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ARTICLE

Novel Proposal of Bio-based Sewing Timber Joint: Learning from Diatoms

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ABSTRACT

The twenty-first century is one of the most complex in the history of humanity, mainly due to the ecological crisis it is going through. The construction sector generates about 40% of CO_2 emissions into the environment; the foregoing should motivate this sector to seek new alternatives to develop new building practices. Taking these current needs into account, this document classifies and presents a multidisciplinary solution that integrates biology, engineering and architecture to develop a new and innovative lightweight timber structure; it divides with a main structure made of timber and an innovative joint system made of bio-polymers connecting all the panels. Through the study of diatoms, it was able to analyze the bio-morphology of the structure, joints and in particular the geometry since they were the inspiration for the design of this structure that presents an innovative and novel design of structural optimization. Through parametric design and digital fabrication, it was able to create a complex geometry that obtains excellent structural behavior. This research discusses and explores how materials, geometry led to the optimization of a structure and how new structures can arise, thanks to biology new solutions can be obtained that are completely sustainable, being a clear example of how to combat the effects of the climate change and in a precise way it highlights the advantages of the bio-design in the architectural design.

Keywords: Diatoms; Timber joinery; Computational method; Topology optimization; Biomimetics; Bio-inspired; Lightweight structure

1. Introduction

The current environmental crisis and the increase in demand for new buildings put the construction sector with many challenges that must find new solutions

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to face climate change since the construction sector is responsible for about a third of emissions, dominated merely by the manufacture of materials such as concrete and steel; this should motivate this sector to seek new alternatives for construction practices and techniques that drive a new way of designing. Changing current conventional construction practices to new ways of innovating structures through timber represents a sustainable alternative in the construction industry. Timber as a construction material has great advantages over other materials, not only for its ecological benefits but also for its negative carbon footprint and its hardness to generate shapes, another great advantage is that it is much cheaper when compared to other materials of construction. If it is able to manage to apply the technological advances that currently exist, construction using timber provides new possibilities and the development of new innovative and sustainable structures.

Through the technological and scientific advances that have been developed during the last decades, being more precise in software and digital fabrication, new structures are being obtained that have greater and better structural performance. Referring to the above and applied to lightweight timber structures, they promise new construction systems; the application materials that are environmentally friendly allow those new lightweight structures could be designed and fabricated very quickly; that's why the interest in timber structures is growing really fast because of their low construction price, material price, high durability and usability.

This present document is the result of the cooperation, knowledge and research of biologists, engineers, architects and builders; with the multidisciplinary perspective, a better result can be obtained for the elaboration of this project; through the combination of knowledge from these areas, it was possible to create a structure that promoted a light and sustainable structure. This research was possible thanks to a research stay at the Institute of Biology and the Faculty of Engineering of both the National Autonomous University of Mexico and the University of La Gran Colombia in Bogota, Colombia.

The objective of biomimicry in architecture is to innovate through biological principles. The purpose of investigating areas is to denote and limit that they are completely different from one another and cannot be compared to a living organism; the important thing to highlight is how you can try to integrate biological principles (geometry, shapes, processes) and integrate them into architectural design. The fields in architecture where it can be applied are diverse and that is why during the last decades, they have been gaining more interest in this sector. In order to carry out this research, a study of several species of *phytoplankton* was carried out and due to their great ecological contribution and geometric principles; that's why for this research it was decided to study diatoms and to be focused on their bio-morphology in order to develop new methods and implement them and as for the design of the joints, as a great result to carry it with sewing joints made of biopolymers, resulting in a new innovative form of construction systems.

The methodology that was used to verify this research is focused on carrying out an investigation at the Institute of Biology, in which it was carried out different analyzes of *phytoplankton*; continued with the development of different design prototypes in which we sought the most suitable geometric shape and for the last part of the conclusion it was with the tests at the Institute of Engineering to carry out the mechanical tests of the bio-polymers. It is important to note that the methodology used was done in different hierarchies; starting first with the analysis that is focused on bio-mimesis and later, the transfer of the geometric shape to the timber panels was carried out so that at the end of this research, it carried out the sewn tests of the biopolymer joints. Due to the above and it should be noted that this investigation has a highly multidisciplinary perspective which helped to obtain a better result.

This prototype is planned to be carried out in an ecological park in Mexico abroad, if compared to a steel and concrete structure, wood has great advantages such as price, time and duration. Regarding maintenance, if it is given a layer of varnish for exterior use, it can withstand the weather and rain, which gives it much greater advantages and is a highly sustainable material.

2. Aim of this research

This document has the purpose of making known how new structures can be developed through the integration of biological principles and how a multi-disciplinary perspective can achieve a better result. The objective of the research is to introduce a new sustainable timber joint union-made of bio-polymers. One of the reasons to develop and apprises this research is that has the purpose of making known how the morphological and biological principles can be an option to develop new lightweight structures. This research concludes with the fabrication of this model and we conclude that it presents great advantages over conventional steel and cement structures. The urgency of designing new construction systems and integrating new materials is one of the main goals for the future of architecture.

3. Diatoms and bio-inspired design

The use of nature in the design process of structures is not something new, it has been applied for several years and day to day it seeks to further expand [1] this knowledge due to the great developments that have been generated in the last decades; in the case of design, it promotes solutions and the development of new designs that integrate new materials and optimal structural forms. During the 20th century, great pioneers of lightweight structures such as Félix Candela, Frei Otto and Fuller Buckminster used biological principles [2] to develop their works and referring to Fuller Buckminster he stated: "I am not trying to imitate nature, I am trying to discover and employ the principles she is using", denoting how nature and biology have much to teach us. During the last century Frei Otto became very interested in biology [3] and it was thus that he worked in collaboration with the biologist J.G. Helmke, being highly interested in *Radiolaria* microorganisms (group of amoeboid protists that produce mineral skeletons) due to their geometry and their structural patterns to develop a balance of light structures. For this emerged his theory, that so-called "From-Finding", which led to his analogic models, like chains or nets of cables [4].

For this research and due to its great interest, we decided to study the diatoms, which are a group of unicellular algae that are part of the *phytoplankton* family, they are photo-synthesizing microorganisms. Most of the oxygen is produced through the *photosynthesis* of *phytoplankton* in the sea, one of which is the diatom, a unicellular alga considered the main generator of oxygen on our planet, so far more than 6 thousand species are known. The function of diatoms in the world's oceans is of great importance since they exhale more oxygen than all the tropical forests of the world and on the other hand, they invisibly recycle the gases that surround our planet. Currently diatoms are considered the "lungs" of the earth since they help to a large extent to be able to produce oxygen and absorb large amounts of CO_2.

Apart from their great contributions to the ecology and well-being of the planet, diatoms have great characteristics linked to their bio-morphology, especially for this research will focus on the shape and geometry that makes them have completely precise geometric shapes. After several analyzes of different diatoms and different species of *phytoplankton*, we concluded that the best species to continue with the analysis of this structure would be two species: *Triceratium Favus* and *Coscindiscus Radiautus* (**Figure 1**). The first one has a completely equilateral triangle shape; under these geometric principles it was chosen to use this species to design the main structure that has an inner radius and three support points in the same way and this benefits structural optimization. The second species has a hexagonal shape. This is the base of the timber membrane that was developed to optimize the main membrane (**Figure 2**).

On the left side the *Triceratium Favus* has a completely triangular structure and on the right side the hexagons that make up the *Coscindiscus Radiautus*, both being observed under a microscope. Learning through morphology and biological principles and applying them to construction is a tradition that has been applied for several years now; but lately it has generated greater because of the endless opportunities and possibilities that give a plus to the design process. In

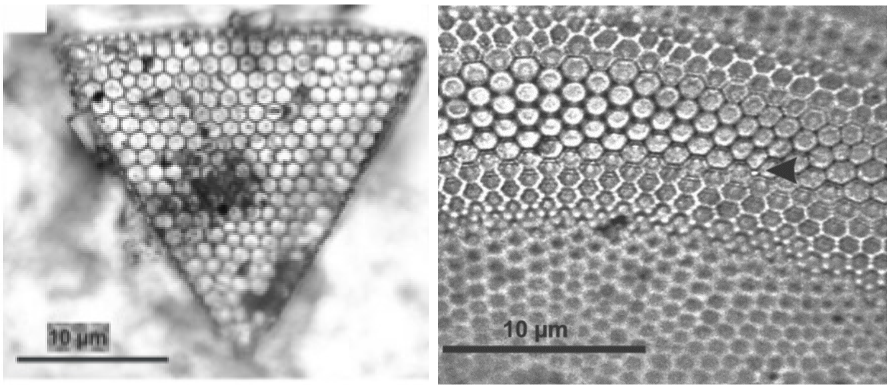


Figure 1. *Phytoplankton* view through a microscope.

the case of the field of lightweight timber structures, biological principles and morphology have helped redefine construction systems [5], construction methodologies, architectural design, and fabrication processes. On the other hand, the great dilemma is based on how to transfer these biological principles to the construction process; these challenges are the crucial part that motivates us to develop innovative solutions and integrate new design methodologies.

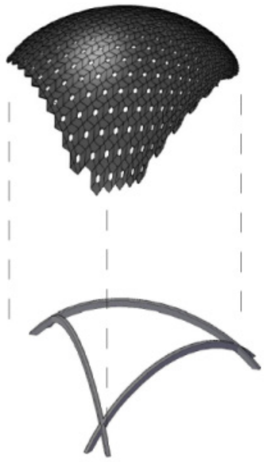


Figure 2. Pavilion divisions.

3.1 Joint connections

One of the essential aspects of any structure is the connections since they are responsible for transferring all the forces, in the case of timber construction there are different types of connections that go from the joints connected with glue, screw and nuts; we chose to integrate biopolymers to develop the sewing joints of each of the panels.

The sewing joints present a great direct opportunity for the union of each one of the panels of the membrane, since it allows the direct transfer of each one of the panels [6], this type of union has already been used in other architectural works, but in the case of this structure, a bio-polymer is used that allows it to be sustainable and rigid at the same time. After the parametric design of the structure, carrying out the tests in the Karamba plug-in, showing behavior and a minimum displacement with the design of the sandwich-type joined panels. The innovation of this structure is that it also has the benefit of being highly adaptable to any geometry or surface and that it can be tensioned correctly, making it a great contribution to the design of lightweight structures.

As a result of the flexible joints, it is able to develop any type of surface and it can be built. In the case of the project carried out, the structural behavior promotes the development of new forms that can be adapted to any design need. This structural behavior is a great advantage compared to concrete and steel structures. Sewing joints present a great promising future since compared to steel or concrete they present great economic and sustainable advantages [7]. In the case of the project presented, each hexagon is connected through this system (**Figure 3**). The goal of this system is to apply new low-tech construction systems by means of timber and sewing joints for the manufacture of lightweight structures and to explore the tension, compression and elasticity of this structure.

Detail of the sewing joint system; the sewn joint is made in the middle of each panel leaving an overlap of 5 centimeters. This allows for an adaptation of the hexagons to any surface. The thickness of the plywood is 1.5 mm. The different test was done and

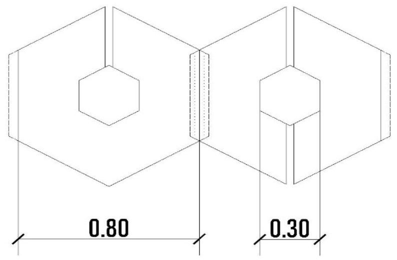


Figure 3. Joint connection between panels.

carried out several samples to be able to know the shear and the stress that these joints could handle. These samples with the sewing machine and different types of joints were tested; through experimentation we came to the conclusion that joints that are overlapped are the best option to be able to transfer loads through the surface (**Figure 4**). Making a reference to the biopolymer, different tests were carried out to find out its resistance and we compared it with a steel cable in which the resistance of the steel cable is greater than 1200 kilos but in the case of the biopolymer its breaking point was 680 kilos (**Graph 1**), which places it as a sustainable proposal and with different experiments we can generate new proposals with this material and increase its resistance.

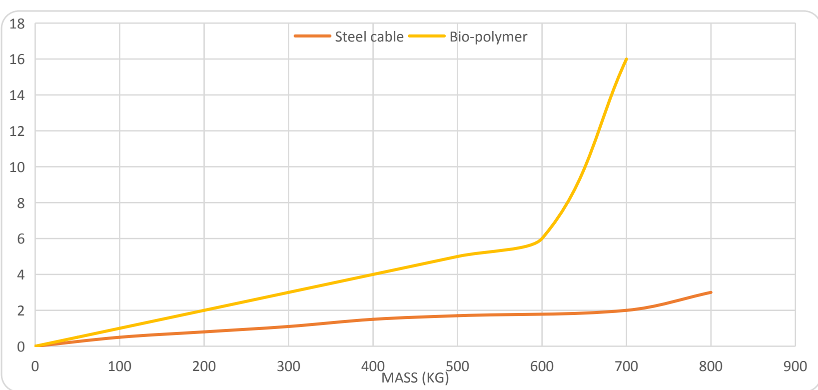
Figure 4. Sewing process of the timber.

3.2 Material and fabrication

For several centuries, timber has been one of the most important construction materials and due to its great sustainability and economic contributions that's why it was used or the main structure and hexagon panels; in the case of biopolymers, they are gaining ground due to its mechanical and structural properties that they promote. It should be noted that the time that infers humanity currently demands analyzing and seeking solutions with a multidisciplinary perspective in order to carry out and generate a better result in the face of the adversities of climate change.

However, the progress during the last decades in digital fabrication, software and new materials has benefited from new possibilities and opportunities of bio-design for architecture and construction, promoting the design of optimal complex geometries. On the other hand, the integration of biology into architecture allows us to better study and understand how to address problems and generate new solutions. Especially in the field of lightweight timber construction, biological role models have helped to redefine building systems, design methodologies, and fabrication technologies.

This research presents the design of an experimental structure that was made in timber and biopolymers for the joints. These materials have a lot of great interest due to their biodegradability, low cost and mechanical properties. In the case of biopolymers have great advantages as a construction material and are gaining a lot of ground in the construction sector; the origin of bio-based additives has been used in construction for several centuries. The Ro-



Graph 1. Analysis of strength of the bio-polymer.

mans for several centuries recognized the role of bio mixes to improve construction materials, an example was the use of proteins that served as retarders for plaster. Another great example it's with Vitruvio, that explained that the use of lime mortar could be mixed with vegetable fat to give a better finish to its walls.

This research presents a new construction system based on timber hexagons that are joined sewing joints, through these joints the use of steel and concrete is completely avoided, presenting a great advantage over conventional construction systems. Using the morphological principles of diatoms, we emulate the unions of the hexagons to generate a new lightweight structure of timber. Sewing joints have a great advantage over steel and cement since they connect each panel of hexagons and help to obtain any radius that can be demanded, simply by adjusting the measurements of each hexagon.

3.3 Applying biological principles to form finding

Different studies were carried out prior to the choice of diatoms for the design of the lightweight structure, different types of phytoplankton were analyzed and the aim was to integrate bio-morphological principles into architecture and engineering; therefore, for the form-finding process, it was limited to the geometric principles of diatoms. In the case of the panels, we opted for the *Coscindiscus Radiatus* species due to its hexagonal shape (**Figure 5**), since this geometric shape has great advantages since it allows different connections with the other panels, thus allowing a better distribution of the load.

It is important to highlight that during the last decades, using biology as part of the form-finding process promotes advantages for the design process, since during this process these principles were transferred to different software such as Rhino7, Grasshopper, Karamba and Kiwi. Helping to better develop and optimize this structure. In the case of this structure, it was decided to use parametric design tools that would allow the development of a structure divided into panels and a main structure; the part of the panels forms the main membrane that is supported by 3 wooden beams anchored directly to the floor. As for the measurements in the central part, it is 3.2 meters high and has a maximum length of 8 meters, with a covered area of 50 m^2 (**Figure 6**).

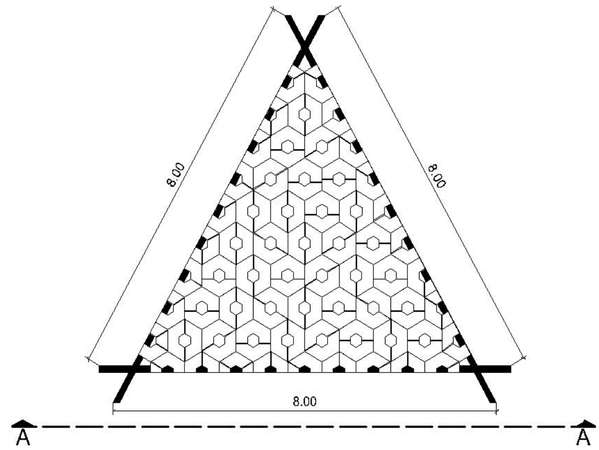


Figure 5. Floor plan of the timber pavilion.

The surface was based on the design of different hexagons that are sandwiched together (one on top of the other) and connected by the biopolymer joints. Different designs were made for the panels and for this structure there were a total of 138 hexagons for the entire surface.

The design of a synclastic structure was chosen, since through the double curvature the shape can be optimized and this is summarized as less material and more covered area. Being a clear example of how to create sustainable and naturally friendly structures. One of the great advantages of this decade is that thanks to technology and digital computing, new opportunities can be developed to develop new geometric shapes that were previously impossible to develop, and this presents great opportunities to develop thanks to form-finding [8]. The development of complex geometric structures and structural optimization are tools of form-finding. Among the innovations of this structure is the link that was obtained from the study of diatoms and how to find the best design for the structure, linking geometry with biology and trying to emulate the principles of biology with the architectural design was a work that helped to develop this structure. This structure integrates a double curvature surface that was developed after several attempts and proposals and this results in an economic structure that also infers not only a lower cost, but also a reduction in energy expenditure and lower CO_2 contributions to the environment. In particular, the demand for double-curvature surfaces has increased in construction, engineering and architecture since compared to other types of surfaces they present great structural and geometric advantages (**Figure 7**).

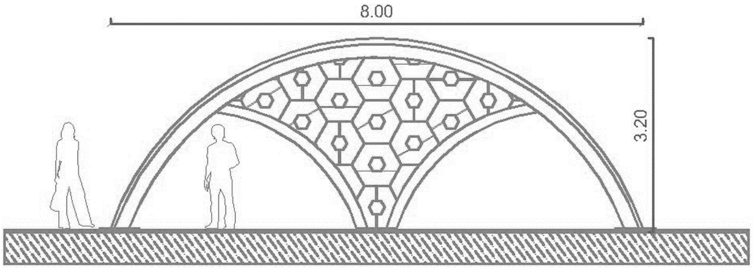


Figure 6. Detail plan of the pavilion.

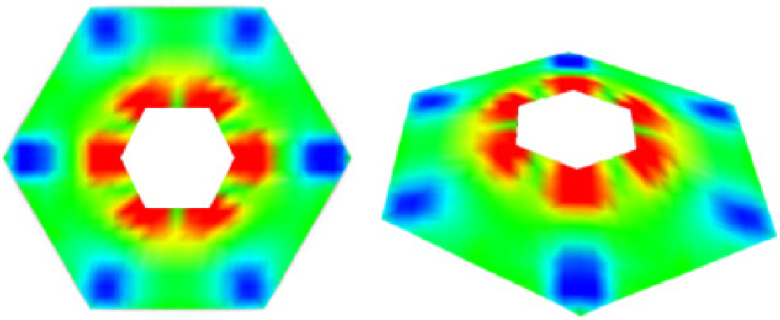


Figure 7. Structural behavior of the panels.

4. Conclusions

The present investigation had a result that encompasses different disciplines such as engineering, biology and architecture and is based on the bio-design of the analysis of diatoms and how their geometric shape can optimize a lightweight structure. On the one hand, the bio-morphology of diatoms can have geometric patterns that are a clear example of structures that have patterns that can develop a new construction and adopt forms that optimize. This means that the integration of bio-materials is a clear example of how new construction systems can be used and generate great benefits for the construction sector.

After using parametric design, digital fabrication and structural optimization new possibilities can be developed to make new and complex geometric shapes and this promotes new practices in design that help to obtain better optimization and structural behavior, this translates as a great opportunity to take advantage of these sustainable and economic advantages to apply them to the actual climate crisis.

Thanks to this research and new proposals that are currently being developed in lightweight structures, the progress and advances that this type of structure has been giving new results as they are a clear example of how the construction sector can contribute to climate change; through geometry, materials and structural optimization an efficient form can be developed. When starting this research, we wanted to see how bio-design can be a great tool for the designer and how biological principles can be transmitted to any design. In the case of biological principles, we chose to transfer the geometry to a hexagonal-shaped wooden panel, which was a great innovation to develop new ways of designing. In the end, we conclude that these biological principles can be applied to different types of wood (shape, geometry, connections, structure...) and that through a multidisciplinary vision they can be applied to any structure.

This research promotes a sustainable, innovative and economic design since after different studies and investigations and thanks to biology it was concluded by the use of diatoms due to their geometric and biological principles. It should be highlighted that with this new construction system, biopolymers were used and neither cement nor steel was used for the manufacture and assembly of the structure. Due to the progress in the investigations of the timber structures, it will be possible to obtain better results that benefit the environment and the economy, the development of new construction systems and the integration of new materials into the structures promote sustainable values. This research is a result of the new construction practices and construction techniques that are currently demanded, which benefit architecture and engineering thanks to digital fabrication and architectural design.

Author Contributions

MG focused on the development of the state of the art and thanks to his experience in the academic world he knew how to land the research questions and the foundations to continue the research. On the other hand, support in the final design of the structure since it has experience in the area of technologies and light structures. through different computer programs I provide the tools to be able to generate a better proposal for the final design as well as the materials that were going to be used.

MD was in charge of executing the research stay at the Biology Institute of the National Autonomous University of Mexico, in which he was in charge of analyzing different diatones in order to find the one that best suited the design needs. Thanks to his experience in the field of light structures and his knowledge in digital fabrication and software, the final design of the structure was obtained. In the same way, I carry out the tests within the Engineering Institute of the same university.

Conflict of Interest

There is no conflict of interest.

Acknowledgement

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