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Review Paper

PARAMETRIC DESIGN OF 3D PRINTED RIBBED SLAB SYSTEM BASED ON NATURE-INSPIRED PATTERNS*

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Abstract. *The interest in pattern geometry and its application to architecture may be seen throughout history. While some authors were fascinated by pattern aesthetics, others were focused on their effectiveness and underlying principles of pattern formation. In continuing with the work of the second group of authors, this paper reviews opportunities for efficient ways of implementing patterns in the design of architectural elements, supported by recent developments in parametric design and digital fabrication techniques. This paper aims to analyze pattern configurations found in nature in order to determine the underlying generation principles and the potential of their application for 3D printed slab systems. Using case study methodology, selected patterns will be applied in developing a generative parametric design system, which will further be tested in creating and (small-scale) fabricating ribbed slab elements. The result of the research is the generalization of a design approach based on principles of natural pattern formation to produce sustainable design solutions that rely on the transposition of the inherent efficiency of natural systems, such as low energy or material consumption.*

Key words: *pattern design, pattern formation, bioinspired design, 3D printing, ribbed slab systems*

1. INTRODUCTION

Pattern geometry has long captivated architects and designers, serving as a source of inspiration and innovation throughout history. While some authors have been captivated by the aesthetic appeal of patterns, others have focused on their effectiveness and the underlying principles of pattern formation. Building upon the work of the latter group of authors, this study explores the effective pattern implementation in architectural design, leveraging recent developments in parametric design and digital fabrication techniques.

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By analyzing pattern configurations found in nature, this paper aims to determine the underlying generation principles and explore their potential application for 3D-printed ribbed slab systems. The main goal of this research is to develop a design approach based on the efficiency of natural systems, leading to sustainable design solutions that minimize energy and material consumption.

Throughout architectural history, numerous authors have recognized the profound impact of patterns on the built environment [1], [2]. One of the most notable authors in this area was architect Christopher Alexander, who explored patterns as fundamental building blocks in architectural design throughout his work, particularly in his book A Pattern Language [3]. Although his work focused more on the experiential qualities of patterns in architectural spaces rather than on the geometric and structural properties, his work paved the way for further exploration of this topic in later years. In contrast to Alexander's emphasis on aesthetics, even prior, another group of authors delved into the scientific principles underlying pattern formation and their potential application in architecture. Thompson, a mathematician, and biologist, investigated the mathematical properties of natural patterns in his book On Growth and Form, focusing on a relationship between physical forces and the formation of patterns in nature, highlighting pattern generation principles and the efficiency of natural patterns [4].

Recent technological advancements have opened new possibilities for integrating patterns into architectural practice [5], [6]. Parametric design, a computational design approach, allows architects to create complex and customizable designs by manipulating parameters and algorithms. Using parametric design enables the exploration of intricate patterns that can be tailored to specific contexts and performance criteria. Additionally, digital fabrication techniques, such as 3D printing, enable the realization of complex geometries with unprecedented precision and efficiency. These technological advancements provide a fertile ground for exploring the implementation of patterns in architectural elements with improved efficiency and sustainability.

Slabs are the structural building element with great potential for optimization regarding material efficiency. Today slabs are primarily made of concrete and take up most of it out of all construction elements in the standard building, making them a significant contributor to global CO_2 emission [7]. This comes as a result of the traditional building technology limitations where non-standard forms require complex formworks to cast concrete, making them cost-inefficient. For this reason, even though ribbed slabs have been proven more materially and structurally efficient, most floor systems are still constructed as flat slabs. To answer this problem, the use of digital fabrication technologies, especially 3D printing, has been extensively researched in recent years and has shown great potential for the fabrication of non-standard geometries through the printing of structural material or, more commonly, the printing of bespoke formworks [8].

Ribbed slabs are optimized alternatives to solid slabs. This study explores the possibilities of harnessing the inherent efficiency of nature-inspired pattern formation for non-standard slab design in order to assess the potential design and fabrication of more sustainable construction elements

2. Methodology

Starting with the literature review, this paper provides an overview of nature-inspired patterns by discussing underlying design principles, generation methods, and potential applications for 3D printed slabs. First, the key points and some of the main authors in the field are recognized in the brief historical review of the topic and some of the current architectural concepts influenced by pattern science. Then, main generation principles are identified and systematized along with their natural manifestations and corresponding mathematical models. Next, using case study methodology, several patterns are selected and applied through the digital design of non-standard ribbed floor systems. Designed slabs are then evaluated, against the standard solid slab, in terms of material efficiency by assessing specific rib configurations to exploit the inherent efficiency of natural patterns to create sustainable construction elements.

3. Nature-inspired Patterns

The first observations in the field of patterns came from the attempts of ancient Greek philosophers and mathematicians, such as Pythagoras or Plato, to understand and explain the universal laws in nature by observing natural phenomena. In the Middle Ages, Fibonacci introduced the Western world to the Fibonacci sequence in the book Liber Abaci [9]. Mathematics and the understanding of patterns experienced accelerated knowledge development from the 15th century with the transition to the Renaissance period. Thus, Leonardo Da Vinci analyzed the appearance of the golden section in nature, noticing, among other things, the spiral configuration of plant leaf patterns. Kepler applied the Fibonacci sequence to describe patterns in nature. The golden ratio and the Fibonacci sequence became two of the best-known mathematical rules that can be used to describe a large number of patterns in nature. During the 18th and 19th centuries, numerous scientists, such as Thomas Browne and Charles Bonnet, further developed these ideas [10]. For example, the problem of minimum area for a given contour was defined by studying soap bubbles. Based on these laws, William Thomson explained the system of efficient packing of cells, that is, one type of pattern formation in space [11].

Previous points to not only interest in aesthetic aspects of the natural patterns but also the significant interest in the underlying mathematical principles that lead to their formation. The attempts to understand naturally occurring visual patterns and their causes have interested many researchers during the last century. One of the first comprehensive research attempts to explain complex physical phenomena in nature was made by D'Arcy Wentworth Thompson from the position of natural science. He explained many phenomena that influence the formation of form and patterns in nature, such as the influence of scale on the formation of patterns [4]. His work emphasized the interconnectedness between mathematics, physics, and biology in understanding pattern formation. He proposed that physical forces, such as tension, pressure, and growth, play a crucial role in shaping natural patterns. Although it did not focus on establishing mathematical models describing pattern generation principles, this work is important from the architectural point of view as it offers a systematized insight into the formation of different structures found in nature and their morphogenesis. These principles were further researched in the following years. For example, Alan Turing, a pioneer of artificial intelligence, studied the mechanisms that influence the formation of patterns in living organisms broadening the understanding of their morphogenesis [12]. Most of the natural patterns were subject to observation and exploration from an early age, but branching, which was noted early on, was explained only much later. First, Lindenmayer presented the L-systems, which can be used to describe the growth of plants in the form of fractals. Followed by Mandelbrot's introduction of the term fractal geometry [13]. The interest in this topic over time evolved and led to the formation of pattern theory, a branch of applied mathematics that analyzes the patterns that the world generates in any modality, in all their natural complexity, intending to reconstruct the processes, objects, and events that produced them [14]. This theory represents the theoretical basis of many disciplines, such as artificial intelligence, image and acoustic signal processing, and pattern recognition.

The concept of morphogenesis, or the creation of form, was originally used to describe biological processes of cellular formation. However, the concept of digital morphogenesis emerged with the development of digital technologies. It refers to applying computational techniques and algorithms to generate and explore complex architectural forms and structures, drawing inspiration from biological processes and natural systems [15]. Patterns in nature represent a source of inspiration for this research direction as they are often formed on principles that favor the logic of optimization, which can be highly beneficial when transposed in structural design [16]. Biomimetics, the design that draws inspiration from nature in terms of an organism's or ecosystem's functional notions, emerged from this concept. It focuses on the interpretation and implementation of natural principles for generating optimized structures through generative design [17].

3.1. Pattern formation principles

A pattern in mathematics refers to any system formed based on defined rules. For this work, visual patterns, those with a geometric manifestation, are relevant. Visual patterns and the rules by which they are formed are mostly present in nature. There were multiple attempts at categorizing natural patterns [18], [19]. According to the literature review, nature-based patterns can be classified into the following categories based on the main generation principles.

Self-Organization: A dynamic process in which complex structures and patterns emerge from numerous interactions, executed using only local information, among the individual lower-level components of the system.

Self-Similarity: Process of forming geometric patterns that exhibit self-similarity, meaning that they are formed by repeating a unit pattern through different scales, such as fractals.

Reaction-Diffusion Systems: A dynamic process naturally found in chemistry involving local chemical reactions and substance diffusion, leading to spatial pattern formation.

Growth and Morphogenesis: Biological growth processes are caused by the distribution of resources, cell proliferation, and physical constraints that determine the spatial arrangement of tissues and organs.

Physical Forces and Constraints: Process of forming patterns under the influence of physical forces (tension, compression, or gravity) or mechanical forces and growth constraints.

Optimization: The natural process of pattern forming under optimization and efficiency principles in nature exhibits remarkable adaptations for resource utilization, energy, and material efficiency, or functional optimization.

Table 1 Overview of patterns and generation principles in nature

Generation principle	Pattern	Computational models
Self-Organization	ant trails, flocking of birds, cell organization, ripple patterns	cellular automata, agent-based simulations
Self-Similarity	branching networks, coastlines, cloud shapes, crystals, waves	recursive algorithms
Reaction-Diffusion Systems	turing patterns, stripes, spots, travelling waves	partial differential equations
Growth and Morphogenesis	tissue and bone morphology, spirals, trees	finite element method
Physical Forces and Constraints	branching structures, honeycomb, spirals, banded patterns, voronoi	finite element method
Optimization	voronoi, packing patterns, Fibonacci sequence and the golden ratio, flow patterns, spider webs, sponges	biological algorithms / including evolutionary algorithms, genetic algorithms, neural networks

Every pattern in nature or its geometric approximation can be classified into at least one listed category (Table 1). However, it is important to note that patterns in nature are often the result of the combination of multiple factors. Patterns from each category can be applied to a surface; therefore, each can be applied as a rib configuration for slab systems. For example, standard rib configurations include regular networks of ribs belonging to regular geometric tessellations or ribs following isostatic lines representing force flows [20].

4. DESIGN OF RIBBED SLAB SYSTEM

In standard building practice, rib configuration selection is often influenced by construction technology limitations rather than achieving maximal efficiency. Previous results in using regular geometric patterns such as orthogonal or triangular grids as they do not require overly complex formworks and can be achieved using modular elements [21]. Pier Luigi Nervi has shown in his work that it is possible to achieve much greater material efficiency using rib configurations that follow isostatic lines of principal bending moments [22]. However, his approach was never widely used because of the needed formwork complexity. Digital fabrication and especially 3D printing techniques have shown a great potential for more efficient fabrication of complex form slabs by allowing bespoke formwork design [23]–[25].

This study explores the potential applications of nature-inspired patterns for the design of non-standard ribbed floor slabs for 3D printing. To do this, a design process, shown in Figure 1, was established and implemented, producing test slab models.

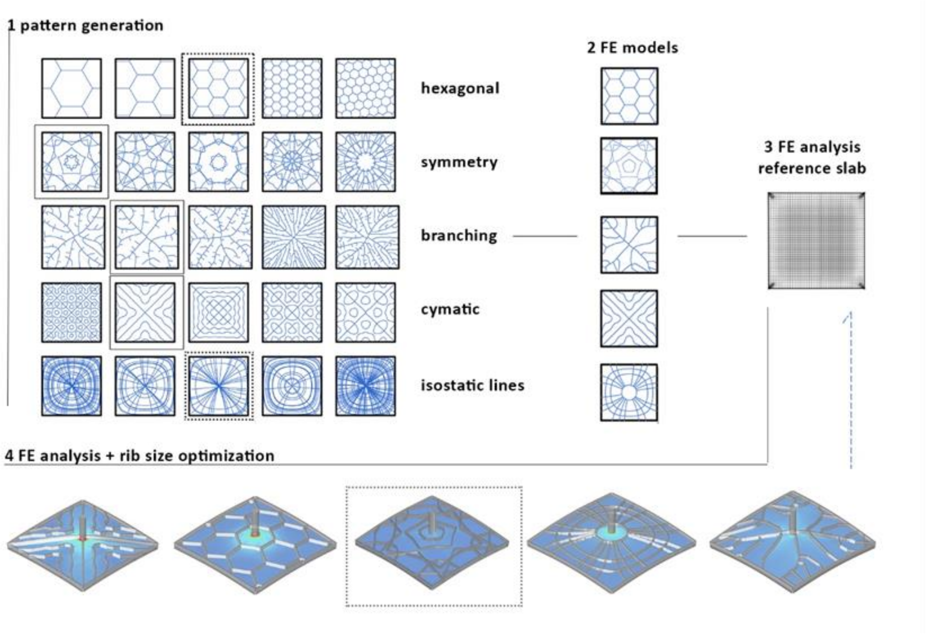

Fig. 1 Design process workflow

First, a model slab was selected as an 8x8m centrally supported two-way slab in reference to the Nervi's Gatti Wool Factory, which was proven to be one of the highly materially efficient built slabs [22], and because it represents a typical span for multistory buildings. The reference solid slab was tested with Finite Element Analysis (FEA) using the Millipede plugin for Rhinoceros 3D/Grasshopper. A solid slab with a thickness of h=22cm was chosen as a reference.

Next, based on the literature review, several pattern generation principles were selected for the slab design. The selection was made considering the optimization potential and compatibility of said principle with the structural requirements of slab elements. Some natural patterns were discarded due to the overly complex geometric nature (e.g., Turing patterns), and some due to the formation principal incompatible with the selected design task. Several patterns were selected and parametrically generated, exploring different configurations and densities. Five pattern groups were then chosen for further testing based on their form, complexity, optimization potential, and aesthetic qualities, with one of them being an isostatic pattern generated through FEA. This pattern was included as a second reference since it is commonly considered an efficient configuration in the building industry.

For each group, one representative configuration was chosen for testing, each with a similar curve density. In the next step, these configurations were applied to the test slab, and digital models were made. These models were then tested using another FEA, and optimal rib size was determined based on the deflection. Finally, all test models were compared with the reference slab in terms of material efficiency.

In the final step, the most efficient configuration was selected, and a 3D model was generated. Based on this 3D model, a formwork for a small-scale prototype was designed for 3D printing on a desktop PLA printer simulating a larger-scale production method of combining 3D printed formwork with traditional concrete casting techniques.

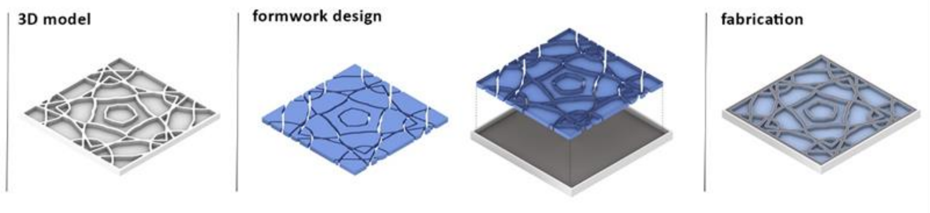

Fig. 2 Formwork design

5. DISCUSSION

The presented case study explored a variety of design solutions for non-standard rib configurations based on the selected generation principles. The results have shown that these rib configurations can lead to a more materially efficient design. Among the analyzes slab models, all had lower material consumption than the reference slab. The weight difference was between 16 - 42%, with the most efficient being rib configuration formed on the principles of multiple symmetry and reflections. Another important finding was that this configuration showed slightly better performance than the tested isostatic pattern, confirming the hypothesis that natural generation principles could lead to innovative and more optimized design solutions.

Although this study confirmed efficiency of ribbed slab systems based on nature-inspired patterns, some aspects could be further developed:

The results of this study can be further verified through the fabrication of small-scale prototypes and model testing.

Further research should consider reinforcement design as it was not included in this research; however, it is an important step for scaling up the prototypes and can potentially alter the design criteria.

The proposed design workflow could be developed in the future to include additional optimization algorithms in the form-finding stage to further improve the material efficiency of the proposed structures.

FEA for this study was done using a Millipede plugin; however, in the future, it would be beneficial to consider using other software that could provide more parameter control to increase optimization and precision.

In this study, designed structures were assumed to be standard reinforced concrete; to increase sustainability, exploring other material alternatives for both construction elements and digital fabrication would be necessary.

6. CONCLUSION

This paper explores the potential of implementing nature-inspired pattern generation principles in the structural element design workflow for creating non-standard ribbed floor systems. The literature review was first conducted to understand the development of the interest in the field of nature-inspired patterns, underlying principles, and their impact on architectural design. The main groups of generation principles were then identified and systematized, along with the corresponding occurrences in nature. Among these, several with the most potential for use in the design of slab elements were selected and applied in the case study. Next, the design workflow was formed and applied to design several slabs with non-standard rib configurations and to compare them against a standard flat slab. Results have shown that using nature-inspired principles for rib configuration form-finding has excellent potential for reducing material consumption. The proposed design method, combined with the novel fabrication techniques, could be used to design more sustainable construction elements.

This study is part of an ongoing research effort into the digital fabrication of structurally optimized architectural elements, through which discussed further research directions and limitations will be addressed.

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PARAMETARSKI DIZAJN 3 D ŠTAMPANIH SISTEMA REBRASTIH PLOČA INSPIRISAN PRIRODNIM OBLICIMA

Kroz istoriju se može videti interes za geometriju uzoraka i njenu primenu na arhitekturu. Dok su neki autori bili fascinirani estetikom obrazaca, drugi su bili fokusirani na njihovu efikasnost i osnovne principe formiranja obrazaca. Nastavljajući rad druge grupe autora, ovaj rad razmatra mogućnosti za efikasne načine implementacije obrazaca u dizajn arhitektonskih elemenata, podržane najnovijim razvojem parametarskog dizajna i tehnikama digitalne izrade. Ovaj rad ima za cilj analizu konfiguracije obrazaca koje se nalaze u prirodi kako bi se utvrdili osnovni principi generisanja i potencijal njihove primene za 3D štampane sisteme ploča. Koristeći metodologiju studije slučaja, odabrani obrasci će biti primenjeni u razvoju generativnog parametarskog projektantskog sistema, koji će se dalje testirati u kreiranju i izradi (malih) elemenata rebrastih ploča. Rezultat istraživanja je generalizacija dizajnerskog pristupa zasnovanog na principima formiranja prirodnog obrasca za proizvodnju održivih dizajnerskih rešenja koja se oslanjaju na transpoziciju inherentne efikasnosti prirodnih sistema, kao što je niska potrošnja energije ili materijala.

Ključne reči: *dizajn obrazaca, formiranje obrazaca, bioinspirisani dizajn, 3D štampa, sistemi rebrastih ploča*