Bio-inspired Lamellar Structures: Studio One Research Pavilion 2018

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ABSTRACT
Gaining rigidity and strength from malleable and flexible parts is the key challenge in the emerging field of bending-active structures. The goal of this construction approach is to use the large elastic deformations of planar elements for the building of complex curved structures. Aiming to contribute to this research and to make new discoveries, the authors of this paper will look at nature for inspiration and explore how structures in the plant kingdom successfully combine high flexibility with high resilience. The focus of this study are the structural principles found in fibrous cactus skeletons. Not only do the cactus skeletons show impressive structural behavior, but also their optimized form, fiber orientation, and material distribution can inspire the further development of bending-active structures. Learning from these models, the authors will present key cactus-inspired design principles and test their practical feasibility in a prototypical installation made from millimeter-thin strips of carbon fiber reinforced polymers (CFRP). Similar to the biological role model, this 6-meter-tall lamellar structure takes advantage of clever cross-bracing strategies that significantly increase stability and improve resilience. The authors explain in more detail the underlying design and construction methods and discuss the possible impact this research may have on the further development of bending-active structures.
INTRODUCTION
This research is the final outcome of UC Berkeley’s post-professional Master of Architecture program called Studio One. In 2017-18, Studio One was instructed by Professor Simon Schleicher and was conceptualized as a new teaching model for exploring the topic of “Bio-inspired Design and Fabrication” (Schleicher et al. 2019). The general aim of the program is to bring architecture, engineering, and biology closer together and to seek new interdisciplinary alliances with partners from industry and academia. Supported by experts and professionals, the goal of last year’s capstone project was to contribute to the broader research on bending-active structures and to approach this topic from a slightly different angle.

More precisely, the students of Studio One were asked to investigate whether bending-active structures could draw inspiration from nature by examining the geometrical variability and structural efficiency of plants and by abstracting their underlying design principles at an architectural scale. The specific assignment for the final project in 2018 was to conceptualize a reusable lightweight pavilion, as shown in Figure 1—a structure that could be shown during the annual exhibition and that has the power to transform one of the main courtyards at the College of Environmental Design (CED). To achieve this goal, the research in this one-year-long program was divided into two parts. In the first semester, students worked individually or in small groups. In the second semester, they teamed up and built one larger-scale prototype together.

The starting point for this research was a material donation by Kreysler & Associates, one of the industry leaders in manufacturing of architectural composites and custom fabrication. They generously provided the class with rolls of pultruded carbon fiber reinforced polymer (CFRP) composites strips. This material has very interesting properties: it is usually valued for its very high tensile strength, and strips of CFRP are also extremely flexible and resilient owing to their minimal thickness of only 1.2 mm. Fascinated by the material’s elastic behavior, the students began to investigate its potential in the context of bending-active structures. The general goal of bending-active structures, as defined by Knippers et al. (2012) is to use large elastic deformations of initially straight or planar building elements for the construction of complex curved geometries and load-bearing systems. Recent work by research teams around the world has shown various successful applications for this concept using bending-active structures for lightweight architectural installations, temporary pavilions, kinetic structures, and compliant mechanisms (Lienhard et al. 2013; Ahlquist and Menges 2013; Schleicher 2015; La Magna 2017; La Magna et al. 2018). However, there are some challenges associated with this construction process. First, how can a rigid and stable configuration be achieved from flexible parts? Second, how can the equilibrium shape of multiple bent and cross-connected elements be predicted? Third, how can the materials’ high flexibility and resilience be best utilized using new design strategies and shapes? In order to address these challenges and to find new sources of inspiration, the team studied the dried cactus skeletons of the (a) Buckhorn Cholla and (b) Prickly Pear.
started exploring soft and flexible structures in nature and studied the strategies with which plants gain their stability and functionality.

**BIOLOGICAL INSPIRATION**

Nature, and in particular the plant kingdom, is full of fascinating lightweight structures that are capable of carrying significant loads despite their often delicate and fragile makeup. A good example is the fibrous anatomy of cactus skeletons like *Cylindropuntia acanthocarpa* (commonly known as Buckhorn Cholla) and *Opuntia basilaris* (known as Prickly Pear), as shown in Figure 2. These wooden structures are fascinating because they are astonishingly robust while using only a minimal amount of material. Unlike smaller, round, or barrel-shaped cacti that only consist of water-storing tissue, these cacti can grow much taller and effectively combine water storage with structural support by means of an inner lignified skeleton. Inside the cylindrical stems of the Cholla or the flattened pads of the Prickly Pear, for instance, are fine reticulate vascular bundles that form lightweight yet very strong lattice structures (Gibson 1978; Altesor and Ezcurra 2003). Over the past years, botanists and biomechanics have studied these wooden skeletons with great interest and investigated how their shape and material composition may be the result of load-adaptive growth processes (Mauseth 2006; Schwager et al. 2013). Fascinated by these structures, the students started their own investigations by looking closer at the fiber arrangement and material distribution in various dried cactus skeletons. These studies led to key observations from which the students derived the following bio-inspired design principles. First, the tall skeletons feature long continuous fibers that give the structure a clear directionality and help to effectively transmit forces along the structure’s main axis. Second, smaller cross-connecting fibers create an interlaced network that braces the structure laterally and significantly increases the overall stiffness. Thirdly, some skeletons seem to feature sandwich-like material compositions with stronger fibers covering a lighter core. Finally, the team noticed that the lignified material in the skeletons is not distributed uniformly, but instead visibly thicker in regions of higher anticipated stresses. This can be seen, for example, when comparing hole sizes and material density. The skeleton features notably smaller openings and more solid material at the lower part of the stem, while being significantly lighter and thinner towards the top.

**DESIGN AND CONSTRUCTION METHODS**

Impressed by the intriguing shapes and structural performance of the cactus skeletons, the students began to transfer the derived design principles into their own bio-inspired formal and structural explorations. In this phase, the team primarily used physical and digital model making for exploration. Physical models were made from thin strips of plywood veneer and were particularly helpful to gain a quick tactile understanding of how multiple strips can be bent and coupled together to create a series of possible pavilion designs, as shown in Figure 3. In comparison, the goal of the digital models was to find new ways...
of generating lattice-like structures that feature characteristics similar to cactus skeletons. The starting point for these explorations was the work by Lienhard et al. (2014) and Nabaei et al. (2015), who developed digital form-finding strategies for the design of interlaced strip systems (Lienhard, La Magna, and Knippers 2014; Nabaei, Baverel, and Weinand 2015). Based on their methods, the students approached the design task by working primarily in two different modeling environments. The first approach took advantage of the opportunities provided by the Rhinoceros plugin Kangaroo Physics for Grasshopper. This interactive tool allowed for real-time simulations of particle-spring systems and made it very easy to produce different design iterations during the early phase of the creative process. Figure 4a, for example, shows a model in which the students assigned different growth rates to a bundle of densely-packed strips, causing a delamination effect that forced the entire structure to bend. The individual strip lengths were then measured and transferred to a physical model, as shown in Figure 4b. While this approach created very appealing results and reflected the actual growth processes in the cactus well, it was also very difficult to control the final shape. Thus, the second approach aimed for control over the form-finding process by using the software SOFiSTiK, which is based on Finite Element Methods (FEM). While this engineering software was originally conceived for post-design structural analysis and can be computationally heavy, the students used it here as an early-stage design tool to accurately simulate the geometry of elastically deformed strips and to ascertain their internal stresses. To produce a bent geometry, as shown in Figure 5, the team implemented the method of contracting cables (Lienhard, La Magna, and Knippers 2014). In this simulation, the team modeled the CFRP strips with a thickness of 1.2 mm, a width of 100 and 50 mm, and Young’s modulus of 165,000 N/mm². The strips were then pulled together with a series of contracting cables that spanned between sliding anchor points along the edges of the strips. The goal of this simulation was to determine a deformed geometry that couples multiple strips in a predefined connection logic, while simultaneously giving each strip the possibility to rotate freely into the one equilibrium shape that results in the least amount of stresses within the given boundary conditions. As a result of this process, each connection detail between the strips had a unique geometry with locally specific clamping angles between the strips. The colors in the image represent the locally varying stress conditions caused by the bending and torsion of the thin CFRP strips. These stresses and the changes in geometry were monitored closely and checked for their compatibility with the material limitations. Prior physical tests on 5 cm wide and 100 cm long specimens resulted in a minimal bending radius of 40 cm and a maximum twisting angle of 30°.
RESULTS FROM PROTOTYPING

To test the practical feasibility of the cactus-inspired design principles and derived form-finding methods, the team conceptualized a temporary pavilion and built it at full scale. In their final design, the students proposed a 6-meter-tall structure that acted both as a space-filling installation during the annual exhibition as well as a seating opportunity in one of the building’s main courtyards.

The entire structure was made from 50 and 100 mm wide CFRP strips with 1.2 mm thickness and sheets of 19 mm and 6 mm thick ACX plywood. The pavilion’s shape is a seamless transition between a dense horizontal bundle of strips that act as a bench and a vertical lattice network that fans out and rises toward the sky. Similar to the biological role model, each strip alone was far too soft to carry bigger compression loads or to reach any notable height. However, when coupled together, the flexible strips supported each other and formed a very lightweight yet rigid system. In order to further stabilize the interlaced lamellar structure, the outermost strips were built as a sandwich structure, in which two strips of CFRP were glued together with a 20 mm thick Styrofoam core. While all other parts in this pavilion were flat-produced and elastically bent into shape, these strips were laminated on a curved formwork that precisely followed the shape determined from the digital form-finding.

To anchor the temporary structure and to secure it safely to the ground, the bench of the pavilion was made of heavier ACX plywood sheets with a thickness of 19 mm. As illustrated in Figure 6 and 7a, its design was based on a radial waffle structure with vertical and horizontal blades that were CNC routed and could be interlocked with each other easily. Despite the use of a heavier foundation, the pavilion was extremely light and weighed only 238 kg. Of this total weight, the CFRP structure only accounted for 60 kg. The students were able to accomplish this impressive result by cross-bracing two types of CFRP strips. The 100 mm wide strips carried the vertical loads and had a total length of 238 m, while the 50 mm strips had total length of 140 m and were used to cross-brace the structure.

Since all strips were fabricated by means of a pultrusion process, and thus composed of only a single layer of lateral fibers, they were particularly prone to fracture and needed to be protected against exceedingly high torsional loads and potential local damages. It was therefore important to handle the strips with great care and to follow an assembly sequence that would not deform the strips beyond their material limitations. Furthermore, it was crucial to develop a connection detail that allowed for quick and easy assembly.

Within two days, the students fabricated and built the 6m-tall research pavilion.

(a) Bench construction and (b) bespoke connection details with custom angles at different locations of the structure.
construction without any cutting, drilling, or bolting that would cause cracking in the strips. In order to address these challenges, the students built the connection details by laser-cutting thin sheets of 6 mm plywood, as shown in Figure 7b and 8. Each connection detail featured a specific slit layout that was custom-made to the required target angle of each node and shaped in such a way that it would be easy to insert the strips from one direction. As shown in Figure 9, this detail simplified the construction process significantly and enabled the students to fabricate and erect the entire pavilion within just two days and to disassemble it after the exhibition in only one day. Finally, 90% of the strips were preserved during the construction process, and the team was able to salvage the precious material and reuse it for a follow-up project.

CONCLUSION
In summary, the research presented here demonstrates that plant structures such as cactus skeletons can inspire the development of new design and construction principles, which are transferable to an architectural scale. With their bio-inspired pavilion, the students have successfully shown that it is possible to build a tall and rigid structure from very lightweight and flexible parts. By taking advantage of physical model-making and new digital form-finding methods, the team was able to balance their design intentions with material and fabrication constraints. Along the way, the students developed impressive skills and managed to carefully control the large elastic deformations of ultra-thin CFRP strips, and reduced the stresses caused by bending and twisting of the material. The resulting design approach is very promising and renders new opportunities for bending-active structures beyond the scope of the shown work. By actually building the pavilion in full scale, the students experienced first-hand how the cactus skeleton achieves its stability and how the principle of cross-bracing significantly increased the pavilion’s rigidity with every strip added to the system. Owing to the design of simple connection details, it was possible to erect the entire pavilion within two days and to disassemble it in one day without destruction of any parts. As almost all strips were in good condition after the disassembly, the team was able to reuse them for another project.

An unexpected outcome of this research emerged when observing the pavilion’s behavior during several storms. Since the structure was relatively tall, it was susceptible to potential collapse when exposed to high wind loads. However, the pavilion performed remarkably well with no harm to the structure due to its high flexibility. In fact, it was easily understandable how the elastic strips absorbed the wind gusts and effectively dissipated their energy with local movements. This incident demonstrated that bending-active structures can be incredibly robust and that local instabilities may not always be considered as a structural failure that needs to be avoided with higher dimensioning or inclusion of further stabilizing elements. Instead, using flexibility strategically could play an important role to create structures of higher resilience in the future!
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REFERENCES


IMAGE CREDITS
Figures 2-6, 9: Pictures derived from Schleicher et al. (2019) All other drawings and images by the authors.

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Studio One Research Pavilion 2038 on display in the courtyard of the College of Environmental Design (CED) during the annual exhibition at UC Berkeley.