Bioinspiration & Biomimetics

OPEN ACCESS

RECEIVED
1 April 2022

ACCEPTED FOR PUBLICATION
11 April 2022

PUBLISHED
24 May 2022

EDITORIAL

Special issue: bioinspired architectural and architected materials

Peter Fratzl[1,2,*], Christiane Sauer[2,3] and Khashayar Razghandi[1,2]

1 Max Planck Institute of Colloids and Interfaces, Potsdam Science Park, Germany
2 Excellence Cluster Matters of Activity, Humboldt Universität zu Berlin, Germany
3 Weißensee School of Art and Design, Berlin, Germany
* Author to whom any correspondence should be addressed.

E-mail: fratzl@mpikg.mpg.de

Architecture stands as a paradigm for the development of structural entities, which define functionality from the nanoscale to entire buildings. However, the distinction between structure and material becomes totally blurred in biological systems where it is impossible to distinguish between material and device or organ. A tree stem, as a prototypical example, is both material and plant organ with specific biological functions. Partially inspired by this, there are recent parallel movements—in materials development as well as in architectural design—towards the merging of materiality, structure and function into one integral construction system [1].

The concept is illustrated in figure 1 that shows the currently tallest wooden building with its architecture, together with the internal architecture of wood based on micrometric wood cells and nanometric cellulose fibrils. This spans dimensions from the diameter of the cellulose fibrils of less than 3 nm to the height of the building of the order of 85 m (that is about 30 billion times larger). Many architectural levels carry the mechanical stability of the cellulose up to the building dimensions.

Bioinspiration in conjunction with new digitally based design and fabrication methods is starting to transform both disciplines, architecture and materials science, towards a fundamentally novel approach. On the one hand, material systems and structures can now be designed specifically for a purpose and become active elements utilizing material properties to their full capacity. On the other hand, new concepts for structural building elements or functional facade devices aim at efficient solutions for material use. As building activities, and accordingly energy and material consumption, will rise dramatically with the growth of our global population, bioinspired concepts that deploy material in an efficient way will be key to a more sustainable approach.

Material properties are traditionally defined by chemical composition and processing of the material. In recent years, additional structures have been introduced by three-dimensional fabrication and other techniques to create architected materials with new types of properties. Examples of architected materials are smart composites, metamaterials, cellular materials, trusses, granular or digital materials and many more [4] (see figure 2). The consequence of this development is that, except for a matter of scale, there is potential convergence of materials science and architectural design through the interplay of materiality and structure.

This special issue focuses on the various aspects of bioinspired architectural and architected materials, defining functionality through structures at all scales. A wide range of properties, from mechanical strength and toughness, thermal management and aerodynamic properties, lead to bioinspired building and product concepts and even to the parallel of such structural concepts in the world of musical composition.

1. Natural architected materials

Many natural materials have a hierarchical structure whereby building blocks are assembled into larger units in several successive steps, from molecules to fiber, layers and larger units [6]. Structural motifs can be related to mechanical performance in a wide range of natural protein materials, for example in [7]. Besides wood, bamboo is a traditional building material with exceptional mechanical properties. In addition to high tensile strength, this allows for extraordinary large deflection due to its hierarchically structured materiality. The contribution to this collection by Chen *et al* [8] quantifies these properties

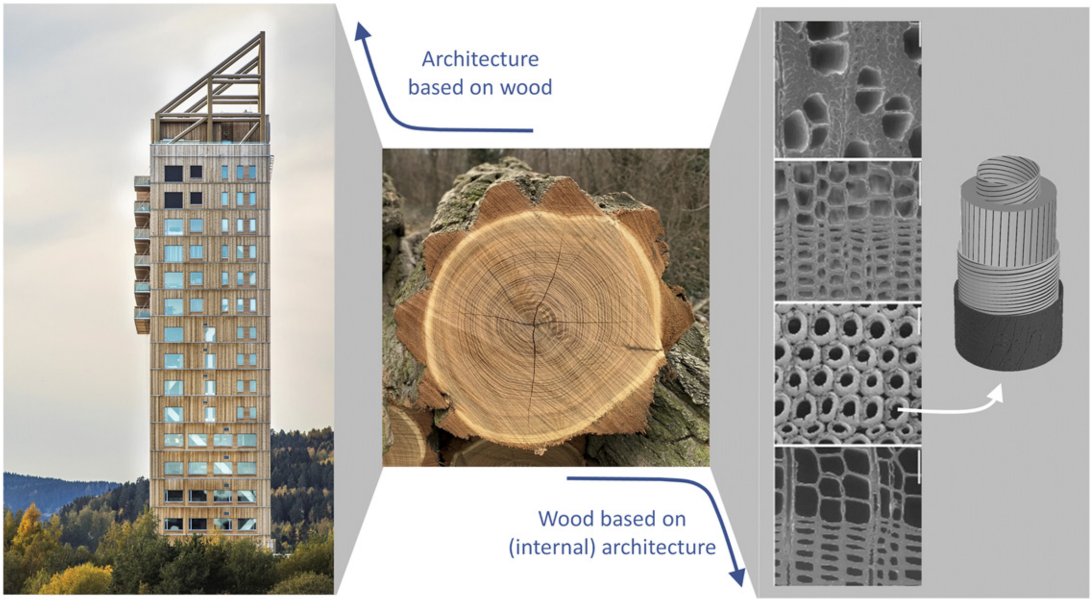

Figure 1. Multiscale architectures. Left: the wooden tower of Lake Mjøsa, Norway Reproduced with permission from [1]. © Voll Arkitekter AS & Ricardo Foto. Right: the internal structure of wood based on parallel tube-like wood cells with diameters in the range of tens of microns (shown for several wood species from top to bottom). The white arrow points to a sketch where nanometer thick cellulose fibrils are indicated by black lines [2] John Wiley & Sons. © 2020 The Authors. Published by Wiley-VCH GmbH.

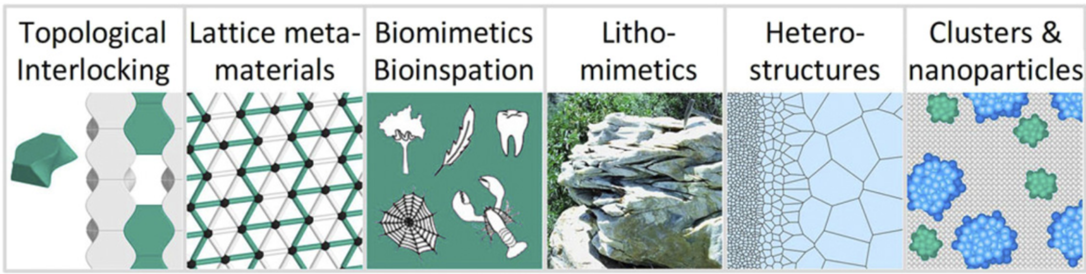

Figure 2. Different principles of architected materials, which by structuting obtain new properties that are not inherent to the materials' chemistry Reproduced from [4]. CC BY 4.0.

and relates them to the inner architecture of the bamboo culm. Bone is another example of a natural material that is structured over multiple length scales. The contribution by Tertuliano *et al* [9] analyses the role of different structural levels, such as layers and fibers, in the fracture resistance of this material.

2. Designing architectural materials

Prospective scarcity of resources demands novel sustainable material concepts in architecture. Granular materials are random loose assemblies of particles, such as sand piles for example. If the particles have non-convex shapes they will entangle and reach topological interlocking. The contribution by Dierichs and Menges [10] shows how the assembly of particles can actually be used to design reconfigurable granular building elements at an architectural scale. Further, Thomsen and Tamke [11] report on bio-design as a material practice that challenges the paradigm of stability and predictability in architecture by exploring the heterogeneity of designed, harvested and living materials as a positive attribution for properties and performance.

3. Architected thermal exchange and insulation

Heat exchange is an important property of skin-like boundaries at all dimensions, such as for wearable devices or for building skins. The contribution by Grinham *et al* [12] shows that an optimized design of the channel architecture within a flexible and transparent heat exchanger can significantly improve its functional properties. Another approach to heat management is evaporative cooling. In their contribution, Rupp and Gruber [13] show that optimizing the design of surface structures inspired by the geometries of plant leaves may improve mass transfer, especially considering aerodynamic effects related to air movements. The proof of concept includes ceramic tiles for architectural application. Porous silica ceramic materials with a lamellar structure and high anisotropy, fabricated by a freezing method, are shown in the contribution by Zhao *et al* [14] to provide both thermal insulation (across the layers) and high strength (along the layers) with application potential for building insulation.

4. Architected shape change and motion design

Textile technology is a traditional approach to additive manufacturing where new properties emerge through a combination of fiber entangling (or interlocking according to the scheme of figure 2) and weaves that may be considered mechanical metamaterials (figure 2). The paper by Guiducci *et al* [15], investigates the shape-generating effect of internal stresses generated by printing rigid rod-like structures onto a pre-stretched textile, which generates an architected material with potential applications in architecture. Another contribution by Shafiei *et al* [16] shows that, with an appropriate design, scaled skins serving as flexible armors for example, acquire increased flexibility in compression by allowing the formation of wrinkles and folds. The paper provides insights into how wrinkles can form reliably based on stable buckling of the scaled skin. Water absorption by cellulosic materials such as wood confers shape-change properties to seed dispersal systems, for example. The contribution by Tahouni *et al* [17] shows how additive manufacturing can be used to generate architected materials that show sequential motion steps based on different levels of responsiveness to humidity.

5. Metamaterials for acoustic control and aerodynamic properties

The contribution by Zhilayev *et al* [18] investigates how artificial wings for flying robotic devices can be designed based on periodic honeycomb patterns. The authors start from the designs observed in insect wings and then use multi-parameter optimization to improve the flapping flight dynamics and the sound of a robotic drone.

6. From musical composition to biological material design

Architected materials use patterns instead of chemical composition to modify the physical properties of materials. The contribution by Milazzo *et al* [19] shows how the patterns of musical composition translate into a three-dimensionally folded protein structure and this structure back into music.

7. Conclusion

This collection of a dozen papers shows the enormous potential of structure at multiple scales to reveal properties and functions that are not inherent to homogeneous materials. The role models for this type of approach are natural materials that nearly always have a multiscale structure where building blocks are assembled into respectively larger units over several length scales. Architectural design typically addresses a size range similar or beyond humans, while materials science makes use of smaller dimensions. Recent efforts explore the inner structure of architectural materials as a means of interacting with their environments at building dimensions. This collection gives an overview over the whole scale from nanometers to meters covering disciplinary approaches that are still not likely to interact but may clearly profit from each other. The analysis of nature leads to design principles, but also the analysis of a design principle like a musical composition can lead to a new scientific viewpoint [19]. The scope of approaches identifies a wide range of possible applications in the field of façade, construction, clothing or products with architected properties and performance. The multidisciplinary contributions open up resilient and sustainable perspectives for shaping our future environment.

Data availability statement

No new data were created or analysed in this study.

ORCID iDs

Peter Fratzl https://orcid.org/0000-0003-4437-7830
Khashayar Razghandi https://orcid.org/0000-0003-3419-4870

References

[1] Bechthold M and Weaver J C 2017 Materials science and architecture *Nat. Rev. Mater.* **2** 17082
[2] Voll Arkitekter 2022 http://vollark.no/portfolio_page/mjostarnet/
[3] Eder M, Schaffner W, Burgert I and Fratzl P 2021 Wood and the activity of dead tissue *Adv. Mater.* **33** 2001412
[4] *Architectured Materials in Nature and Engineering* ed Estrin Yuri, Bréchet Yves, Dunlop John and Fratzl Peter (ed) 2019 (New York: Springer)
[5] Estrin Y, Beygelzimer Y, Kulagin R, Gumbsch P, Fratzl P, Zhu Y and Hahn H 2021 Architecturing materials at mesoscale: some current trends *Mater. Res. Lett.* **9** 399–421
[6] Fratzl P and Weinkamer R 2007 Nature's hierarchical materials *Prog. Mater. Sci.* **52** 1263–334
[7] Harrington M J and Fratzl P 2021 Natural load-bearing protein materials *Prog. Mater. Sci.* **120** 1–144
[8] Chen Q, Razi H, Schlepütz C M, Fang C, Ma X, Fei B and Burgert I 2021 Bamboo's tissue structure facilitates large bending deflections *Bioinsp. Biomim.* **16** 065005

[9] Tertuliano O A, Edwards B W, Meza L R, Deshpande V S and Greer J R 2021 Nanofibril-mediated fracture resistance of bone *Bioinsp. Biomim.* **16** 035001

[10] Dierichs K and Menges A 2021 Designing architectural materials: from granular form to functional granular material *Bioinsp. Biomim.* **16** 065010

[11] Thomsen M R and Tamke M 2022 Towards a transformational eco-metabolistic bio-based design framework in architecture *Bioinsp. Biomim.* (accepted)

[12] Grinham J, Hancock M J, Kumar K, Bechthold M, Ingber D E and Aizenberg J 2021 Bioinspired design and optimization for thin film wearable and building cooling systems *Bioinsp. Biomim.* **17** 015003

[13] Rupp A I K S and Gruber P 2021 Bio-inspired evaporation from shaped interfaces: an experimental study *Bioinsp. Biomim.* **16** 045001

[14] Zhao N, Mao A, Shao Z and Bai H 2022 Anisotropic porous ceramic material with hierarchical architecture for thermal insulation *Bioinsp. Biomim.* **17** 015002

[15] Guiducci L, Kycia A, Sauer C and Fratzl P 2022 Self-organized rod undulations on pre-stretched textiles *Bioinspir Biomim* (accepted)

[16] Shafiei A, Pro J W and Barthelat F 2021 Bioinspired buckling of scaled skins *Bioinsp. Biomim.* **16** 045002

[17] Tahouni Y, Krüger F, Poppinga S, Wood D, Pfaff M, Rühe J, Speck T and Menges A 2021 Programming sequential motion steps in 4D-printed hygromorphs by architected mesostructure and differential hygro-responsiveness *Bioinsp. Biomim.* **16** 055002

[18] Zhilyaev I, Anerao N, Kottapalli A G P, Yilmaz M C, Murat M, Ranjbar M and Krushynska A 2022 Fully-printed metamaterial-type flexible wings with controllable flight characteristics *Bioinsp. Biomim.* **17** 025002

[19] Milazzo M, Anderson G I and Buehler M J 2022 Bioinspired translation of classical music into de novo protein structures using deep learning and molecular modeling *Bioinsp. Biomim.* **17** 015001