LEARNING FROM BEES: THE UTILIZATION OF HEXAGONAL STRUCTURE AS A COMPOSITIONAL TOOL IN ARCHITECTURE

Anastasia Kotzaitsi[1*], Ioanna Symeonidou[1]

[1]Department of Architecture, University of Thessaly, Volos 38334, Greece
koanastasia@uth.gr, symeonidou@uth.gr

Abstract

This study examines the hexagonal structure as a compositional tool in architecture. Hexagons are frequently employed in nature, showcasing efficiency and stability. By studying the formation of honeycombs and other natural systems where hexagonal tessellations occur, this research seeks to implement hexagonal structures in architecture. The study looks at several different scales of architectural applications and highlights their advantages, including material efficiency, structural stability, and energy-saving potential. Findings reveal that hexagonal layouts reduce waste, enhance load distribution and maximize space, offering sustainable, functional and aesthetic solutions for contemporary design.

Keywords: honeycomb, hexagonal prism, architecture, material efficiency

1 INTRODUCTION

The hexagonal form, a recurring pattern in both nature and human innovation, embodies a balance of simplicity and sophistication. Its prevalence is attributed to its exceptional geometric properties, including material efficiency, structural stability, and space optimization. While honeycomb is the most prominent example of this form in nature, the underlying principles of hexagonal structures extend beyond bees, offering profound implications for design, architecture, and engineering. This work delves into the fundamental characteristics of the hexagon, exploring its application in diverse fields and scales and its importance for creating efficient and sustainable solutions for man-made systems.

2 BEES

Beehives are an example of highly optimized biological structure, formed as a negotiation of the building behavior of bees and pressure [1]. They have fascinated the scientific community for centuries. Their hexagonal geometry (Fig.1) ensures maximum storage with minimum material consumption, reducing wax production, which is a costly material for the bees [2], [3]. Additionally, the hexagonal pattern enhances stability and resistance to compressive or tensile forces and vibrations, as cell walls share loads and forces, preventing collapse under pressure [4], [5]. The hexagonal shape also facilitates air circulation, aiding in the regulation of hive temperature and humidity [6]. After their primary use, cells are thoroughly cleaned and reused by the bees, maintaining the structural integrity of the hive [7].

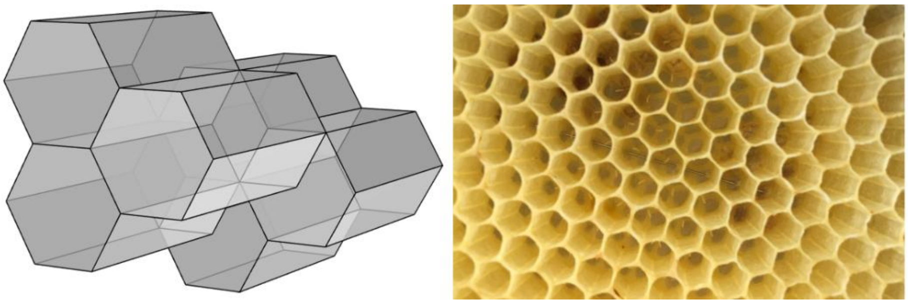

Fig.1. Illustration of the two parallel arrays of hexagonal cells on a honeycomb and real-life honeycomb cell structure.

3 HEXAGON AS A SHAPE/ STRUCTURE

Hexagon is one of the most important geometric shapes occurring in nature, possessing properties that make it ideal for efficient use of space and materials. With six equal sides and angles of 120°, it distinguishes itself from other regular polygons (Fig.2), allowing it to cover surfaces without gaps, saving material and energy. The total wall length of hexagons is the minimum possible for a given volume [8], making the shape highly economical in construction. Moreover, its geometry ensures resistance to compression and tension, forces are distributed evenly, preventing unwanted deformation.

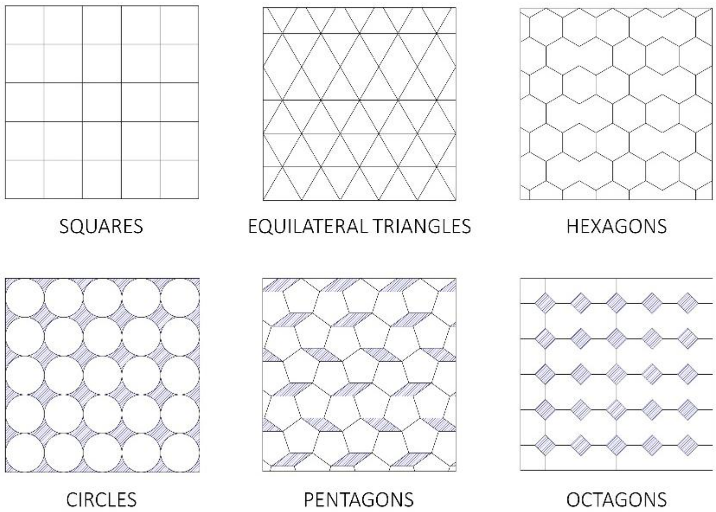

Fig.2. Tessellations of regular (1st row) and irregular polygons (2nd row) on a plane. The blue areas symbolize the unusable space.

Honeycombs are indicative of the hexagon's advantages, however they are not the only example of hexagonal pattern that occur in nature. Soap bubbles form hexagonal grids when minimizing surface tension [9], while snowflakes adopt hexagonal symmetry due to geometric balance during their formation [10]. In mud and lava cracks, the hexagonal pattern emerges from natural cooling and contraction processes [11] (Fig.3).

The mathematical arrangement of close-packing explains the natural tendency of hexagons to appear in dense layouts, such as in insect eyes, where hexagonal tessellation allows optimal lens distribution for precise vision [12]. Furthermore, the division of the hexagon into equilateral triangles offers design flexibility, as seen in dragonfly wings and architectural structures, where strength and efficiency are combined [13].

The geometry of the hexagon maximizes stability, while its internal angle of 120° contributes to the uniform distribution of loads, making hexagonal arrangements energy-efficient; it tends to approach a state of minimal energy, maintaining high strength and firmness [14].

Fig.3. Hexagonal patterns can be found on a variety of natural forms such as an array of soap bubbles, snowflakes and lava cracks.

4 ARCHITECTURAL APPLICATIONS OF DIFFERENT SCALES

Hexagonal structures are present in a variety of man-made applications, as their geometric properties become increasingly studied and understood. They appear at several different scales from engineered material structures to urban plans.

Honeycomb-like materials with hexagonal structures, such as sandwich panels, are lightweight, durable, and effective in thermal and acoustic management, thus they are applied across a wide range of fields, from aeronautics to construction [15], [16]. Hexagonal forms in construction display flexibility and modularity maximizing usable space (Fig.4). Hexagonal modular systems are visually attractive and sustainable; they reduce cost, construction time and environmental impact [17].

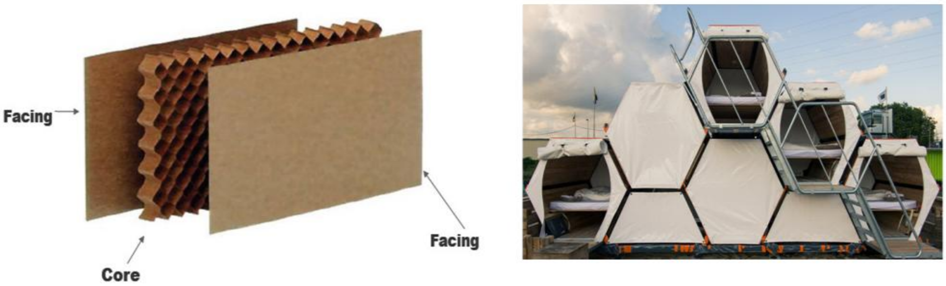

Fig.4. Layers of a honeycomb-type material (link), B-and-bee modular sleeping unit by Barbara Vanthorre & Ron Hermans (link)

Hexagons are frequently used on facades for shading, lighting, and heat management. They become a compositional element resulting in dynamic surfaces that incorporate transparency, shading, and texture. Iconic buildings such as the Watercube National Swimming Centre in Beijing by PTW Architects [18] and the Eden Project by Grimshaw Architects demonstrate how this geometry enhances building performance and aesthetics [19] [20] (Fig.5).

Fig.5. Beijing National Swimming Centre (link), Eden Project (link).

With regards to floor plan distributions, hexagons are also present in a wide range of public buildings educational facilities and office buildings; the circulation within hexagonal interior layouts enhances functionality and space use.

In urban planning, the incorporation of hexagonal grids has been repeatedly implemented in cities [21]. It has been proven through studies that hexagonal urban plans may lead in the improvement of microclimate, traffic safety, and energy efficiency. Grammichele in Sicily (Fig.6) is a rare example of urban planning that leverages the properties of hexagon for seismic protection [22] and contributing to the city's sustainability and resilience.

It is seen from the above that, the geometric properties of the hexagon relating to strength, adaptability, and functionality, enable its use as a compositional tool for highly optimized architectural structures, from small-scale material applications to large-scale constructions and planning.

Fig.6 Satellite view of the city of Grammichele in Sicily (link)

5 DISCUSSION

The hexagonal form, while advantageous in many cases, presents certain drawbacks when applied in human-engineered systems. The main disadvantage is its limited capacity for geometric adaptation within predefined contexts, namely its difficulty in integrating with orthogonal or circular grids resulting in complex fabrication and assembly. Additionally, hexagons become challenging for covering spherical geometries uniformly as they require additional shapes like pentagons. These challenges highlight the need for further research into hybrid geometries and adaptive solutions that retain the hexagon's strengths while addressing its limitations in specific applications.

6 CONCLUSIONS

Hexagon is a sophisticated geometric shape with properties that make it a powerful tool for design and construction with a wide range of application possibilities. Its advantages are mathematically proven and prominent in nature, as this structure has been optimized through thousands of years of evolutionary development. Its structural efficiency, ability to maximize space, and inherent ability for repetition without gaps, enable resource savings in materials, energy, and labor. Found in nature, from honeycombs to snowflakes, its properties and multi-criteria optimization inspire sustainable, innovative architecture and engineering. Future research would investigate its prominence in sustainable construction, such as modular housing or lightweight materials that mimic honeycomb structures for enhanced strength-to-weight ratio. Moreover, its geometric efficiency could inspire advancements in urban planning, creating tessellated layouts that maximize land use. Exploring its role in energy systems, particularly in fluid dynamics or heat exchange designs, may also yield valuable results. Expanding hexagonal frameworks into adaptive or dynamic systems could revolutionize their utility across various industries.

REFERENCES

[1] F. Nazzi, “The hexagonal shape of the honeycomb cells depends on the construction behavior of bees,” *Sci. Rep.*, vol. 6, no. 1, Art. no. 1, Jun. 2016, doi: 10.1038/srep28341.

[2] K. von Frisch and O. von Frisch, *Animal architecture*. New York, Harcourt Brace Jovanovich, 1974. Accessed: Apr. 04, 2023. [Online]. Available: http://archive.org/details/animalarchitect00fris

[3] K. Dutta, “Natural Hexagons,” *Resonance*, vol. 26, no. 3, pp. 399–413, Mar. 2021, doi: 10.1007/s12045-021-1138-8.

[4] D. Goss *et al.*, “Biomimetics | Free Full-Text | Bioinspired Honeycomb Core Design: An Experimental Study of the Role of Corner Radius, Coping and Interface.” Accessed: Nov. 16, 2023. [Online]. Available: https://www.mdpi.com/2313-7673/5/4/59

[5] R. Franklin, S. Niverty, B. A. Harpur, and N. Chawla, “Unraveling the Mechanisms of the Apis mellifera Honeycomb Construction by 4D X-ray Microscopy,” *Adv. Mater.*, vol. 34, no. 42, p. 2202361, 2022, doi: 10.1002/adma.202202361.

[6] T. D. Seeley and R. A. Morse, “The nest of the honey bee (Apis mellifera L.),” *Insectes Sociaux*, vol. 23, no. 4, pp. 495–512, Dec. 1976, doi: 10.1007/BF02223477.

[7] M. L. Winston, *The biology of the honey bee*. Cambridge, Mass: Harvard University Press, 1987.

[8] T. C. Hales, “The Honeycomb Conjecture,” May 20, 2002, *arXiv*: arXiv:math/9906042. Accessed: Apr. 03, 2023. [Online]. Available: http://arxiv.org/abs/math/9906042

[9] J. Wagensberg, *La Rebelion de Las Formas*. TusQuets, 2005.

[10] P. Ball, *The Self-Made Tapestry: Pattern formation in nature*. Oxford University Press, 1998. doi: 10.1093/oso/9780198502449.001.0001.

[11] P. Ball, *Patterns in Nature: Why the Natural World Looks the Way It Does*. Chicago, IL: University of Chicago Press, 2016. Accessed: Jan. 21, 2024. [Online]. Available: https://press.uchicago.edu/ucp/books/book/chicago/P/bo23519431.html

[12] P. Pearce, *Structure in nature is a strategy for design*. Cambridge: MIT Press, 1978.

[13] D. W. Thompson, *On Growth and Form*. in Canto. Cambridge: Cambridge University Press, 1992. doi: 10.1017/CBO9781107325852.

[14] A. A. M. Yusof, M. A.-F. M. S. Januddi, K. M. Isa, and M. N. Harun, “The tendency of Nature towards Hexagon Shape Formation due to Minimizing Surface Energy,” *Int. J. Integr. Eng.*, vol. 14, no. 1, Art. no. 1, Mar. 2022.

[15] E. C. Onyibo and B. Safaei, “Application of finite element analysis to honeycomb sandwich structures: a review,” *Rep. Mech. Eng.*, vol. 3, no. 1, Art. no. 1, Mar. 2022, doi: 10.31181/rme20023032022o.

[16] L. J. Gibson, “Cellular Solids,” *MRS Bull.*, vol. 28, no. 4, pp. 270–274, Apr. 2003, doi: 10.1557/mrs2003.79.

[17] D. Mitsimponas and I. Symeonidou, “Identifying Trends and Typologies of Modular Constructions in Architecture,” *Nexus Netw. J.*, vol. 26, no. 1, pp. 49–69, Mar. 2024, doi: 10.1007/s00004-023-00752-x.

[18] J. Kim and K. Park, “The Design Characteristics of Nature-inspired Buildings,” *Civ. Eng. Archit.*, vol. 6, pp. 88–107, Mar. 2018, doi: 10.13189/cea.2018.060206.

[19] P. Gruber, *Biomimetics in Architecture: Architecture of Life and Buildings*. Vienna : Springer-Verlag Vienna, 2011. Accessed: Nov. 30, 2023. [Online]. Available: http://archive.org/details/Biomimetics_in_Architecture_Architecture_of_Life_and_Buildings

[20] M. Pawlyn, “Biomimicry in Architecture-RIBA Publishing (2019),” Scribd. Accessed: Jan. 06, 2024. [Online]. Available: https://www.scribd.com/document/500658618/Michael-Pawlyn-Author-Biomimicry-in-Architecture-RIBA-Publishing-2019

[21] E. Ben-Joseph and D. Gordon, “Hexagonal Planning in Theory and Practice,” *J. Urban Des.*, vol. 5, no. 3, pp. 237–265, Oct. 2000, doi: 10.1080/713683965.

[22] Q. Zhang *et al.*, “Bioinspired engineering of honeycomb structure – Using nature to inspire human innovation,” *Prog. Mater. Sci.*, vol. 74, pp. 332–400, Oct. 2015, doi: 10.1016/j.pmatsci.2015.05.001.