete slabs with an even greater degree of geometric complexity than before while increasing production efficiency. Diverse studies have lately examined the application of digital fabrication for concrete floor systems (Žujović et al., 2022). Some studies focus on the 3D printing (3DP) of optimized structural elements (Hansemann et al., 2020), while others rely on the more traditional concrete casting and reinforcement methods while using digital fabrication for formwork production (Anton et al., 2020; Burger et al., 2022; Nicolas et al., 2017). Despite the recent increase in research on the topic, digital fabrication of materially efficient rib-stiffened concrete floor systems remains a relatively new and unexplored field with a great opportunity for the sustainability increase of the building industry by lowering the consumption of cement-based materials.

This paper examines the opportunities for optimizing the material efficiency of digitally fabricated ribbed concrete slabs by applying nonstandard rib patterns. Starting with the overview and classification of used rib configuration, the paper aims to discuss underlying design principles, generation methods, and potential applications of 3DP slabs. To achieve previous, the study provides a brief overview of the evolution of ribbed slab systems over the past century, identifying and classifying the applied rib patterns and their characteristics. Finally, using the case study methodology, selected patterns are applied and assessed through the digital design of nonstandard rib-stiffened floor systems.

RIB-STIFFENED CONCRETE SLAB SYSTEMS

Ribbed floor slab systems are one of the alternates, more materially efficient design options than the commonly used solid slabs. They consist of thin slabs and ribs (T beams or joists) that are typically straight or curved depending on the applied pattern configuration. One-way slabs transfer the load to supports predominantly in one direction. Two-way or waffle slabs transfer the load to supports in both directions. Conventionally, ribbed slabs were designed as planar, but recently there have been attempts to design funicular ribbed floor systems (Block et al., 2017; Jipa et al., 2019; Ranaudo et al., 2021). All ribbed slabs can be supported by linear supports (walls, beams), while two-way slabs can have point supports (columns). The overview of the ribbed floor systems and standard pattern configurations is presented in Table 1:

Table 1: The overview of the ribbed floor systems

Cross-section	Load transfer	Rib type	Configuration	Support	Span ratio (l_x/l_y)
Planar	One-way	Straight	Parallel	Linear	≥2
	Two-way	Straight	Orthogonal 90°	Linear	≤ 1.5
			Orthogonal 45°		≤ 2
			Hexagonal		≤ 2
		Curved	Isostatic	Point	≤ 2
				Linear	≥ 2
Funicular	Two-way	Curved	Isostatic	Point	≤ 2*
				Linear	
* Based on the available research data (Ranaudo et al., 2021)					

The development of concrete slabs started simultaneously with the emergence of reinforced concrete in the mid-19th century. Wilkinson patented a floor system that utilized hollow plaster domes in 1854, marking one of the earliest efforts (Wight, 2016). However, back then, theoretical knowledge of reinforced concrete and its structural performance was insufficient and mostly empirical, but by the 20th century, several patents for reinforced concrete structures were developed. Hennebique first successfully introduced a ribbed reinforced concrete floor slab system with orthogonal ribs through a series of patents during 1880s.

Ribbed slab systems were further developed during the first half of the 20th century. The most notable advancements in terms of material efficiency and aesthetic qualities are ferrocement ribbed slabs constructed using isostatic rib patterns designed by Nervi (Halpern et al., 2013). Although more efficient from a structural and material standpoint than typical solid flat slabs, these structures were never cost-efficient enough for standard use due to the complex formwork systems. Nervi's floor systems were only efficient because they utilized then readily available ferrocement instead of wooden or steel formworks that were not as available in Italy at that time (Burger et al., 2022).

Table 2: Summary of the planar and funicular ribbed floor system main characteristics

Cross-section	Characteristics
Planar	• Requires reinforcements • Requires rib configuration adaptation with span change (two-way) • Smaller rib spans (<1m) have structural properties similar to solid slabs • Potential for material optimization (depends on the rib configuration type) • Rib placement affects alignment of building system installations • Prefabricated, partial prefabricated (one-way) or cast on-site
Funicular	• Compression only structure • Curved rib-stiffened shell geometry • No reinforcements • Requires rib configuration adaptation with span change • High potential for the material optimization • Potential for the integration of building system installations • Prefabricated or cast on-site with prefabricated formwork

Ribbed slabs have become a research topic of interest due to advancements in digital fabrication. There have been several studies on using digital fabrication tools, mostly 3DP and CNC milling, to design non-standard concrete ribbed slabs (Anton et al., 2020; Nicolas et al., 2017). Most of this research is still in the early and experimental phases, although projects like The Smart Slab from ETH

Zurich have been tested on a real-life scale (Graser et al., 2020). Another new research direction that has emerged over the last decade is funicular floor systems by Block Research Group (Jipa et al., 2019). This floor system is a curved compression-only shell stiffened with curved ribs. The approach allows for even greater material efficiency than planar ribbed floors. The main properties of floor systems are summarized in **Table 2**.

PATTERN CONFIGURATIONS FOR RIB-STIFFENED SLABS

The choice of rib pattern configuration depends on multiple factors, with formwork complexity, available construction materials, the amount of manual labor required, and structural requirements like span or support types being the most important. As they transfer loads in a single, shorter span direction, one-way slabs tend to have the simplest rib configurations with the array of parallel ribs crossing the shorter span (Figure 1a).

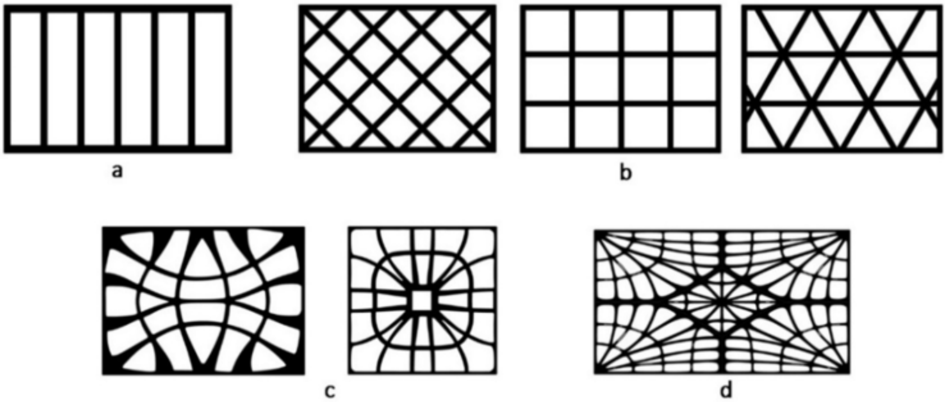

Figure 1: a – parallel one-way ribs; b – orthogonal two-way ribs, c – isostatic rib patterns [adapted from Nervi's Large Sports Palace and the Gatti Wool factory (Halpern et al., 2013)], d – Funicular rib pattern [adapted from (Block et al., 2017)]

This paper focuses on the rib configurations of two-way slabs because of their greater variety. Traditionally two-way or waffle slabs are made with orthogonal or hexagonal rib patterns since they provide an optimal level of complexity and manual labor (Figure 1b). They consist of two sets of straight ribs that can be placed parallel to the sides or diagonally. Diagonal configurations have higher total rib length but require the same amount of material as they provide better structural performance. In addition, hexagonal patterns have greater structural efficiency than orthogonal patterns, as the ribs are positioned closer to the principal stress lines. However, the main downside of this configuration is that, despite a regular geometric grid, paneling surface with only equilateral triangles is not possible, which leads to uneven rib lengths near the edges, increasing the formwork complexity (Radosavljević & Bajić, 1990).

Both funicular and planar two-way slabs can be designed with rib configurations aligned with the isostatic lines of the principal bending moments in a specific boundary and loading condition (Figure 1 c, d). Unlike straight ribs that need linear supports, isostatic rib configurations are often used for column-supported slabs. The application of these configurations has shown their good potential for increasing material efficiency.

ISOSTATIC RIB PATTERN GENERATION METHODS

The use of isostatic lines for determining rib configurations was first developed and implemented in multiple projects by Nervi and Arcangeli. They discovered that two families of orthogonal curves tangential to the main bending moment trajectories are produced when a 2D continuous body is subjected to normal forces. Along these isostatic lines, torsional moments are also equal to zero. Arcangeli developed theoretical calculations based on the thin plate theory for determining principal bending moment directions at a selection of nodes. Ribs were then constructed by iteratively drawing lines in said directions at consecutive nodes repeating until reaching the boundary. This method was further explained by Halpern (2013).

Currently isostatic lines are usually calculated using Finite Element Analysis (FEA) (Tam & Mueller, 2015).Several FEA software could be used to calculate and represent isostatic lines based on the principal bending moment trajectories, including Sofistik (through interface for Rhino), Karamba3D and Millipede plugins for commercial CAD modeler Rhino 3D/ Grasshopper.

DESIGN AND FABRICATION OF THE TEST SLAB

This study focuses on applying isostatic rib patterns for 3DP slab elements. These patterns have good potential for optimizing material efficiency while producing a nonstandard geometry that is feasible and efficient for constructing using digital fabrication. For this reason, a design process workflow, presented in **Figure 2**, was developed, implemented, and tested by producing a proof-of-concept digital model and scaled prototype.

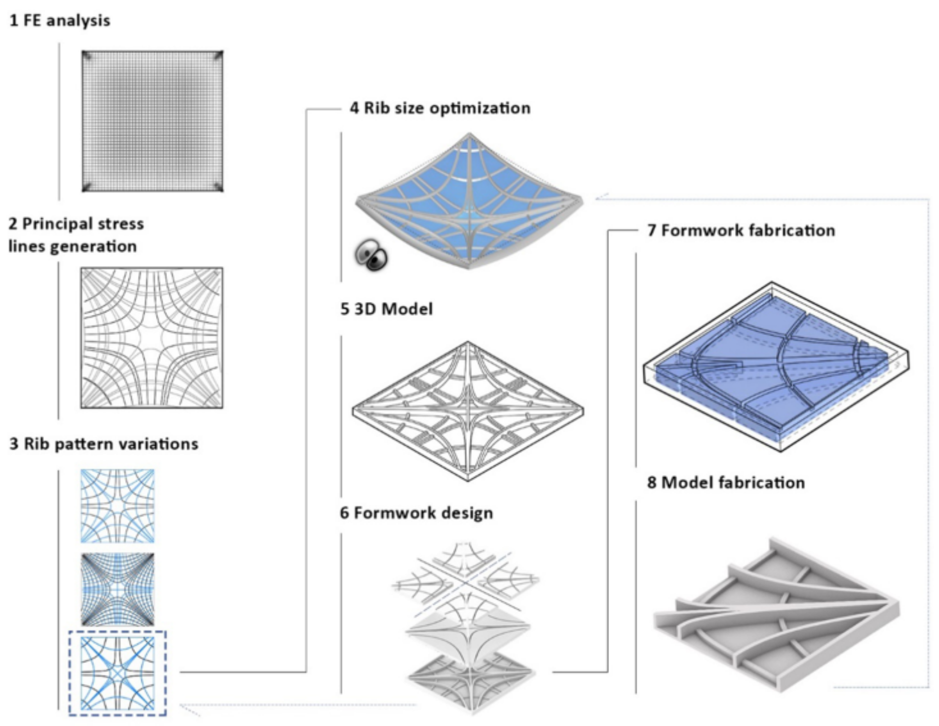

Figure 2: Design and fabrication process workflow

In the first phase, the test model, a standard slab geometry, was chosen based on Nervi's slab systems. A rectangular 8x8m flat slab model with point supports in corners, and an evenly distributed area load of 3 kN/m^2 representing an estimated quasi-permanent load was chosen for the initial FEA using Millipede. Based on this analysis flat slab with a thickness of 22cm was determined to be a suitable reference for material optimization estimate. Next, principal stress lines were calculated, and the density of the rib pattern was optimized using the evolutionary solver Galapagos and FEA to evaluate structural performances.

The previously calculated model of the slab with optimal rib configurations was further refined through another optimization loop using Galapagos to increase material efficiency by varying the rib height based on the maximal allowed deflection while minimizing total weight. The result of the prior optimization is a 3D model of a test slab with a hierarchical rib pattern with rib width b=12cm, which was a minimal requirement based on a fire regulation of EC2, heights of d_1=20cm and d_2=34cm, and slab thickness of 8cm. In the final phase, a formwork model was designed as a negative of a previously obtained 3D model and divided into four parts simulating a larger-scale production process with a maximum segment size of 4m. Finally, a slab segment was fabricated as a 1:15 scale model (**Figure 3**). Formwork was printed using a PLA filament and a desktop 3D printer, and then plaster was cast, simulating cast concrete.

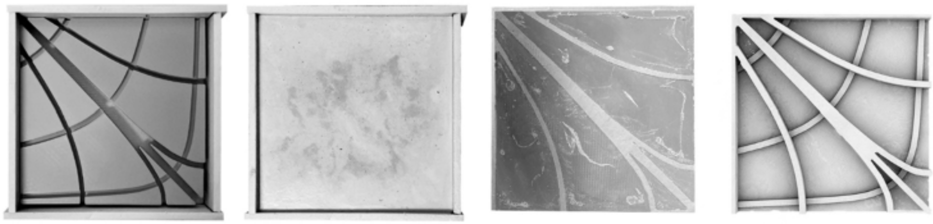

Figure 3: Physical model prototype

DISCUSSION

This study proposes a workflow for the design process and demonstrates its application on a model slab by creating a material-optimized model and a scale prototype. The design method proved efficient in terms of material optimization, resulting in the ribbed slab that reduces 36% of material compared to the reference flat slab. However, several aspects could be developed in future research.

- The Millipede plugin was used for calculating isostatic line patterns. It was concluded that the graphic presentation of lines could be coarse at times lacking fine parameter control. The development of a program module for Rhino/Grasshopper with the improved geometrical representation of isostatic lines could be considered for further research.
- This research achieved material reduction by optimizing rib height against the maximally allowed deflection. In the future, other variable parameters (such as rib radius, material type, or rib cross-section variation) could be explored to increase material efficiency further.
- This research used a PLA filament for formwork fabrication, but exploring other more sustainable material alternatives or recycling options would be advisable. Another option would be to factor in formwork material into the design process, reducing the amount of material used and enabling easier demolding as it proved challenging.
- This research does not consider reinforcements design which would be a necessary step in the scaling-up process.

- This research focuses on reinforced concrete floor systems; however, the application of alternative, more ecologically sustainable materials could be considered in future research.
- The main challenge that needs to be addressed in the future would be the scaling-up of the fabricated model to the full scale and its testing for construction applications.

CONCLUSIONS

This paper investigates the potential for optimizing the material efficiency of rib-stiffened floor systems through the application of non-standard rib patterns and digital fabrication. In the first part, this research offers a brief overview of the application and development of ribbed slab systems and the classification of the rib configurations. Next, the isostatic rib configurations were deemed good optimization potentials and were chosen to be tested through a case study. As demonstrated in this study, digital design based on optimization and digital fabrication of the formwork using 3DP technology can be a suitable solution for increasing the material efficiency and sustainability of the rib-stiffened slab elements. Furthermore, this technology enables the manufacturing non-standard geometrically complex structural elements more sustainably than traditional methods. Also, the proposed workflow incorporates the two loops of optimization in the design process to further decrease material consumption. As a result, the proposed combination of novel methods, fabrication strategies, and geometrically optimized elements addresses the potential course of design development for more sustainable architecture.

Despite shown potential of the suggested approach, there are still numerous discussed limitations and directions for further improvement of the design and fabrication processes of structurally optimized elements. Some of these aspects will be addressed in subsequent studies since this study is part of ongoing research into the use of digital fabrication for the construction of structural elements in architecture.

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