Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

A Framework for the Design of Biomimetic Cellular Materials for Additive Manufacturing

T. McNulty*, D. Bhate†, A. Zhang†, M. A. Kiser*, L. Ferry**, A. Suder†, S. Bhattacharya#, P. Boradkar*

*The Biomimicry Center, Arizona State University; †Phoenix Analysis & Design Technologies, Inc.; **School of Mathematical and Natural Sciences, Arizona State University; #Autodesk Inc.

Abstract

Cellular materials such as honeycombs and lattices are an important area of research in Additive Manufacturing due to their ability to improve functionality and performance. While there are several design choices when selecting a unit cell, it is not always apparent what the optimum cellular design for a particular application is. This becomes particularly challenging when seeking an optimal design for more than one function, or when the design needs to transition spatially between different functions. Nature abounds with examples of cellular materials that are able to achieve multifunctionality, but designers lack the ability to translate the underlying principles in these examples to their design tools. In this work, we propose a framework to bridge the gap between nature and designer. We present a classification of natural cellular materials based on their structure and function, and relate them in a manner amenable for use in guiding design for Additive Manufacturing.

Introduction

Cellular materials are a particularly exciting research frontier in Additive Manufacturing (AM) due to their ability to improve performance in a wide range of applications, while minimizing material usage and structural mass. Some of these applications are classified in Figure 1. Since most cellular materials engineers work with tend to be composed of synthetic materials, it is easy to forget that humans have been using *natural* cellular materials like wood and cork for millennia. The first documented observations of cells in materials were conducted by Robert Hooke in 1665, who concluded that these cells were responsible for the curious behavior of the material (1). Since then, many engineering structures such as honeycomb sandwich panels, metal foams and architectural domes, owe their designs, at least in part, to nature's inspiration.

Nature is full of examples of cellular materials. 3.8 billion years of evolution have resulted in cellular geometries that conserve material usage and enhance performance under the different conditions where life thrives (2). A wide range of natural cellular materials have been studied and their functions postulated, which are summarized in Figure 2. The similarity between figures 1 and 2 is evidence of the strong correlation between functional benefit obtained through cellular materials in engineering applications and in nature.

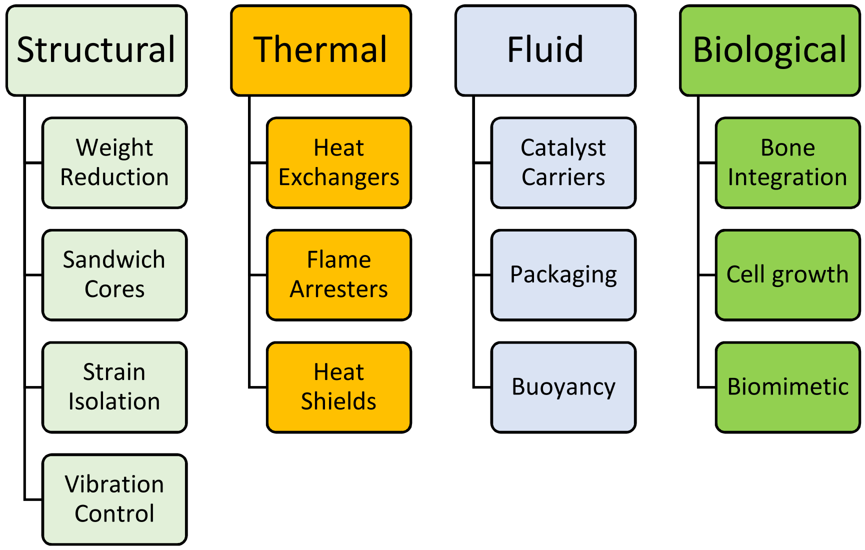


Figure 1. Application areas for cellular structures in engineering solutions that can leverage their special properties to enhance overall functional performance, adapted from (3)

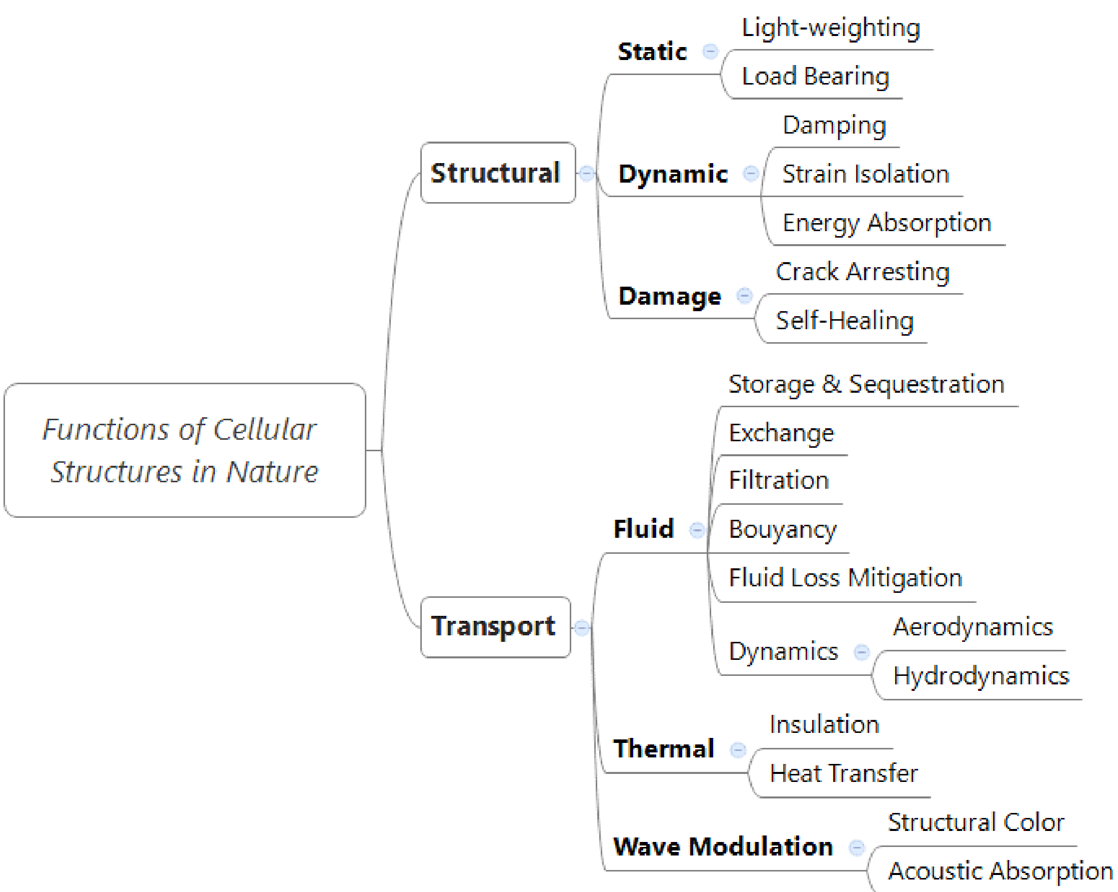


Figure 2. Classification of functions of cellular structures in nature, adapted from (1)

Recent advances in software have made it feasible to design structures that incorporate intricate cellular structures and AM technologies have enabled these designs to be realized. However, it is not always apparent to the designer which cellular geometry is ideal for a specific function. This becomes particularly challenging when designing for multiple functional objectives. It is this challenge that we seek to address by using a biomimetic approach to help a designer select an appropriate cellular structure for a specific function and integrate it into a larger structure. We propose a four-level framework to integrate this biomimetic approach into an overall design and manufacturing strategy, as shown in Figure 3.

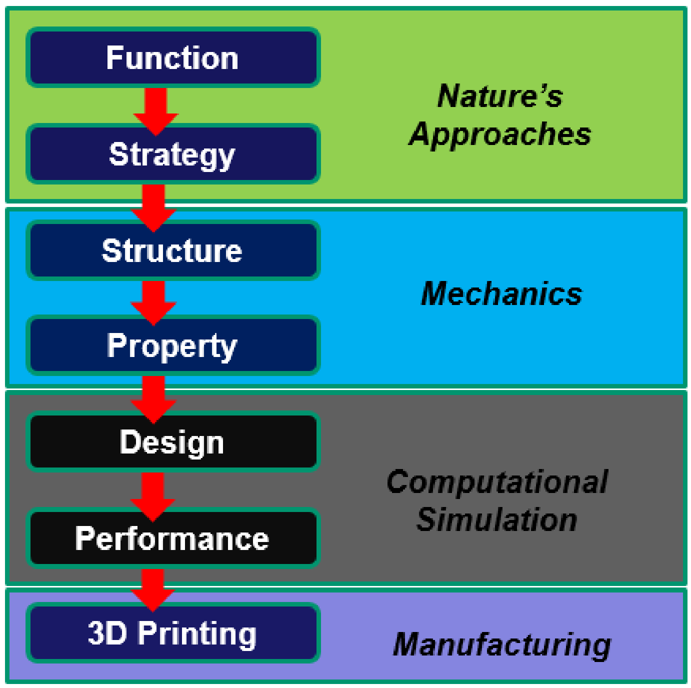


Figure 3. Proposed framework for implementing a biomimetic approach in the design and manufacturing of parts with cellular materials

In this paper, we seek to develop the top level of this framework. We first review the methodology we used to discover natural models (i.e. species in nature), and how this selection was narrowed in scope. Next, we present a set of candidate natural cellular design structures that we discovered, followed by a classification of these structures and the load-bearing functions that are of relevance to the design of engineering structures. Finally, we discuss limitations of this approach.

Methodology

While the use of biomimicry to address problems and uncover opportunities is not new, it is only more recently that a methodology for applying the subject systematically has emerged (2). The methodology can be used in two different ways: in the first approach, the solution to a specific challenge is sought in nature ("Challenge to Biology"). In the second approach, a study of the biological organism(s) leads the way to inspiring designs ("Biology to Design"). For this work, we used the first approach, but with the specific intent of finding examples of cellular materials in nature that manage structural forces effectively. With this approach, multiple design principles will emerge together to inform the design space. For our purposes, we define 'cellular' materials as those materials with a specific, repeating structure that forms the basis of the material itself. The specific steps we used in this work are as follows:

1. The "Challenge to Biology" approach enables the discovery of natural models which are relevant to our functional needs within contextual considerations. Through a wide survey of the available literature, we identified approximately 70 different natural models that were constructed at least partially of cellular materials, ranging from the well-known bee's honeycomb to the Venus' flower basket, a sea sponge that has a crack-arresting hierarchical lattice structure.
2. Having identified these models, we studied and vetted our selection in the literature against the function and context of interest to establish the nature of the cellular material (design strategy), as well as evidence of a functional basis for the structure in question (i.e., the function of the material was for providing support to the structure). In some cases this was a hypothesis bolstered with circumstantial observations, in others the structure's functionality was validated through experimental or numerical techniques. Some natural models were discarded from consideration since the causality between structure and function could not be robustly identified.
3. Finally, we narrowed the scope to examining how these specific cellular design strategies responded to, and managed, imposed loads. This is a non-trivial aspect of the work since many natural cellular models have arisen (over evolutionary time) for more than one function, and a sub-optimal solution for managing forces may exist a trade-off for another function, such as buoyancy or thermal management.

Natural Cellular Design Strategies

Our study of cellular materials in nature resulted in the identification of 11 models for which we identified adequate evidence of a causal link between observed structure and function, and further that this function was of a structural (load-bearing) nature. In our study, it emerged that cellular materials in nature could be broadly classified as being used to either fill space (3D), develop surfaces (2D) for protection, or use cellular design in cylindrical structures. These three categories align well with engineering structure design. We discuss these natural models for each of these three categories in turn.

1. 3D Space-Filling Structures

The most significant driver for the use of cellular materials with AM is their potential to reduce material usage and mass – this is critical for aerospace applications but also relevant for the wider transportation sector as well as for the biomedical and construction fields. Mass reduction is most effective when it is applied to as much of the structure in question, and is thus relevant for designing 3D space-filling structures.

Nature often seeks to minimize costly material usage, which has been described as one of "life's principles" (2). The specific strategy for minimizing mass for a particular organism is a function of the specific loading conditions the structure is aiming to withstand, which in turn is influenced by the context the structure is experiencing. In Table 1, we list 3 different examples of 3D space-filling with cellular materials in nature, along with references that discuss the biological basis for the structure in greater detail than is in scope for this discussion.

Table 1. Space-filling (3D) cellular materials in nature

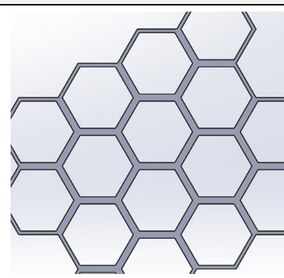
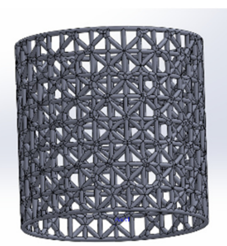
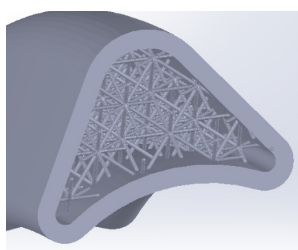
#	Organism / Organ	Cellular Material Representation	Design Strategies & Principles	Attributed Structural Benefit
i	Honey Bee Nest (*Apis*) 		Transversely isotropic and uniform hexagonal columns (1) (4)	High specific stiffness under self-weight (1)
ii	Venus Flower Basket (*Euplectella aspergillum*) 		Enclosed lattice struts (5)	Resilience to hydrostatic (compression) forces (5)
			Hierarchical structure (6) (7)	Crack growth arresting (6)
iii	Toucan Beak (*Ramphastidae*) 		Lattice struts & closed cell foam (8)	High flexural (bending) stiffness (8)

Image Attributions:

i. Honeycomb: public domain, no attribution available or needed

ii. Venus' Flower Basket: NOAA Okeanos Explorer Program, Gulf of Mexico 2012 Expedition

iii. Toucan: By Nicolas Billebault, via Wikimedia Commons

2. Surface (2D) Structures

Several engineering structures involve enclosing an entity in an external surface. These span a range of scales from spacecraft and submersible hulls to aerodynamic skinsuits for cyclists. In keeping with the overall scope of this paper, we limit ourselves here to the discussion of surface structures that excel at managing mechanical loads and have identified a few organisms in Table 2 that achieve this through different strategies.

Table 2. Surface (2D) cellular materials in nature

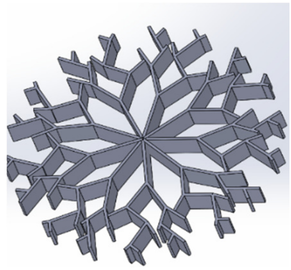
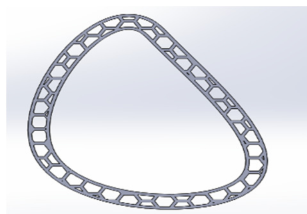
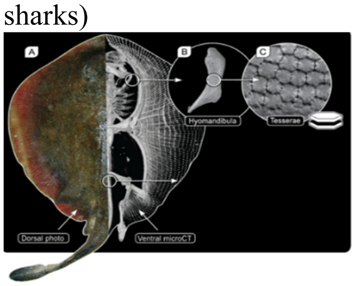
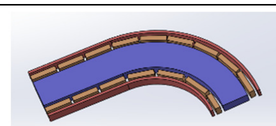
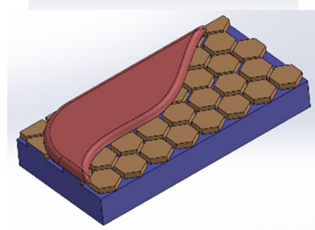
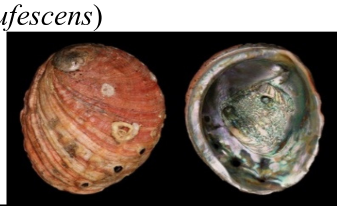
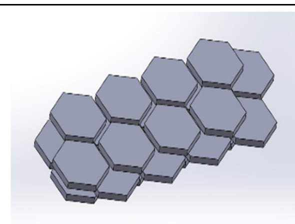
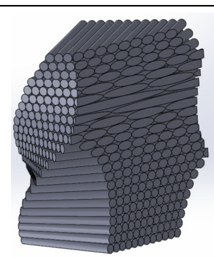
#	Organism / Organ	Cellular Material Representation	Design Strategies & Principles	Attributed Structural Benefit
i	Amazon Waterlily leaf underside (*Victoria amazonica*) 		Veining	Stiffness (9) (10)
ii	Pomelo skin (*Citrus maxim*) 		Open-cell foam (11) (12)	Impact resistance (11) (12)
iii	Elasmobranchii skeleton (rays, sharks) 	 	Uniform tessellation, Composite sandwich (13)	Bending flexibility (14)
iv	Red Abalone shell (*Haliotis rufescens*) 		Uniform tessellation, Composite sandwich (15)	Fracture toughness under tension (16)
v	Mantis Shrimp club (*Stomatopod*) 		Helical trusses Nanoparticle coating (17)	Impact resistance (17)

Image Attributions

i. *Amazon Waterlily: By Jojona, via Wikimedia Commons*
ii. *Pomelo: Allen Timothy Chang Starr, Forest & Kim Starr derivative work via Wikimedia Commons*
iii. *Elasmobranchii: Dean Mason (rights reserved), modified from Seidel et al.* (13)
iv. *Red Abalone: By Merlin Charon, via Wikimedia Commons*
v. *Mantis Shrimp: By Silke Baron, via Wikimedia Commons*

3. Cylindrical Structures

In addition to using cellular materials in constructing space-filling structures and surfaces, nature also leverages these materials for cylindrical structures, examples of which are shown in Table 3.

Table 3. Examples of cellular materials in cylindrical structures

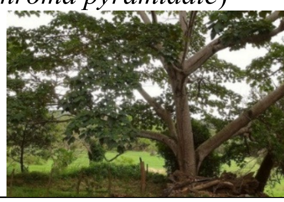
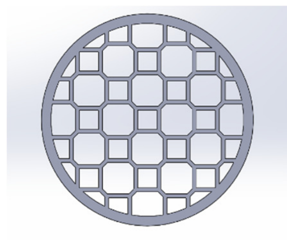
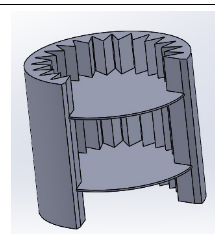
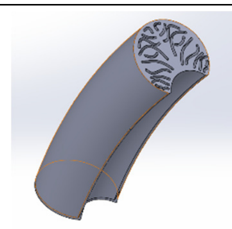
#	Organism / Organ	Cellular Material Representation	Design Strategies & Principles	Attributed Structural Benefit
1	Balsa trunk and branches (*Ochroma pyramidale*) 		Vertical hexagonal columns (1)	High stiffness under tension and shear (18) Strength under compression (19)
2	Hedgehog quill (*Erinaceinae*) 		Stiffeners (1)	Bending, ovalization and buckling resistance (20)
3	Banana petiole (*Musa textilis*) 		U-shaped structure Hierarchical partitions (21)	Bending stiffness Torsional flexibility (21)

Image Attributions

1. *Balsa Wood: Gabriele Kothe-Heinrich, via Wikimedia Commons*
2. *Hedgehog: By Lars Karlsson (Keqs), via Wikimedia Commons*
3. *Banana: public domain, no attribution available or required*

While many cylindrical structures in nature such as plant stems, serve a transport function, they are nonetheless also structured to resist bending, ovalization and buckling. As shown in Figure 4, these has led to a range of strategies for adding cellular designs within cylindrical structures to achieve these benefits.

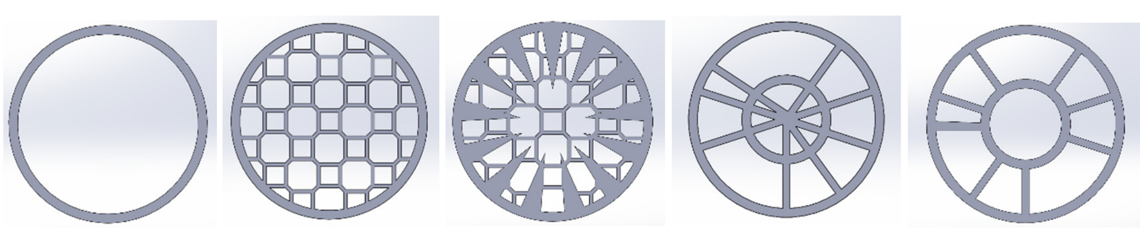


Figure 4. Design strategies for improving bending, ovalization and buckling resistance in cylindrical structures found in animal quills and plant stems, adapted from (20)

Biomimetic Cellular Materials Design

The main objective of this work is to propose a framework for the design of biomimetic cellular materials that can be integrated into the larger design and manufacturing system proposed in Figure 3. Towards this end, we need to identify the underlying patterns emerging from our biological models by using classifications that allow us to explore both the design options and the functional requirements. Finally, we need a framework that associates design and function to guide selection of a specific cellular design for a larger component. We deal with each of these three aspects in turn.

1. Classification of Design Options

There are several ways to classify cellular materials (22; 23; 3). In the context of the present work, we take our cues from nature and propose a separation based primarily upon the use of the material for either 2D (surface) or 3D (space-filling) purposes, while also identifying strategies that cut across both approaches. This classification is compiled in Figure 5, with self-explanatory representations of the associated geometry.

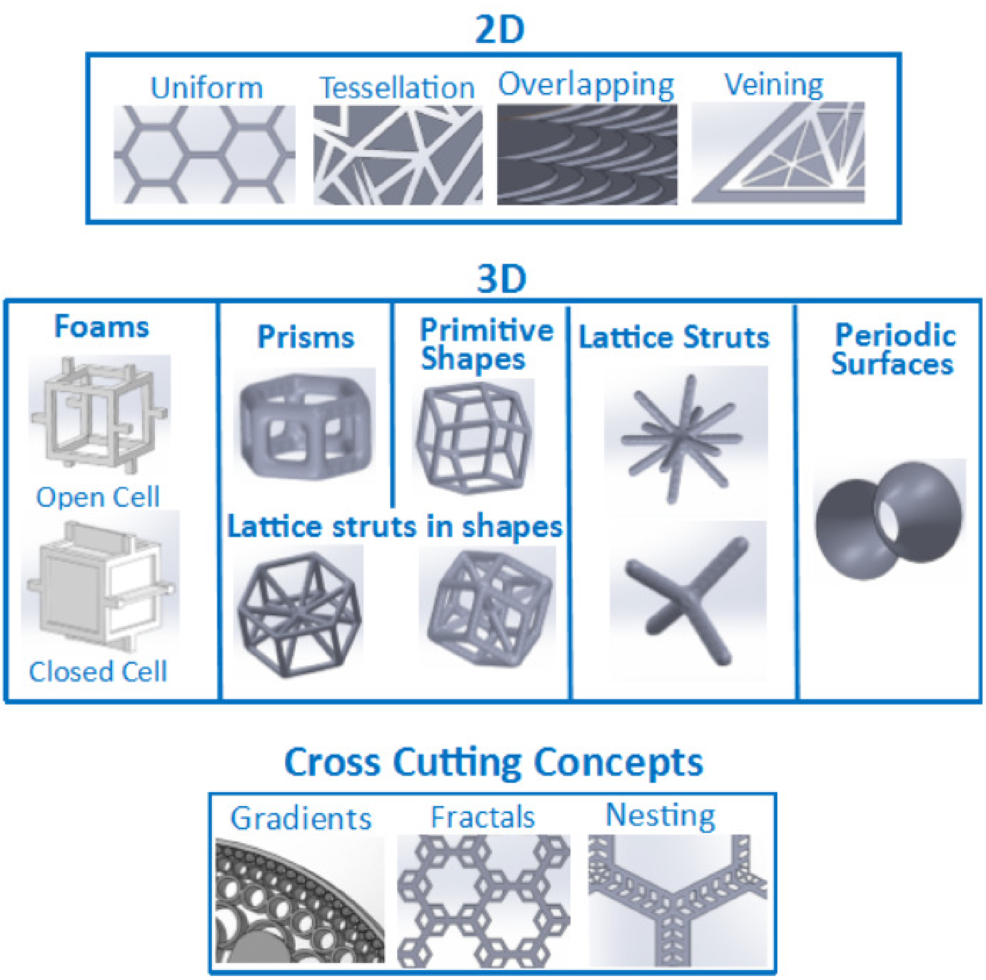
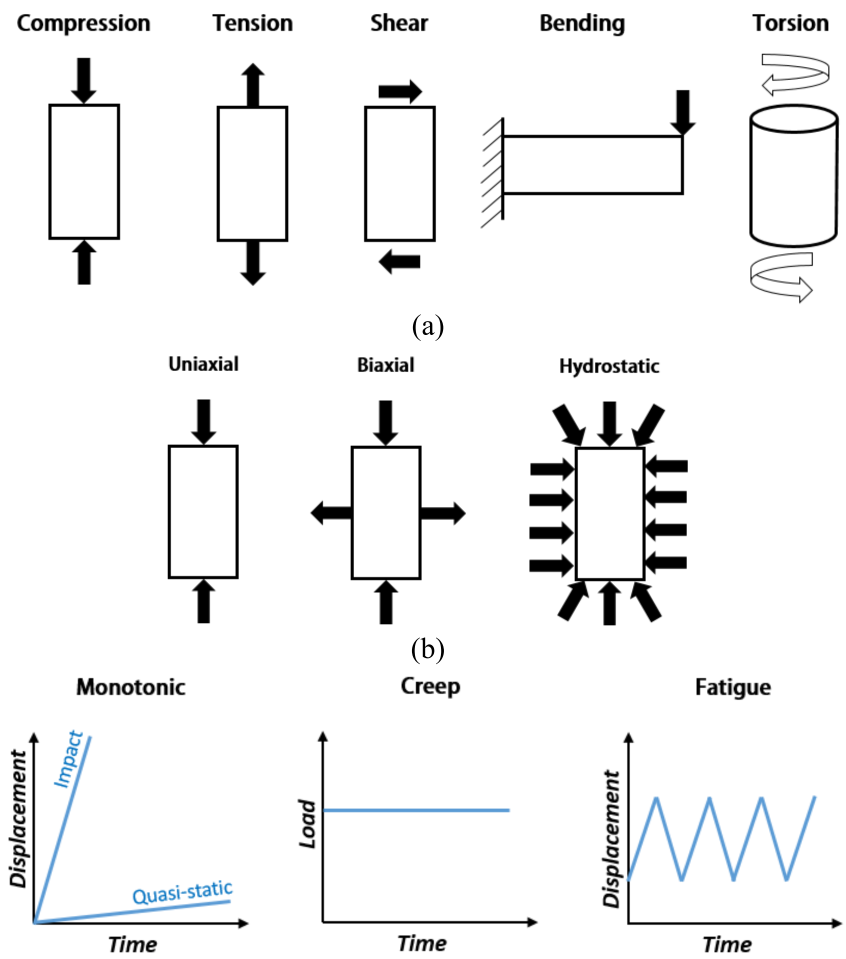


Figure 5. Proposed classification for cellular material designs, grouped in terms of 3D and 2D and cross-cutting concepts that apply to all cellular designs

2. Classification of Functions (Load-bearing)

Natural and manmade structures both perform one, or more, functions in a larger system. More fundamentally, however, a structure defines form and must have properties that enable it to retain this form while meeting functional requirements in its environment for the duration of its useful life. In engineering structures, the most important properties of interest are stiffness (or rigidity; the ability to resist permanent deformation), strength (the ability to resist buckling) and toughness (the ability to resist fracture). These properties are defined in context of the conditions experienced by the structure. With regard to the nature of loads, these are typically classified as compression, tension, torsion, bending and shear, or some combination of these (24). Further, these loads may be applied in one or many directions (such as uniaxial, biaxial and hydrostatic) and with different durations (such as varying strain rates, fatigue and vibration). Thus, the loading condition can be adequately described by specifying three pieces of information (see Figure 6):

1. Loading type
2. Loading direction, and
3. Period of application



(c)

Figure 6. Proposed classification for loading conditions: (a) Loading type, (b) loading direction and (c) period of application

3. Structure-Function Relationships

With the classification established for both cellular material design and load-bearing functions, the final step in developing a usable framework is to relate the two. In Table 4, we relate the function to the structure, which forms the basis of a design recommendation which we make limited to the organisms we identified in Tables 1-3.

Table 4. Structure-function design guidelines

Space-Filling (3D)				
Function			***Structure***	
Loading Type	***Loading Direction***	***Period of Application***	***Cellular Design***	***Additional Design Concepts***
Tension or Compression	In-plane	Static	Hexagonal honeycomb	Align plane of loading along isotropic plane of honeycomb
Compression	Hydrostatic	Dynamic, Fatigue	Enclosed lattice struts	Hierarchy to improve fracture toughness
Bending	Multi-axial	Impact	Mix of open and closed cell foam	Stiffness and energy absorption co-optimized
Surface (2D)				
Function			***Structure***	
Loading Type	***Loading Direction***	***Period of Application***	***Cellular Design***	***Additional Design Concepts***
Bending	Uniaxial	Static, Dynamic	Veining	Vein thickness per Murray's Law (25)
Compression	Multi-axial	Impact	Open cell foam	
Bending	Multi-axial	Fatigue	Tessellation	Composite sandwich
Tension	Multi-axial	Static, High Strain Rate	Tessellation	Composite sandwich
Compression	Uniaxial	Impact	Helical trusses	Nanoparticle coating
Cylindrical Structures				
Function			***Structure***	
Loading Type	***Loading Direction***	***Period of Application***	***Cellular Design***	***Additional Design Concepts***
Bending	Multi-axial	Static, Dynamic	Hollow cylinder	-
Ovalization	Multi-axial	Static, Dynamic	Hexagonal columns	Addition of transverse stiffeners
Buckling	Uniaxial	Static	Longitudinal stiffeners	Removal of central unstressed core

Considerations

The key research objective sought in this work has been to assess the feasibility of developing a framework to guide the design of cellular materials for use in parts to be manufactured using additive manufacturing. We have attempted to synthesize principles from several different natural models and while we have demonstrated that much is to be gained from such an approach, it is important to stress a few considerations that need addressing prior to implementation in design and manufacturing.

1. Uniquely Biological Considerations

A key challenge faced by living organisms is the need to grow, and in several cases, the maintenance of function *during* growth (24). It is feasible that a specific structure is sub-optimal for a specific engineering application since it was constrained by this need. Another challenge with the biomimetic method is the de-confounding of the functional basis for structure since natural structures are often compromises for more than one (sometimes competing) function(s), and identification of the "weights" of optimization for these objectives is non-trivial. In some cases, the effects of evolutionary baggage also result in sub-optimal design, where features are retained through evolution despite their inadequacies since they either have low inherent costs, or it was less expensive to make a particular compromise: the giraffe's convoluted Recurrent Laryngeal Nerve (RLN) is one such example (26). This highlights the importance of extracting underlying principles, as we have sought to do here, rather than emphasizing one-off discoveries.

2. Additive Manufacturing Constraints

While AM processes greatly expand the possibilities for manufacturing parts with cellular materials, they do have additional constraints (i.e., 'design rules') that limit the selection of cellular material designs. These constraints include:

- Smallest feature size attainable (typically in the hundreds of microns for most production-scale machines)
- Largest overhang in lattice-like cellular materials
- Need for support in most processes, which constrains the cellular design to be self-supporting
- Need for removing trapped powder, in powder bed processes, constraining the smallest size of voids possible in 3D structures

These constraints need to be fully comprehended prior to the selection of a cellular material design.

3. Hierarchy, Gradients and Multi-Materials

Cellular materials are just one of many design strategies found in nature (23). Cellular materials themselves consist of multiple materials such as the examples of the abalone shell and mantis shrimp club discussed previously, which currently still poses a challenge for functional part additive manufacturing. Additionally, cellular materials often have functional gradients or a hierarchy of structure at varying scales, several of which may be below the ability of AM processes to resolve. Nonetheless, as AM technologies improve, it is likely that an increasing number of biomimetic designs are rendered feasible.

Conclusions

In this paper, we have demonstrated how a biomimetic approach can be used to enable the selection of cellular material designs for structural load-bearing applications. Our work has led us to draw the following conclusions:

- Employing the biomimicry methodology of scoping and discovering complimentary models allows for a "Challenge to Biology" approach to identifying biological structures of interest
- Nature tends to employ cellular materials in structural applications in three categories that align well with engineering design thinking: space-filling (3D), surface (2D) or cylindrical structures
- Natural models tend to demonstrate hierarchy and the use of multiple materials, along with cellular material designs to achieve a specific performance
- Defining a classification for cellular material structure and load-conditions, as we have done here, enables the formulation of a structure-function relationship that is the first step to developing an integrated framework for designing biomimetic cellular structures

In ongoing and future work, we are seeking to use computational simulation to validate these biomimetic design concepts, which is a key step in developing a quantifiable correlation between structure and performance. This in turn, has the potential to unlock the ability to enable true multifunctional cellular materials design.

References

1. **L. Gibson, M. Ashby, B. Harley.** *Cellular Materials in Nature and Medicine.* s.l. : Cambridge University Press, 2010, 1st Edition.

2. **Baumeister, D.** *Biomimicry resource handbook: a seed bank of best practices.* Missoula, MT : Biomimicry 3.8, 2014.

3. **Ashby, Evans, Fleck, Gibson, Hutchinson, Wadley.** *Metal Foams: A Design Guide.* s.l. : Butterworth-Heinemann, 2000, 1st Edition.

4. *Bioinspired engineering of honeycomb structure – Using nature to inspire human innovation.* **Zhang, Qiancheng, et al.** 2015, Progress in Materials Science, Vol. 74, pp. 332-400.

5. *Siliceous spicules and skeleton frameworks in sponges: Origin, diversity, ultrastructural patterns, and biological functions.* **Uriz, M., et al.** 4, 2003, Microscopy Research and Technique, Vol. 62, pp. 279-299.

6. *Skeleton of Euplectella sp.: Structural Hierarchy from the Nanoscale to the Macroscale.* **Aizenberg, J.** 5732, 2005, Science, Vol. 309, pp. 275-278.

7. *Hierarchical assembly of the siliceous skeletal lattice of the hexactinellid sponge Euplectella aspergillum.* **Weaver, James C., et al.** 1, 2007, Journal of Structural Biology, Vol. 158, pp. 93-106.

8. *The toucan beak: Structure and mechanical response.* **Seki, Yasuaki, et al.** 2006, Materials Science and Engineering C, Vol. 26, pp. 1412-1420.

9. *Victoria regia's bequest to modern architecture.* **Nielsen, D.** 2010, Design and Nature V, Vol. 138

10. **Attenborough, D.** *The Private Life of Plants.* s.l. : Princeton University Press; 1st edition, 1995.

11. *Structure–function relationship of the foam-like pomelo peel (Citrus maxima)—an inspiration for the development of biomimetic damping materials with high energy dissipation.* **M Thielen, C N Z Schmitt, S Eckert, T Speck and R Seidel.** s.l. : Bioinspiration & Biomimetics, 2013, Vol. 8. 2.

12. *Pummelos as Concept Generators for Biomimetically Inspired Low Weight Structures with Excellent Damping Properties.* **Fischer, Sebastian F., et al.** 12, 2010, Advanced Engineering Materials, Vol. 12.

13. *Ultrastructural and developmental features of the tessellated endoskeleton of elasmobranchs (sharks and rays).* **Seidel, R., Lyons, K., Blumer, M., Zaslansky, P., Fratzl, P., Weaver, J., & Dean, M.** 5, s.l. : Journal of Anatomy, 2016, Vol. 229.

14. *Mechanics of shark tessellated cartilage [dissertation].* **Liu, X.** s.l. : ProQuest LLC, 2012.

15. *Growth and structure in abalone shell.* **Lin, Albert and Meyers, Marc Andre.** 390, 2004, Materials Science & Engineering A, pp. 27-41.

16. *An Experimental Investigation of Deformation and Fracture of Nacre – Mother of Pearl.* **F. Barthelat, H. D. Espinosa.** 3, s.l. : Experimental Mechanics, 2007, Vol. 47.

17. *Deadly strike mechanism of a mantis shrimp.* **Patek, S. N., Korff, W. L. and Caldwell, R. L.** 6985, 2004, Nature, Vol. 428, pp. 819-820.

18. *Structure–property relations for balsa wood as a function of density: modeling approach.* **O. Shishkina, S. Lomov, I. Verpoest, L. Gorbatikh.** s.l. : Arch Appl Mech, 2014, Vol. 84.

19. *Compressive response and failure of balsa wood.* **Silva, Andre Da and Kyriakides, Stelios.** 25-26, 2007, International Journal of Solids and Structures, Vol. 44, pp. 8685-8717.

20. *Biomimicking of animal quills and plant stems: natural cylindrical shells with foam cores.* **G. Karam, L. Gibson.** s.l. : Materials Science and Engineering C2, 1994.

21. *The functional morphology of the petioles of the banana, Musa textilis.* **Ennos, A.r.** 353, 2000, Journal of Experimental Botany, Vol. 51, pp. 2085-2093.

22. **L. Gibson, M. Ashby.** *Cellular Solids: Structure and Properties.* s.l. : Cambridge University Press, 1999 (2nd Edition).

23. *Structural Design Elements in Biological Materials: Application to Bioinspiration.* **Naleway, Steven E., et al.** 37, 2015, Advanced Materials, Vol. 27, pp. 5455-5476.

24. **Vogel, S.** *Cat's Paws and Catapults: Mechanical Worlds of Nature and People.* s.l. : W. W. Norton & Company, Inc., 1998.

25. *The physiological principle of minimum work. I. The vascular system and the cost of blood volume.* **Murray, C.** s.l. : Proc. Natl. Acad. Sci., USA, 1926, Vol. 12.

26. **Dawkins, R.** *The Greatest Show on Earth: the evidence for evolution.* s.l. : Free Press, 2010, 1st edition.