DIATOMA: A BIOMIMETIC FABRICATION-AWARE LIGHTWEIGHT PAVILION

SHABNAM LOTFIAN[1], MÜGE BELEK FIALHO TEIXEIRA[2], JARED DONOVAN[3] and GLENDA CALDWELL[4]
[1,2,3,4] Queensland University of Technology (QUT)
[1] Building 4.0 CRC, Caulfield East, 3145, Victoria, Australia
[1]f.lotfian@qut.edu.au, 0009-0007-4822-2314
[2]muge.teixeira@qut.edu.au, 0000-0003-0593-9597
[3]j.donovan@qut.edu.au, 0000-0002-8025-1947
[4]g.caldwell@qut.edu.au, 0000-0003-0837-9310

Abstract. Rethinking conventional design and fabrication methods, this research presents a biomimetic fabrication-aware design workflow for building a lightweight pavilion. Exploring different natural organisms reveals that the optimized structures of diatoms (unicellular microalgae) could serve as a biological model to design a load-responsive lightweight pavilion. The interdisciplinary research outcome primarily involves translating diatoms' structural and symbolic logic to component modules populated on a given free-form shell. The generative design workflow enables the designer to continuously monitor quantitative metrics such as deflection, span length, number of components and joints, size and depth of components, and weight. The model is tightly intertwined with structural analysis and optimization results. The design algorithm utilizes Rhino, Grasshopper, incorporating essential plugins such as Karamba, Octopus, and Kangaroo. The proposed fabrication method is Robotic Incremental Sheet Forming (RISF), and the material is ultra-thin aluminum sheets (0.3 mm thickness). This paper's focus is on the design phase of the research.

Keywords. Biomimetic design, Diatom, Generative design, load-responsive shell, fabrication-aware design, Lightweight pavilion.

1. Introduction

Sustainability and efficiency are the main reasons for designing lightweight and optimum structures. The construction industry is the main sector that has a direct effect on the rate of material consumption and construction waste (Peng et al., 2022). Moreover, rapid urbanization necessitates a significant enhancement in the efficiency of design and fabrication. To avoid relying on repetitive design and the monotony of building practices from the previous century, it is imperative to adopt new methods. The objective is to build more with fewer resources (Menges & Knippers, 2020).The

ACCELERATED DESIGN, Proceedings of the 29th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2024, Volume 3, 191-200.

increasing significance of optimising material utilisation and advancements in design and fabrication tools resulted to a growing interest in lightweight structures (Plocher & Panesar, 2019).

Throughout the evolution process biological organisms have developed multifunctional solutions to adapt to the ever-changing environmental conditions by means of selection and interaction (Knippers & Speck, 2012). The materialization process in nature unfolds in a systematic evolution of form, structure, and performance. (Naboni et al., 2019) (Heil et al., 2023) As J. Vincent mentioned "in biology material is expensive but shape is cheap (the opposite is true in the case of technology)"(Vincent, 2009). Nature employs strategies that involve generating forms that maximise performance while using minimal resources, achieved through the variation of local material properties (Menges, 2012b). Nature's approach involves eliminating unnecessary material from specific regions and efficiently repurposing it in areas subjected to high strain levels (Naboni et al., 2019).

Biomimetic research is a consequence process including various analysis scales such as macro, meso, and microscale. The macroscale refers to structure's topology, the mesoscale to the components suited for discretising the global shape, and the microscale to the process of settling the structure based on changeable criteria, such as porosity. In summary, the concept of Macroscale encompasses the definition of structure and topology, while Mesoscale addresses components and assembly. At the Microscale, the focus shifts to material deposition and porosity. (Figliola & Battisti, 2020) (Ayres et al., 2014).

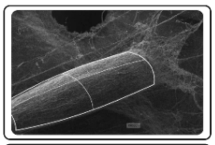
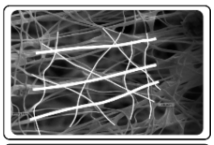
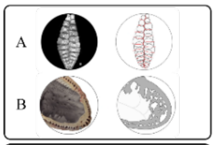
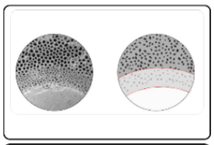
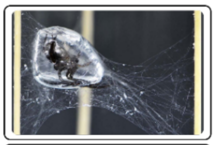
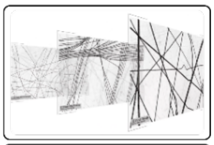
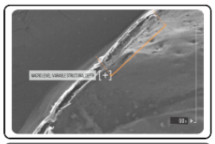
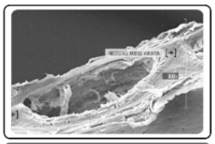
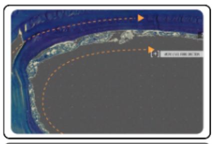
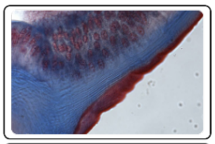
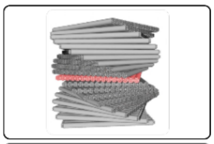
1.1. BIOMIMETIC STRUCTURES FROM PAST TO PRESENT

Throughout history, architects and structural engineers have frequently drawn inspiration from the natural world (Sabin & Jones, 2017). However, while there have been some successful instances of bio-inspiration, the majority are mainly limited to forms and ornaments (Dixit & Stefańska, 2023). Exploring recent biomimetic structures shows that ICD/ITKE research pavilions showcase the incorporation and integration of biological principles, design constraints material behaviour, structural capacities and robotic fabrication (Solly et al., 2018). This integration considers weight, as well as manufacturing, and assembly process. Therefore, the concept of lightweight construction is being redefined in a novel and more inclusive manner (Menges & Knippers, 2020). These pavilions have demonstrated success in the realm of biomimetic design and fabrication. Certain earlier research pavilions were composed of carbon fiber, which is lightweight but lacks recyclability. Their shift to natural fibers and timber in their recent projects underscores the importance of incorporating environmentally friendly materials in the biomimetic projects.

1.1.1. Biomimetic Structural Analysis

The Table 1 compares the levels of inspiration drawn from biological role models in the ICD/ITKE pavilions. It is evident that the majority of the pavilions draw inspiration from all three scale levels (Macro, Meso, Micro). However, in the case of the ICD/ITKE Research Pavilion 2014-15, the design is approached holistically, lacking distinct components and joining systems. As a result, the Meso and micro levels appear to be merged to some extent (Table 1). It can be understood that not all structural forms would enable researchers to incorporate inspiration from all three levels in the design.

Table 1: comparison of the levels of inspiration in the design of the ICD/ITKE pavilions

Pavilion	Macro	Meso	Micro
			
Pavilion 2016/17 Inspiration: Leaf Miner Moths	Bent Leaf	Volumetric Winding	Fiber Directionality
			
Pavilion 2015-16 Inspiration: Sea Urchin	A: Plate Growth B: Double Layer	Fiber & Finger Joint Connections	Material Differentiation
			
Pavilion 2014-15 Inspiration: Water Spider	Hydrophobic Surface Traps Air		Internal Fiber Reinforcement
			
Pavilion 2013-14 Inspiration: Elytron	Variable Structural Depth	Module Variation	Fiber Direction
			
Pavilion 2012 - Inspiration: Arthropods' Exoskeletons	Functional Integration	Material Differentiation	Hierarchical Material Organization

1.2. FABRICATION-AWARE DESIGN WORKFLOW

The growing interest in biomimetic design can primarily be attributed to advancements in computational design tools and robotic fabrication techniques, which caused a shift from form-designing to form-finding (Dixit & Stefańska, 2023). Generative design techniques arise as reflections of natural systems, not as mere imitations, but as a transdisciplinary interpretation of adaptability, growth, and complexity in architectural forms (McCormack et al., 2004). These advancements enable designer to simulate nature and test the natural responses and allow pathways for interdisciplinary research

((Menges, 2012a) Menges & Knippers, 2015). Robotic fabrication process is highly linked to the digital model, enabling rapid evaluation and comparison of various design options, assisting designers in adapting to the era of accelerated changes.

The Design-to-Fabrication (DtF) workflow is crucial for bridging the gap between the design and fabrication phases. This integration results in enhanced accuracy and customization (Skoury et al., 2024). The contemporary design and construction process commences with architects' spatial concepts, followed by engineers' technical processing, workshop prefabrication, and construction site implementation. This linear and hierarchical process must be dismantled to release true innovations that go beyond incremental efficiency improvements of existing design methods. Creating something new necessitates considering different project aspects from the outset and how they mutually influence one another (Menges & Knippers, 2020).

To design innovative and efficient structures, a holistic approach is necessary, involving iterative design process informed by material and fabrication techniques, guided by the computational designer. This biomimetic fabrication-aware design workflow introduces fabrication considerations and constraints as well as material dimensions into the design process to suggest a load-responsive lightweight structure by employing diatoms' principles. The DtF process aims to using material efficiently by designing with and for the proposed fabrication technique (RISF).

1.3. ROBOTIC INCREMENTAL SHEET FORMING (RISF)

Incremental Sheet Forming (ISF) transforms planar 2D metal sheets into 3D complex double curved geometries without any mould or die by means of a ball head end effector that goes through predefined paths (CUI et al., 2022). Single point sheet forming (SPIF) and double point sheet forming (DPIF) are two methods used in RISF. (Lublasser et al., 2016). RISF is a practical and feasible method to fabricate complex, arbitrary and double-curved shells as architectural cladding. In comparison with developable surfaces with multiple joints, it has the potential to fabricate self-supporting panels with different geometries (Kalo & Newsum, 2014). By stretching the sheet material, the overall geometry changes and the thickness decreases, which causes significant change in the field of lightweight skins. For instance, in a stressed skin formed by ISF, while the thickness decreases almost by 3.3 times (from 0.5 to 0.15 mm), the strength grows by almost 1.9 (from 220 to 410 MPa) (Nicholas et al., 2016).

2. Methods

This research employs a biomimetic and generative design methods. Biomimetic design includes Diatom analysis. The generative design workflow transforms biomimetic ideas to a digital model and includes 5 main steps: Form finding, Structural evaluation, structural optimization, discretization, and component design. In the following sections we present steps that adapt a free-form shell to a load responsive lightweight structure.

2.1. DIATOM ANALYSIS

The architecture of the diatom frustules and the composition of the silica are the reasons for forming the lightweight structure of diatoms. The lightness of diatoms is because of prevention of rapid sinking, limited resources, or the need to move efficiently (Hamm, 2015). By analysing scanning electron microscope (SEM) images of diatoms we realized regardless of their shape or size, the hard but lightweight, porous multi-layer structures of diatoms are unique features that can be translated into design parameters for a lightweight structure (Figure 1).

Diatoms are often treated as individual cells in most ecological models, disregarding the significance of their chain formation. Experimental studies demonstrate that in environments with increased turbulence, diatoms have a tendency to form longer chains (Macro scale) (Kenitz et al., 2020). The diatom silica, also known as frustule structure, is primarily composed of pure silica, serving as a protective covering for cells. It consists of two valves that are bound together by girdle bands, which encircle and hold them in place (meso scale). Each valve is comprised of stacked hexagonal chambers separated by silica plates. (Zhang, 2019) And in many species they have an uneven undulating valve surface (micro).

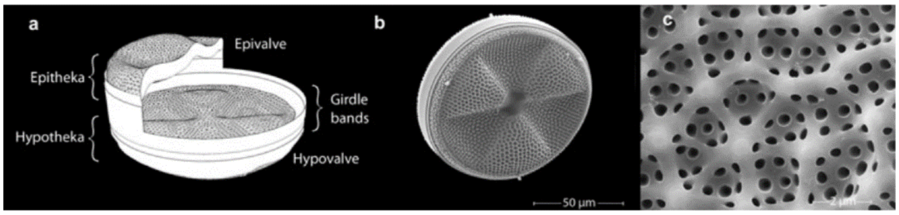


Figure 1: (a)A schematic 3D model of a frustule from Actinoptychus senarius. (b) SEM image depicting the entire frustule. (c) Frustule surface's detail. (Friedrichs et al., 2012)

2.2. FABRICATION-AWARE DESIGN WORKFLOW

The design workflow was tightly intertwined with structural analysis and structural optimisation to improve material efficiency. The numerical values for the evaluation criteria used to rank top solutions of the optimizations are weight, deflection, number of components and number of joints (Figure).

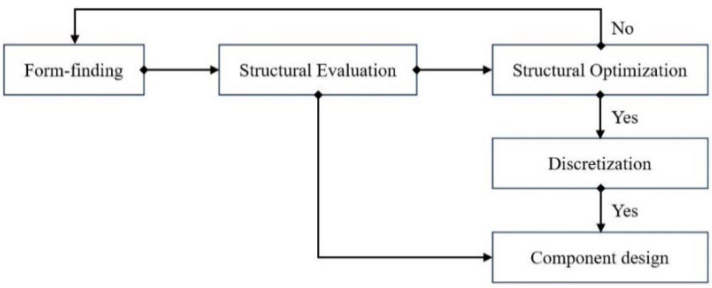


Figure 2: Design workflow

2.2.1. Form-finding

The form-finding process is closely tied to structural optimization and involves defining a generic shell structure through the lofting of three arches, with two at the ends and one in the middle. The size and location of these arches were treated as variables within an acceptable range for optimization purposes. The design workflow was developed to facilitate the adoption of various shell geometries for discretization. Within the available design space, two squares measuring 1m x 1m were defined as boundaries for the location of the start and end points of each arch. The height and rotation of each arch are treated as variables. In the formulation of the model, the minimum and maximum ranges were established to filter unacceptable solutions during the optimization process. The minimum dimensions are three meters in length, two meters in width, and a height of 2.2 meters at its center peak. The dimensions were chosen to ensure that at least one person could pass through the middle of the shell. The maximum sizes are limited by optimization process (Figure 4a).

2.2.2. Structural evaluation & optimization

Through the optimization process, the structural properties of each shell, including weight and deflection, were evaluated. These parameters obtained from the Karamba plugin the optimization itself was carried out using the Octopus plugin. The fitness function aimed to minimize both the weight and deflection of the shell, ensuring it remained sufficiently robust to allow the passage of a person beneath it. During the optimization process, thousands of different forms were generated and one from the top 10 fittest solutions was selected based on aesthetic considerations (Figure 4b).

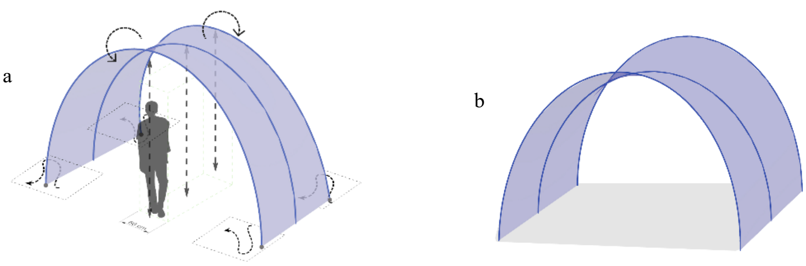


Figure 4 (a) design parameters for form-finding, (b) optimized shell

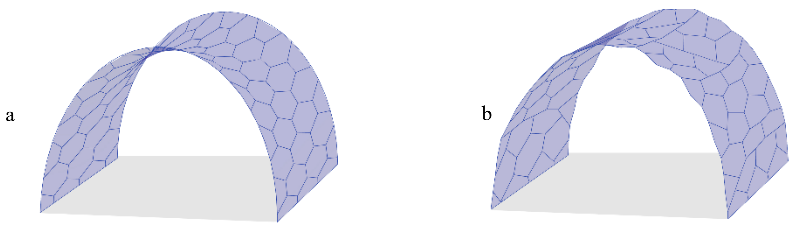


Figure 2: (a) Hexagonal subdivision (b) planarized panels-boundary of components

2.2.3. Discretization

Triangular, square, and hexagonal patterns were considered for discretization, with the hexagonal pattern ultimately chosen for subdivision due to its structural integrity and assembly feasibility. Another reason for this choice was the hexagonal-ordered structures on the valve surfaces of diatoms. To facilitate fabrication, the hexagonal panels were planarized using the Kangaroo plugin, causing the component boundaries to transform from regular hexagons to irregular and in some cases concave polygons. By introducing the width of the aluminum sheets (30 and 45 cm) as a constraint for panel sizes, we determined the number of panels and joints (Figure 2**Error! Reference source not found.**).

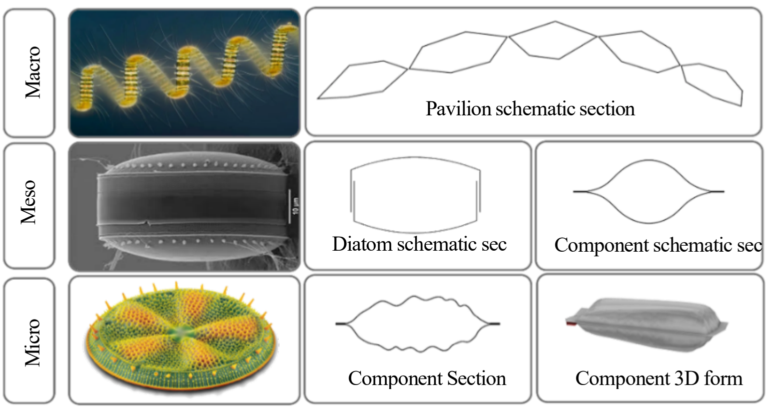
2.2.4. Component design

The influence of diatoms is evident throughout the various levels of design and specifically at component design. As it was mentioned earlier, diatoms consist of two halves. This structural pattern was adopted for the design of the components of the pavilion. By employing the RISF, incorporating components in two halves instead of flat components increase the moment of inertia significantly with the minimum required material. The results from shell discretization delineated the boundaries of the components (Figure 2b), and the analysis of load distribution within the selected shell determined the depth and form of the components (Figure 5).

3. Diatoma

In Diatoma, translation occurred across macro, meso, and micro scales. Starting at the macro scale, the concept of defining an elongated form for the pavilion, resembling chains formed by a series of diatoms, emerged from examining their inclination to develop short colonies, thereby shaping the global topology. Transitioning to the mesoscale, the hexagonal components were composed of two halves, following the primary principle of diatoms. Lastly, at the microscale the focus was on further enhancing surface moment of inertia while reducing material consumption and weight. Depending on the components' proximity to force flows, certain areas on their surfaces exhibit greater depth, resulting in an undulated surface (**Error! Reference source not found.**)

Table 2 Applying structural principles of diatoms to design parameters at different scales



The primary depth of each valve of component is determined by the number of intersection points between tension and compression load paths in each cell (Figure 5a). As the number of intersection points increases, so does the depth of the component (Figure 5b). The ultimate components surface features variable depths resembling the undulating surface of the diatoms, which further enhances their depth. The primary surface of each side of the components is initially convex, and it is populated with points. The proximity of these points to the compressive load paths defines surface undulation (Figure 5c). Points that are closer to the load path lines experience a greater displacement from their base location in the intended direction (Figure 6).

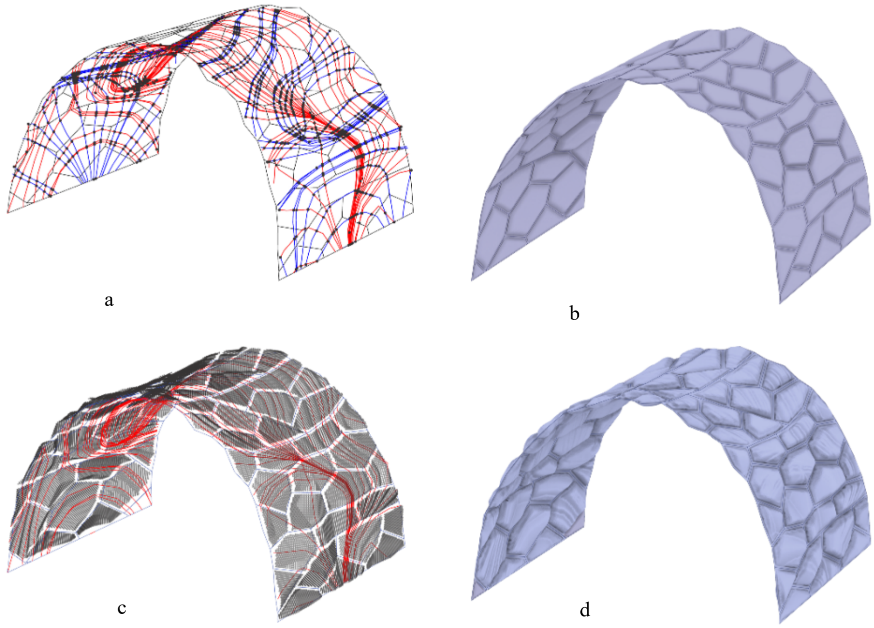


Figure 5 (a)intersection of tension and compression load paths in each cell; (b)convex component surface; (c) dislocation of points based on their proximity to the compressive load paths (d) undulated component surface

4. Discussion

This research proposes a biomimetic fabrication-aware design workflow for designing a load responsive shell. The translation of the diatoms to a lightweight structure is on a macro, meso, and micro scale. The design process stages are inherently linked and inform each other. The base shell geometry can be modified to accommodate different forms with minor adjustments, allowing subsequent stages to be adapted to create a lightweight, self-standing structure. This is similar to the mechanism observed in diatoms, which strategically allocates materials to regions where they are most required. The generative design workflow enables the researcher to comprehend the correlation between the values and the relevant parameters, facilitating modification and calculation of the optimal settings and considering fabrication considerations and material specifications as design parameters. Considering materiality in the initial stages of the design and designing with and for it is more beneficial than imposing it on a predetermined structure. Integration of design and fabrication leads to a more precise outcome compared to current linear design processes. The innovation in designing the Diatoma Pavilion offers opportunities for significantly reducing material consumption and construction waste generation.

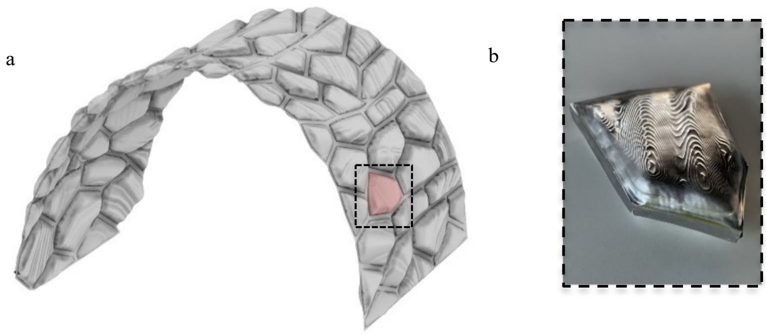


Figure 6 a) Diatoma Pavilion, b) A prototype of the highlighted component

The translation of identified principles into design parameters necessitates various levels of abstraction. Natural organisms differ from man-made structures mainly in scale and material composition. Throughout this transition, designers strive to remain faithful to the fundamental principles of nature. However, due to the aforementioned distinctions, coupled with fabrication constraints, the inevitability of sacrificing elements from the natural model arises. The final lightweight structure is materially efficient compared to conventional models, which is a significant achievement. Nevertheless, it still differs from the perfect image of nature's structures.

The design workflow iteratively refines based on physical prototype evaluations. However, for real-world applications, future work aims to fabricate the structure and conduct physical validation on an architectural scale. The design is flexible and can be used for a range of spans, suitable for various purposes such as covering, cladding, or temporary structures. To ensure long-term durability in open-space environments, further research is essential. It's worth noting that RISF allows for cost-efficient production of customized parts compared to other sheet metal forming processes.

Acknowledgements
This research is supported by Queensland University of Technology and Building 4.0 CRC. The support of the Commonwealth of Australia through the Cooperative Research Centre Program is acknowledged.

References

Ayres, P., Støy, K., Stasiuk, D., & Gibbons, H. (2014). Multi-Scalar shape change in pneumatically steered tensegrities. FABRICATE 2014,

CUI, Q., PAWAR, S. S., HE, M., & YU, C. (2022). FORMING STRATEGIES FOR ROBOTIC INCREMENTAL SHEET FORMING CAADRIA,

Dixit, S., & Stefańska, A. (2023). Bio-logic, a review on the biomimetic application in architectural and structural design. Ain Shams Engineering Journal, 14(1), 101822.

Figliola, A., & Battisti, A. (2020). Post-Industrial Robotics: Exploring Informed Architecture. Springer Nature.
Friedrichs, L., Maier, M., & Hamm, C. (2012). A new method for exact three-dimensional reconstructions of diatom frustules. Journal of Microscopy, 248(2), 208-217.
Hamm, C. (2015). Evolution of lightweight structures: analyses and technical applications (Vol. 6). Springer.
Heil, N., Perricone, V., Gruber, P., & Guéna, F. (2023). Bioinspired, biobased and living material designs: a review of recent research in architecture and construction. Bioinspiration & biomimetics.
Kalo, A., & Newsum, M. J. (2014). An investigation of robotic incremental sheet metal forming as a method for prototyping parametric architectural skins. In Robotic fabrication in architecture, art and design 2014 (pp. 33-49). Springer.
Kenitz, K. M., Orenstein, E. C., Roberts, P. L., Franks, P. J., Jaffe, J. S., Carter, M. L., & Barton, A. D. (2020). Environmental drivers of population variability in colony-forming marine diatoms. Limnology and Oceanography, 65(10), 2515-2528.
Knippers, J., & Speck, T. (2012). Design and construction principles in nature and architecture. Bioinspiration & biomimetics, 7(1), 015002.
Lublasser, E., Braumann, J., Goldbach, D., & Brell-Cokcan, S. (2016). Robotic forming: rapidly generating 3d forms and structures through incremental forming.
McCormack, J., Dorin, A., & Innocent, T. (2004). Generative Design: A Paradigm for Design Research.
Menges, A. (2012a). Biomimetic design processes in architecture: morphogenetic and evolutionary computational design. Bioinspiration & biomimetics, 7(1), 015003 %@ 011748-013190.
Menges, A. (2012b). Material computation: Higher integration in morphogenetic design. John Wiley & Sons.
Menges, A., & Knippers, J. (2015). Fibrous tectonics. Architectural Design, 85(5), 40-47.
Menges, A., & Knippers, J. (2020). Architecture Research Building: ICD/ITKE 2010-2020. Birkhäuser.
Naboni, R., Breseghello, L., & Kunic, A. (2019). Multi-scale design and fabrication of the Trabeculae Pavilion. Additive Manufacturing, 27, 305-317.
Nicholas, P., Stasiuk, D., Nørgaard, E., Hutchinson, C., & Thomsen, M. R. (2016). An integrated modelling and toolpathing approach for a frameless stressed skin structure, Fabricated using robotic incremental sheet forming. In Robotic fabrication in architecture, art and design 2016 (pp. 62-77). Springer.
Peng, Z., Lu, W., & Webster, C. (2022). If invisible carbon waste can be traded, why not visible construction waste? Establishing the construction waste trading 'missing market'. Resources, Conservation and Recycling, 187, 106607.
Plocher, J., & Panesar, A. (2019). Review on design and structural optimisation in additive manufacturing: Towards next-generation lightweight structures. Materials & Design, 183, 108164. https://doi.org/https://doi.org/10.1016/j.matdes.2019.108164
Sabin, J. E., & Jones, P. L. (2017). Labstudio: design research between architecture and biology. Routledge.
Skoury, L., Treml, S., Opgenorth, N., Amtsberg, F., Wagner, H. J., Menges, A., & Wortmann, T. (2024). Towards data-informed co-design in digital fabrication. Automation in Construction, 158, 105229.
Solly, J., Frueh, N., Saffarian, S., Prado, M., Vasey, L., Felbrich, B., Reist, D., Knippers, J., & Menges, A. (2018). ICD/ITKE Research Pavilion 2016/2017: integrative design of a composite lattice Cantilever. Proceedings of IASS Annual Symposia,
Vincent, J. (2009). Biomimetic patterns in architectural design. Architectural Design, 79(6), 74-81.