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Rhipsalis baccifera: a counterintuitive role model for the architectural tectonics of nodeless nodes

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Abstract

Botanical exploration allows us to glean insights into structures that showcase the optimum use of materials, multifunctionality, and aesthetic appeal across different scales. The way plants naturally branch out reveals their adaptability and flexibility in thriving and evolving. Also, it inspires structural and architectural design about the tectonics and topology of efficient and sustainable structures. In botany, branching represents an inherent mechanism, through which plants develop fresh stems originating from nodes of pre-existing stems. This process plays a crucial role in energy harvesting, space occupation or increase of external surface, defining a plant's overall form and dimensions. The configuration of branching is shaped by various environmental factors, including light, water, and nutrients. The ability of plants to modify their branching structures in countless, bespoke variations in response to individual or fluctuating environmental conditions, showcases their impressive adaptability. In the realm of vascular plants' branching, certain plants opt for geometric solutions, efficiently accumulating material in the nodes as expected from a structural point of view. Examples from the Cactaceae family, including *Rhipsalis baccifera* show counterintuitive, tectonic strategies, minimizing material use in their nodes. To delve into the branching domain of *Rhipsalis baccifera,* we apply three-dimensional Computed Tomography (3D CT) scanning. This enables us to meticulously and to non-destructively observe the cellular structure within the node region. We recognize that the node of the plant is not limited to a single point, but that stem and branch are intertwined in a complex way. We present the digitalized geometries of the individual tissues, fibers, and strand courses, and their abstraction for the development of associate, novel 3D joint prototypes. This biomimetic approach not only mimics the material optimization strategy but, moreover, allows for tectonics of assembly and disassembly. Overall, our approach opens up new paths for architectural tectonics that not only minimize material consumption but also transfer the efficiency and multifunctionality of the natural model into technology.

Keywords: Architecture, Botany, Biomimetics, Branching, Tectonics, Structures.

1. Introduction

In botany, branching is a natural process where new elements are being generated from existing ones. This process plays a significant factor in forming the overall shape and size of a plant. Adaptation in plants is a remarkable feature to adjust their branching patterns to the different environmental conditions.

But also, this pattern can be affected by food resources or genetics. As an example, plants grow a few taller branches in crowded environment when they need to capture more solar energy, while they spread shorter ones but more in numbers to maximize their exposure to solar energy [1].

Rhipsalis baccifera is a plant that shows a counterintuitive solution in comparison with the other vascular plants by using fewer materials in the node area. This cactus is an epiphyte in the forests of Brazil and, therefore, its morphology is specialized to grow on trees. Also, its shoots are characterized by a cylindrical shape and a relatively consistent diameter across both the old and the newly formed shoots [2]. Those features can be considered significant factors with direct applicability to structural considerations, offering insights into potential strategies for applying them to architecture.

In recent years, the study of biomimetics as an interdisciplinary field has gained significant importance in understanding nature-inspired designs to create innovative solutions to human daily life problems [3]. This approach has led to many applications in different fields including architecture [4]. Biomimetics, unlike biomimicry and bionics, focuses on mimicking the forms of nature in the first and replicating the functions of the natural systems in the second. Biomimetics involves the implementation and application of structural systems, and processes, considering the materials utilization and development principles of biological systems[5].

In the field of architecture, tectonics refers to the articulation of elements' assemblage and construction, as well as the appropriate utilization of materials, which creates an artifact's structural expression. This articulation could be through using digital tools or craftsmanship or a combination of digital tools and craftsmanship could be used. In both tectonics and biomimetics, there is an emphasis overlapping on understanding and analyzing the concepts of “structure” and “material”.

Our research presents a detailed visualization of a node in Rhipsalis baccifera through a CT scan showing the distribution of the tissues and the way they are structured. Also identifying the utilization of the materials which is represented by cells inside the node. We propose a series of joint prototypes inspired by the Rhipsalis baccifera plant. In our proposed prototypes we consider the assembly and disassembly, material optimization, multifunctionality, and aesthetic factors as well.

2. Biological Observation (CT scan)

For 3D visualization, a node of R. baccifera was cut from the plant and immediately frozen at -20°C followed by freeze-drying. Thereafter, the dry sample was scanned in an X-ray micro-computed tomography (MicroXCT-200, Zeiss Carl Zeiss, Jena, Germany). Scans were performed with 30 kV tube voltage and 200 µA current. Two scans were performed with different magnification (4x and 10x). 3D data construction was performed via the software XMReconstructor 8.1.6599 (Zeiss Carl Zeiss, Jena, Germany).

3D segmentation and reconstruction were performed with the software 3D slicer (Slicer Community, www.slicer.org) and ImageJ (NIH, www.imagej.net). The scans were segmented into the individual tissues: Epidermis, palisade cortex, inner cortex, cortical bundles, libriform fibers, and crystals.

2.1 Node anatomy

The overall growth form of Rhipsalis baccifera is optimized for the epiphytic mode of life of this cactus (Figure 1A). On the one hand, this plant reduces its surface area to a rod-like shape, so it can reduce the exposure to sun and heat at the top of the tree. On the other hand, as the older shoots branch preferred at the tip, they have to withstand high tension forces due to the weight of the multitude of younger shoots. However, the nodes of R. baccifera employs a counterintuitive solution but still geometrically optimized solution. The internal structure around the node reveals several cortical bundles which are arranged circular and close to the center of the shoot forming the inner cortex (Figure 1B). Most of the bundles are, additionally, capped by libriform fibers (Figure 1C). Both types of fibers are lignified and thick-walled cells, responsible for structural stability regarding tension forces. This structural part is surrounded by the palisade cortex; a thick layer of unlignified and thin-walled parenchymatic cells with many big crystals, responsible for photosynthesis and water storage. Finally, this tissue is surrounded by a smooth epidermis layer.

At the node, both younger shoots are separated by a neck region, formed mainly by the inner cortex. Some of the cortical bundles split in the older shoot, so that the ring of bundles is closed again in the younger shoots (Figure 1D). Contrary, the libriform fibers vanish short before the node in the parenchymatic tissue of the old shoot and new fibers reappear in the younger shoots. Additionally, the cortical bundles at the node fuse partly together, as most of the individual fibers collapse and create a denser section (more cell wall per µm³) (Figure 1E and F). Further, single strands of the cortical bundles reveal a twist at the neck region, as the single bundles get rearranged (Figure 1G).

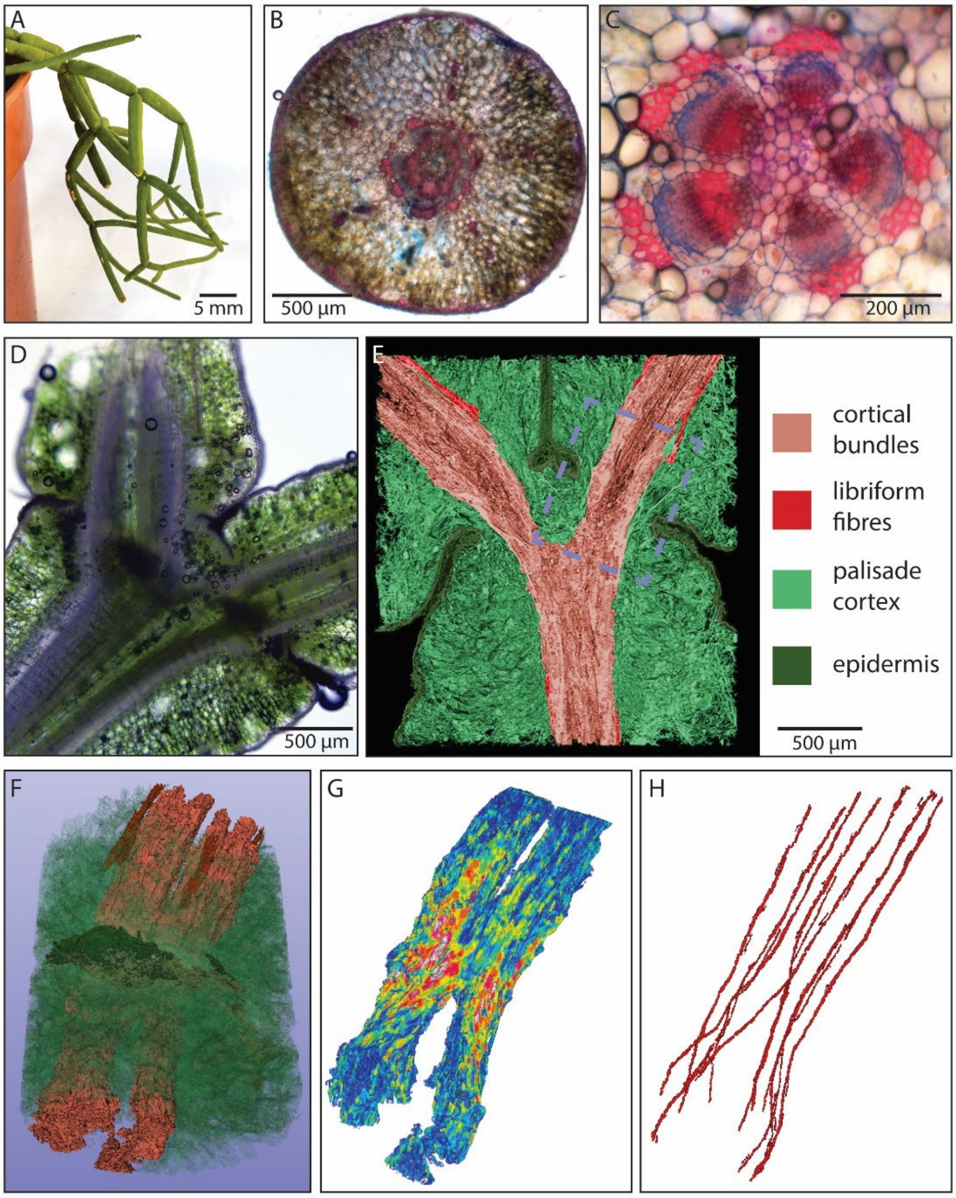


Figure 1: A) Overall growth form of R.baccifera. B) cross-section of a shoot stained with astral blue and safranin highlighting the parenchymatic (blue) and the sclerenchymatic tissues (red). C) Close-up of the inner cortex showing the cortical bundles and the additional libriform fibers (bright red). D) longitudinal section of a node revealing the splitting of some cortical bundles before the neck-region. E) Cross-section of the CT- scan of a node of *R. baccifera* showing the segmented tissues. F) 3D reconstruction of the neck-region (marked in E) with parenchymatic tissue in green and sclerenchymatic tissue in red (pinkish-red = cortical bundles, dark red = libriform fibers). G) Density map of the cortical bundles showing a denser region at the neck region. H) Single strands of the bundles slightly twist at the neck-region.

3. Structure-function-relationship of *Rhipsalis baccifera.*

3.1 Optimized tissue arrangement of Rhipsalis baccifera

In *R. baccifera* two main tissue types can be differentiated: sclerenchyma and parenchyma. To the sclerenchyma belong the cortical bundles and the libriform fibers, and both cell types are thick-walled and lignified. However, the bundles are responsible for the conduction of water and also give the plant structural support. In contrast, the libriform fibers have only a supporting function. The location of these cells close to the center indicates an adaptation to predominantly occurring tensile stresses [6]. That the libriform fibers are not growing through the node speaks for its later appearance during development. These fibers may be formed later due to the increased tensile stresses as the younger shoots get more and heavier.

To the parenchyma belong the palisade cortex and the epidermis. These cells are roundish and thin-walled and, therefore, can change their shape depending on their water content. Besides the water storage, they are also responsible for photosynthesis. These cells are covered by the epidermis, which protects the tissue from the environment. This tissue plays a minor role in structural support against tension stresses, however, it is essential to give the cactus its shape and can have an influence on the fracture resistance of branches in cacti [7].

The architectural tectonics of the cactus can be simplified to these two tissues, as can be seen in Figure 2. The parenchyma is still the shape-giving element of the biomimetic node, however, the shape follows a radial symmetry around the center, so that all elements look the same. In contrast, the sclerenchyma follows the natural model in connecting the lower (older) shoot with one of the upper (young) shoots but not the two younger shoots together. Also, the multimodal build-up of the cortical bundles is considered with the splitting and twisting of the individual bundles.

3.2 Tensioned Triangles – transferring tissue geometries of Rhipsalis baccifera to architecture

R. baccifera employs a counterintuitive solution for branching strategy in comparison to the other plants which align to geometrical solution in branching having tensioned triangles principle. However, we can see this principle in the sclerenchyma tissue in the plant which is responsible for structural stability.

The tension triangles method is proposed by Claus Mattheck [8], which is a graphic technique used to analyze and optimize the structural design of components subjected to the flow of forces as for example notch stresses can be reduced. These tension triangles are used to visualize a smoother path with the forces flowing within the structure. His method graphically can be illustrated by establishing a connection to a shaft shoulder of the two branches by dropping a plumb line from the angle bisector onto levers to distribute the load evenly, building tension triangles around the connection point, rounding off corners, and setting an arbitrary point, possibly pushing it upwards to increase installation space. Mattheck suggests that this method can create a smooth flow of the forces as well as better structural performance of the branches than other notch connections.

The concept emphasizes the importance of aligning branching geometry with the direction of forces to ensure structural efficiency. This may involve rounding transitions, accommodating bending or forking of materials, and optimizing the distribution of forces to minimize stress concentrations [8, 9].

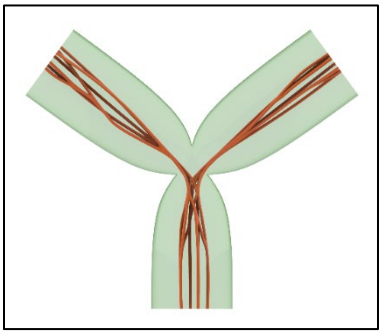


Figure 2: Optimized tissues arrangement

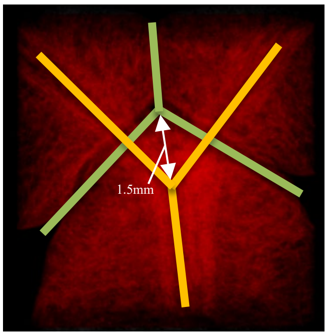


Figure 3: shifting centers

Figure 4: Tensioned triangles

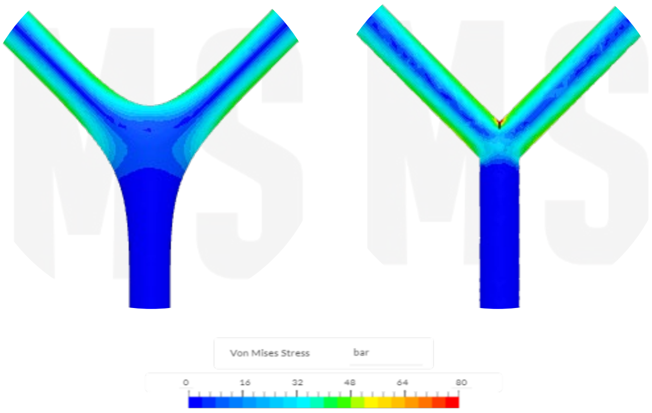


Figure 5: Von Mises stress for branches comparing a tensioned triangle and angled version

Using Simscale platform (demo version) (www.simscale.com) we test the tensioned triangle method by applying a distributed load of 1 N compression on two types of branching, mimicking simplified bundles in R. baccifera. One type follows the tensioned triangles method, while the other involves a kink, respectively angled version. The dimensions of this sclerenchymatic node are 10mm for the stem and 14.14mm for branches with a diameter of 1mm, and the material is wood to replicate the actual tissue in the plant.

Table 1 - Results show that the tensioned triangle branch has a lower value of Von Mises stress in comparison with the kink branches.

Tensioned triangle method	von mises stress (bar)			
Node type	min	max	average	volume mm3
Kink/Angled Version	0.24989791	92.59748	8.764467311	29.2
Tensioned triangle	0.234818438	44.243015	7.934746703	29.5

3.3. Shifting the centers

Shifting the centers within a node is a notable principle in the R.bacciferra's node. It is essential for ensuring the optimal distribution of forces and maintaining overall stability in the studied plan. The center is shifted 1.5 mm. This principle involves intentionally relocating the central point of force within the node to achieve a more balanced and resilient structure. In our investigation, exemplified in Figure 3, we observe this principle in action with the bundle layer, represented by the reinforcing core, purposefully shifted away from the node's actual center.

This adjustment plays an important role in enhancing the structural integrity of the node. By shifting the center of the bundle layer, we promote a more uniform distribution of forces throughout the structure. This, in turn, minimizes stress concentrations and reduces the risk of localized failure, ultimately contributing to greater stability and durability.

Furthermore, this strategic shift ensures that the structural elements within the node work together more effectively to withstand external loads. By distributing forces more evenly, we enhance the node's capacity to handle forces of tension, compression, or bending.

3.4 Intertwined cores

Twisting the cores is a distinctive feature of the R.bacciferra plant, as illustrated in Figure 1H. This characteristic plays a crucial role in enhancing the tensile strength of the plant and providing additional reinforcement to the node. This twisting action creates a more robust internal structure, adding extra layers of reinforcement within the node.

4. Prototyping

The prototype design is based on redistributing the direction of the forces, with a focus on integrating and extending the elements as biomimetic principles of the R.bacciferra joint plant as in Figure 5. The assembly process follows a non-sequential approach which is based on a non-sequential joint that can be assembled with simultaneous movement of all parts and blocked only by its kinematic [10].

Our prototypes are designed to experience tension and compression forces. In these prototypes, we apply the biomimetic principles which are inspired by the R.bacciferra node including: layering, tensioned triangles method to the cores, shifting the centers, and intertwining the cores. Since we are transforming biological components as a growing system into an artificial system. We consider that our prototype allows assembly and disassembly we drive our prototype to have a nonsequential assembly approach that is inspired by biological tectonics in the plant represented by the tissues' geometries

Figure 7 shows our proposed multiple prototypes. Prototype 1 involves the stem core dividing into two branches at the branching point. Prototype 2 features two stem cores intertwining before separating into two distinct cores. Prototype 3 introduces a twisting motion in the cores, forming a helical shape, with each core diverging in opposite directions. Prototype 4 expands upon this by incorporating a helical twist in the cores and branching each stem into two separate branches.

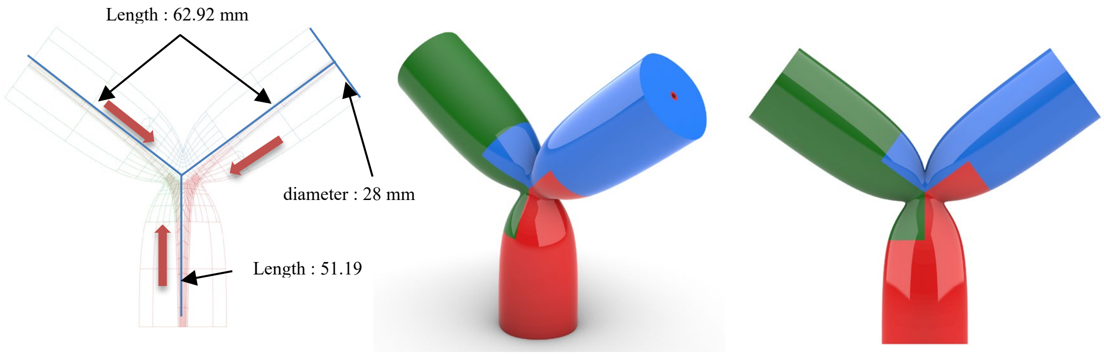


Figure 6: Prototype concept

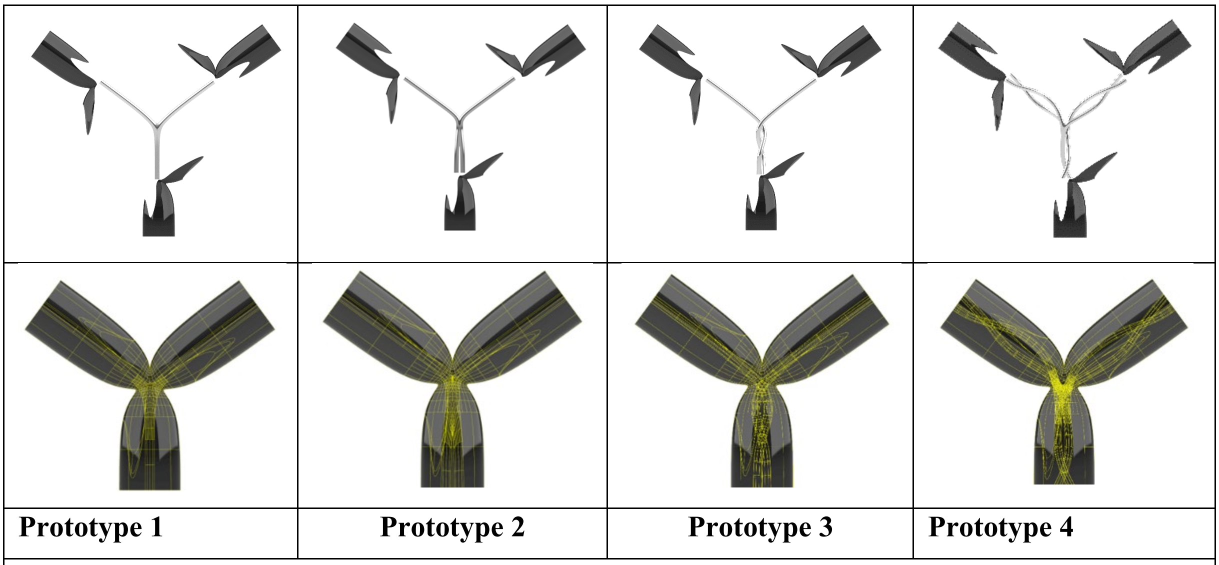


Figure 7: proposed Prototypes

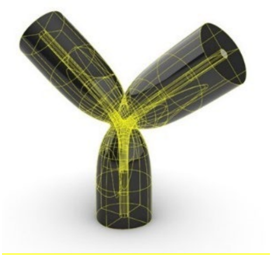
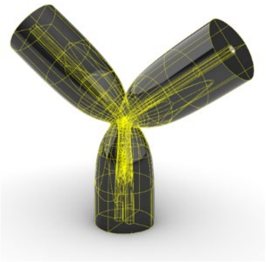
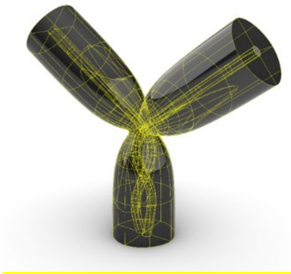
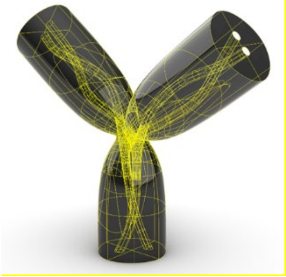
			
Prototype 1	**Prototype 2**	**Prototype 3**	**Prototype 4**

Figure 7: proposed Prototypes

5. Structural simulation

We conduct static simulations using the Simscale platform (www.simscale.com) to analyze the structural behavior of our proposed prototypes. We apply materials of PLA (Plastic) for the overall shape and steel for the bundles), we apply an external force of 1 N, representing the external load in the vertical direction on the faces of the branches and fixed support in the bottom face of the stem as in Figure 8. (compression) These factors combined to influence the Von Mises stress, Cauchy stress, strain, and displacement as in Figures 9. The reason for selecting the materials PLA (plastic) and steel is to make a simulation to a 3D printed physical model we fabricate in the same scale of simulation.

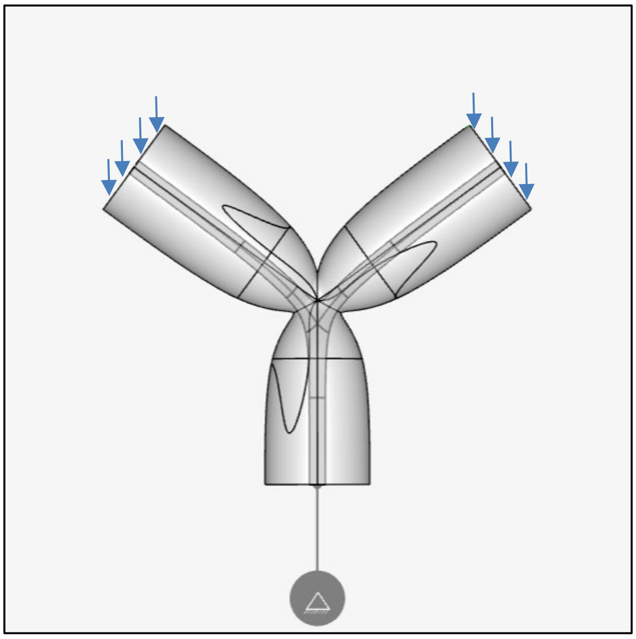
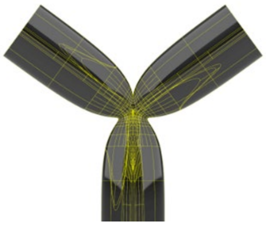


Figure 8: Boundary conditions

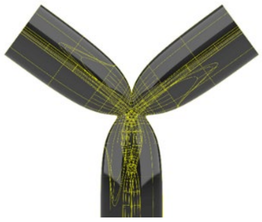
Table 2- Volumes of proposed prototypes

Volume mm3			
Prototype Volume	PLA (joint)	Steel (core)	Steel to PLA
Prototype 1	86003	2538	2.95%
Prototype 2	85884	2992.01	3.48%
Prototype 3	85550	3025	3.54%
Prototype 4	84950	3638	4.28%

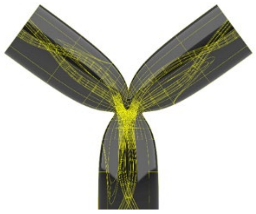
Prototype 1



Prototype 2



Prototype 3



Prototype 4

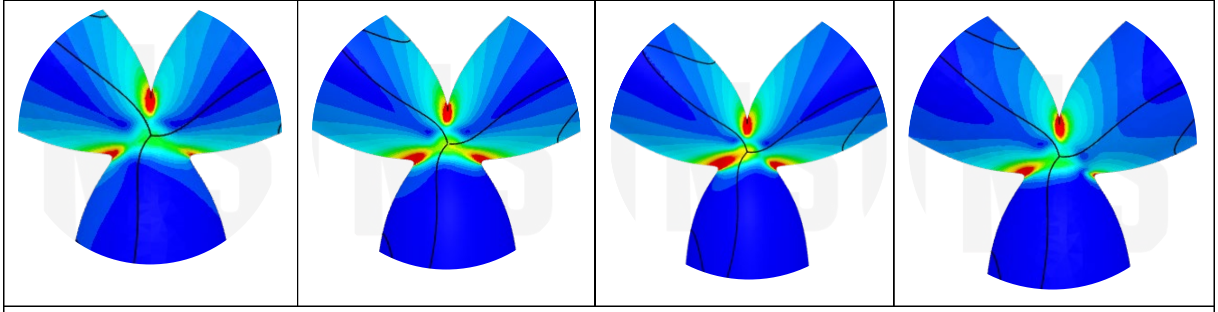


Figure 9a: Von mises stress Simulation

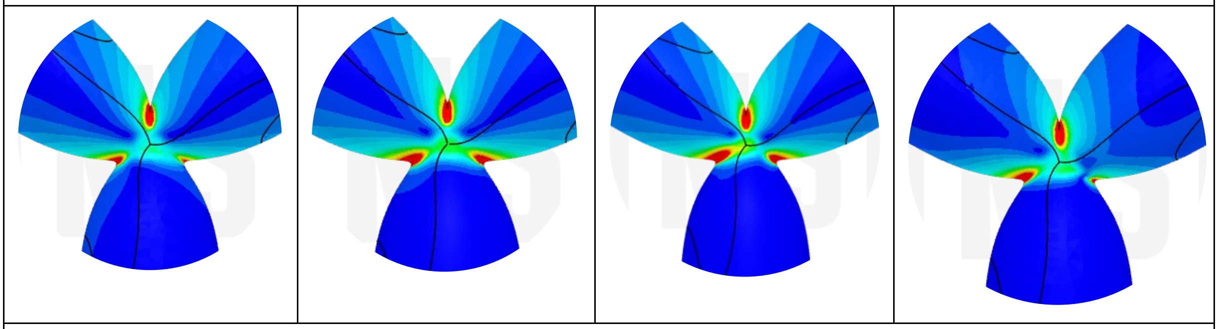
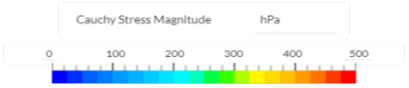


Figure 9b: Cauchy stress Simulation



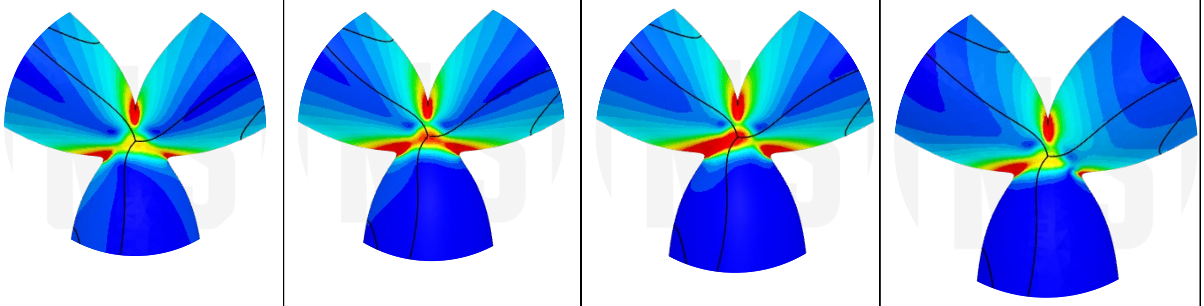
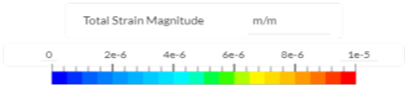


Figure 9c: Strain Simulation



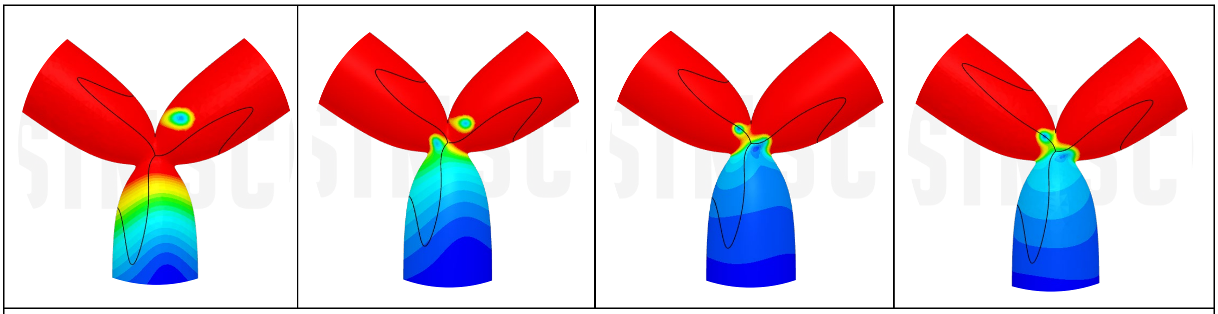


Figure 9d: Displacement Simulation

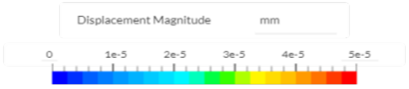


Figure 9: Structural Simulation

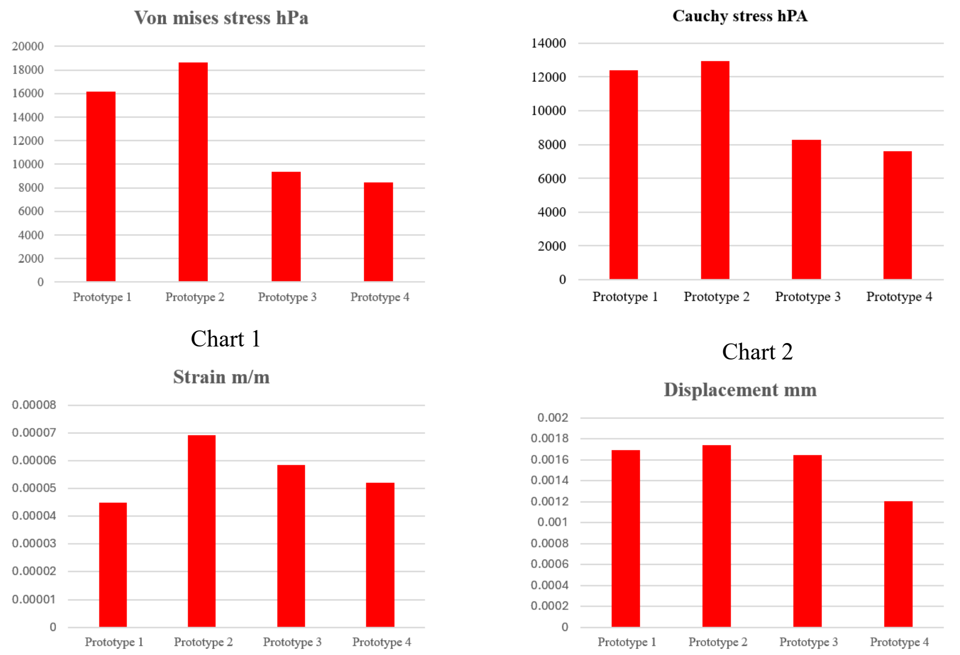


Chart 1

Chart 2

Chart 3

Chart 4

Figure 10: maximum values of structural simulation

Figure 10 charts 1,2 represent the maximum values of both Von Mises and Cauchy stress measurements conducted across the prototypes. Prototype 4 records the lowest maximum Von Mises stress: 8468.49 hPa and Cauchy stress: 7614.39 hPa while Prototype two records the highest maximum values of 18615.02 hPa for Von Mises stress and 12938.65 for Cauchy stress.

Figure 10 chart 3 represents strain. The prototype 1 shows the lowest maximum value of strain under the applied loads 4.492E-05 m/m while prototype 2 displays the highest value as 6.93E-05.

Figure 10 chart 4 represents displacement, indicating the amount of movement under applied loads, recording Prototype 2 to as the highest maximum value of 0.0017 mm. On the other hand, Prototype 4 displays the least displacement among the prototypes which is 0.0012 mm, indicating the least movement under applied loads.

The structural simulations reveal also that the distribution of the stresses, strain, and displacement varies from one prototype to another as per the design of the core bundles. Furthermore, the results show that prototype 4 is the best-performing design, closely replicating the physiological traits of the plant node, considering the biomimetic principles that include tensioned triangles of the cores, shifting the centers, and intertwining the cores.

This prototype showcases the capability of reducing stress levels and displacement compared to the other prototypes. On the other hand, Prototype 1 demonstrates the lowest amount of strain, showcasing the wide variety of abilities embedded in our biomimetic design approach. The results support the significant impact plant tectonics in leading the development of joints as sustainable structural elements that emulate nature's intricate adaptations.

7. Discussion and Conclusion

The research demonstrates the potential of biomimetic design in architecture by considering inspiration from the node of Rhipsalis baccifera. The prototypes developed in the study incorporated features inspired by the plant's node considering the structural function relations of the various tissues in the plan. Structural simulations revealed differences in performance between the prototypes, with Prototype 4 closely replicating the plant's node and exhibiting the least amount of maximum stress and displacement. However, Prototype 1 displayed optimal strain characteristics.

By comparing the performance of the prototypes considering the biomimetic principles we observed in the plant and applied it into the prototypes, we identify differences in stress, strain, and displacement values.

The discrepancies observed between the prototypes suggest that while geometric replication is essential, but it may not fully capture the full properties of biological materials and structures. This highlights the complexity of biological systems and the need for a holistic understanding when translating them into designs. The study concludes that biomimetic design has the potential to inform innovative structural elements such as joints in architecture.

By studying the structural functions of Rhipsalis baccifera and developing prototypes based on its principles, the research demonstrates the feasibility of integrating botanical insights into architectural innovation. More research is needed to refine biomimetic design methods and understand the complex interplay between form, function, and material properties in natural systems.

However, the proposed prototypes not only prioritize structural performance but also emphasize material efficiency, multifunctionality, and aesthetics. Inspired by Rhipsalis baccifera's characteristics, the designs aim to optimize resource utilization, integrate multiple functionalities, and enhance visual appeal. Furthermore, the proposed prototypes are designed to accommodate tension and compression forces, inspired by the adaptive strategies observed in Rhipsalis baccifera. By integrating features such as tension triangles and layered tissues, the structures are equipped to distribute loads efficiently. This holistic approach to structural design enhances the resilience and functionality of the prototypes. Moving forward, further exploration of these principles will contribute to the development of innovative and sustainable architectural solutions.

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