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Biomimetics: emulating the biological behavior of orb-web-weaving spider-silk's structural strength as a newfangled design approach

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ABSTRACT

Biomimetics is likely to play an increasing role in design strategies through simulating natural systems, as it attains highly effective biological solutions in response to life-debilitating circumstances through an adaptive design process, where organisms adapt their morphologies, evolving their form, materials and structures in response to diverse functions and environments.

And thus nature metamorphoses -as a response of various environmental forces and climatic conditions- with minimum energy utilization. Correspondingly, materials are subjected to a methodology of adaptation towards the influence of substantial forces acting on it achieving a state of equilibrium with a maximum performance through usage of limited and minimum resources in a closed ecological cycle.
In this comprehensive grasp, the paper's particular framework is developed based on intensive studies for the spider's silk as a biological material resulting from a complex interplay between surface morphology, physical and chemical properties.
The orb-web-weaving araneid spiders have evolved highly specialized web construction behaviours providing an exemplary model for studying the functional design of protein-based structural materials.

According to researchers, the spider's silk represents an idealistic biological framework, capable of exploring novel methodologies in fibrous architecture addressing sustainability and energy efficiency in terms of forms, materials, hierarchical organizations into structural components, design and processing.

Spider silk is an outstanding model for the development of a more efficient and streamlined overall approach to the design and construction of fibrous systems and its implementation in lightweight structures, interior space planning and furniture design, within an approach emulating its structural strength and material's performance, through utilizing distinct methods of construction that minimize the input of material and disbursement of energy while maximizing the subsequent strength accomplished.

As one of the strongest materials known, measuring just one-thousandth of a millimeter across, is five times stronger than steel of the same thickness. However, it is not only the strength of the silk that makes a spider's web so malleable, but the functionality of the silk, the softness and stiffness when pulled.

And hence the authors aim to investigate the connate properties controlling the spider's silk for a more extensive understanding of its ecological properties, in order to develop an extended lightweight structure, emulating the distinct behavior and performance of the spider's silk concerning its material and structure.

Keywords:Biomimetics, Bio-inspired architecture, Spider's silk, Weaving system, Simulation, Lightweight structures, Natural systems,Shading strategy

1. Introduction

Nature has developed structures with highlyperformative structural capacities, utilizing commonly found materials. These function on the macro-scaleto the nano-scale. The comprehension of the capacities provided through processes found in nature can guide us to emulate and develop complex structures with high performance and ecological manners.

Biologically inspired design or adaptation or derivation from nature is referred to as 'biomimecry', which is imitating biology or nature.

Biology has had to solve engineering problems in an adaptive behavior since subsequent to the presence of life on earth. As design and function in plants and animals have been optimized under evolutionary pressures over millions of years, a small step at a time.
In order to make the most out of nature's genius, it is vital to comprise the fields of biology and engineering. This crossing over exertion can be e a key to transforming natural behaviors into engineering capabilities, architectural designs, and material systems. (1)

In order to integrate nature in engineering terms and architectural framework, it is crucial to sort biological capacities along technological categories using a bottom up approach or vice versa.
Time and scales may be different but design constraints and objectives are fundamentally the same, multi-functionality, optimization, adaptation and expense viability.

Hence, it is not astounding that humankind has constantly respected biological structures and often been inspired by their principles and behaviors, for we can appreciate their aesthetic attributes as well as their engineering framework and design strategies.
And by narrowing the research scope with regard to investigating the spider's silk where orb-web-spinning spiders produce a variety of high performance structural fibers with mechanical properties unmatched in the natural world and tantamount with the absolute best manufactured synthetic fibers produced by modern innovative technology.

Its biological materials are exceptionally sorted out from the molecular to the nano scale, micro scale and macro scale, regularly in a hierarchical progressive manner with complex nano architecture that ultimately makes up a horde of diverse functional elements (2).

Its material properties and surfaces result from a complex integration between the surface structure, the morphology, the physical and chemical properties.

And hence the complete understanding of the silk/web system and transferring its morphology into a fibrous architectural system and building technologies, requires deep investigations for its material and structural performance, from the protein sequence to the geometry of the web as a highly adapted system with exemplary mechanical properties for the construction of an extremely light-weight performative structures.

2.Historical approach for biomimetic research

Biomimetics is extracted from the Greek word biomimesis. From an authentic standpoint the term biomimetics was introduced in the 1950s by Otto Schmitt, an American inventor, engineer and biophysicist who was in charge of developing the field of biophysics and establishing the multi-disciplinary field of biomedical engineering.

Otto Schmitt was a brilliant biophysicist, whose doctoral research was an endeavor and strong attempt to produce a physical device that unequivocally impersonated the electrical action of a nerve. (3)

2.1FreiOtto

Architecture is an indispensable aspect for Frei Otto. He is not intrigued by designing only for a single person, he needs his structures to contribute to enhancing everybody's living conditions.(4)

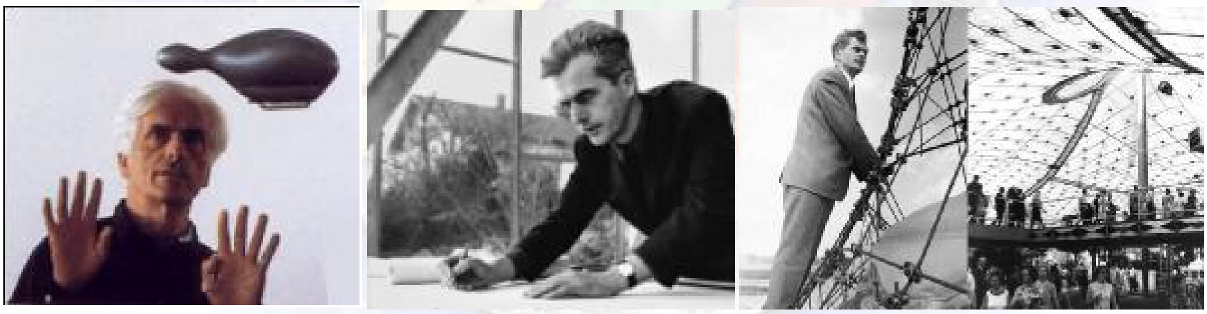

Fig.1 (shows architect Frei Otto, a pioneer in lightweight structures (5,6,7)

Frei Otto’s inventiveness for materials and structure has pushed him to analyze and test the cutoff points of lightweight structures.

In 1952 he built up a studio at Berlin. He earned his doctorate on tensioned constructions in 1954 with a thesis concerning the subject of “The Hanging Roof.” Through its framework, he undertook the first comprehensive analysis and experimentation of the construction technology of tensile planar structures. In 1957 he established the “Development Center for Lightweight Construction” in Berlin.

Subsequent seven years in 1964 he transferred the center's approaches to the "Institute for Lightweight Structure" in Stuttgart where he directed the institute till his retirement as university professor (8)

Fig 2(shows architect Frei Otto in the institute

for lightweight structure and conceptual design at Stuttgart) (9,10)

Otto is the world's most famous architect who designed with lightweight tensile and membrane structure and has pioneered advances in structural analysis and civil engineering.

In the 1950s he utilized models to define and test complex tensile morphologies. As the scale of his projects expanded, he pioneered a computational framework for determining their form and behavior. He regularly created pavilions composed of primary membrane elements in an additive substance arrangement.

.In 1960 Otto established a biological examination research unit to study natural structures, their principles and behaviors. He created a system for grid shell structures that followed the same concepts and principles of free form framework and structural lightness.

Fig.3 (Shows the Mannheim multihall, its constructional process and form finding) (11,12,13)

In 1960 Otto also established a biological experimentation research unit to investigate natural structures. Havinginspiration from plant cells, spider webs, bubbles and other natural structures.

2.1.1 The Olympic Stadium in Munich, a computational framework

The Olympic Stadium in Munich, 1972, was considered progressive for its time. This included huge sweeping canopies of acrylic glass stabilized by steel cables that were firstly utilized on a large scale. Without the use of FE Software, the sweeping and transparent canopies would have not been possible. (8)

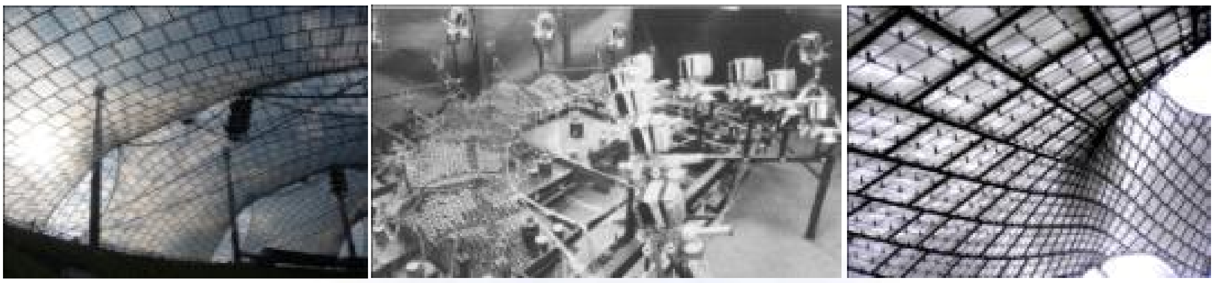

Fig.4 (shows form finding methods for the roof of the Olympic stadium in Munich) (14,15,16)

2.1.2 Indoor stadium and minimal surface

The roof of the Olympic Stadium in Munich, which covers and brings together the stadium, tracks and pools, was developed in view of the utilization of computerized numerical systems in deciding their structure and behavior, bringing about an architectural form of "minimal surfaces initially utilized in voltage covered with these dimensions, 74.800m2

Minimal surfaces, as tension equilibrium structures, are the perfect premise to assemble the most efficient lightweight tension membrane structures with a minimum amount of mass and materials.

Frei Otto believes in innovative technology and imagined structures of extreme lightness as well as extreme structural strength and stability. Sketching and modeling worked at a small scale but for his work and structures to grow he required FE Software.

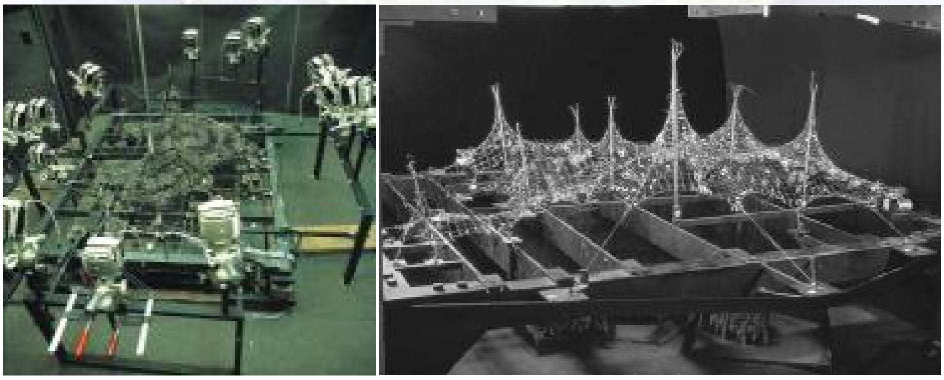

Fig.5 (Shows a computational framework for

Frei Otto at his Institute for lightweight structure and conceptual design) (17,18)

He shows how important the relationship between drawing, modeling, experimenting with structure and materials, and construction is in the architectural process.

Correspondingly, today's technological and computational approaches plays a vital role in advanced mimicking for form and material behaviors, through computational strategies' frameworks, additionally develops physical prototyping that was once exclusive to the fabrication process

3. Research problem

[Case study: Alexandria University, Faculty of Fine Arts Campus]

Space is a limited University resource and, consequently, it must be managed responsibly and in a way that promotes the advancement of the University's mission and the strategic priorities of the campus.

It's widely noticed that the University campus comprises several outdoor spaces concerning parking slots, theatre, café and few administrative spaces all suffering a lack of coverage systems and structures inscribing these functions

Putting in consideration the primary zones located within the campus, there is no space for any extended structures to be added. Moreover roof alterations will not be appropriate with the current physical characteristics of the historical building as it can't bear any extra vertical loads.

And through analyzing the campus's location corresponding to climatic circumstances, the campus is subjected to direct sun light during summer that results in rising temperature, in addition to high wind flow during winter.

Taking into account these two major problems' aspects and through further studies, the authors have started through a biomimetic design strategy, pursuing several analysis to translate it into an architectural scale through a proposed design system which is ultra lightweight structure compatible with the structural analysis of the historical building, further more it's wind resistant and a scattering system for excess sun light.

Fig.6 (shows the location of the Faculty of Fine Arts and the proposed space for installing the extended lightweight structure)

Fig.7 (shows the Faculty of Fine Arts as a case study, photos taken by the authors)

4. Research's objectives

The research is concerned with developing an experimental performative light-weight structure with complex structural morphologies emulating the orb-web-weaving araneid spider's ecological behavior within a framework investigating the sophisticated silk web-structure.

It aims to explore novel biological constructional principles for the orb-web spider regarding its environmental manner through evolving its high-performance structural fibers and transfer these principles into the architectural scale.

The research investigates the connate properties controlling the exceptional mechanical properties of self-assembling silk, initiating a neoteric approach for a more extensive understanding of the protein-based structural fiber through a novel fabrication framework.

The research explores novel methods for developing advanced structures from ordinary natural composite materials.

And thus the research explores the biological principles that can be reproduced and then applied into architecture with new structural load-bearing morphologies.

Subsequently the authors attempt to introduce a biologically-inspired design methodology based on the analysis of the orb-web-weaving araneid spider's behavior within diverse aspects as shown

5. Research's methodology

The research's methodology will be based on an analytical approach introducing deep investigations for the constructional process of the orb-web-weaving araneid spider's web, 3d scanning its complex structural morphology, in order to exploit the full potential of the three dimensional web and the way it contributes to an ultimate structural behavior.

The research will be immersed in analyzing the ecological properties with regard to the protein-based silk material behavior concerning its fabrication principles, specifications, strength and stretch ability, its physical properties, in addition to its molecular structure and mechanical function.

The research will develop further investigations for transferring the ingrained properties of the complex web structure and its material organization into the architectural scale, and constructional principles for extended light-weight structures.

6. Analysis of the orb-web model

6.1 Studying the constructional process for the orb-web

Orb-weavers spin their webs at night.From a suitable beginning stage, for instance, the branch of a tree, they discharge a string of solid silk from their spinnerets into the wind. Once it catches on something, the spider pulls the thread tight and anchors it.

At that point, it strolls forward and backward, reinforcing fortifying the line by including more strings. This is known as the bridge line; it will support the weight of the whole web. On the off chance that the starting thread doesn't catch, the spider may eat it to reuse the protein before attempting once more. Bridge thread isn't sticky.

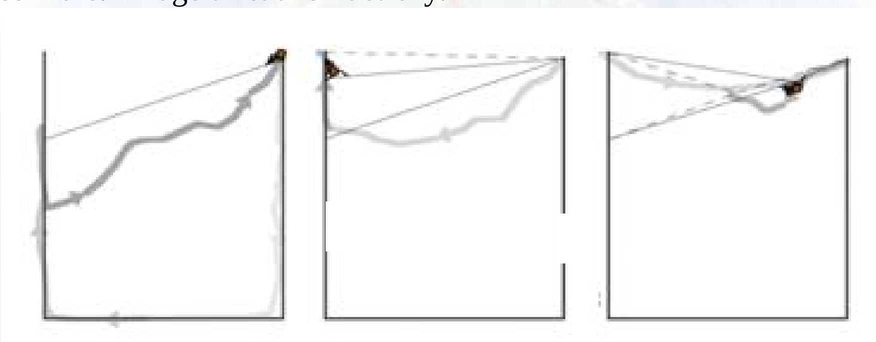

Fig.8(shows the first phase in the web's constructional process) (19)

Next, the spider strings a loose string, sort of U-shaped thread, from the bridge, then moves to the base of the U and drops a thread from it, framing a Y-shape.
After that, the spider shapes a primary concern to join the tail of the Y string, and this finishes the edge.

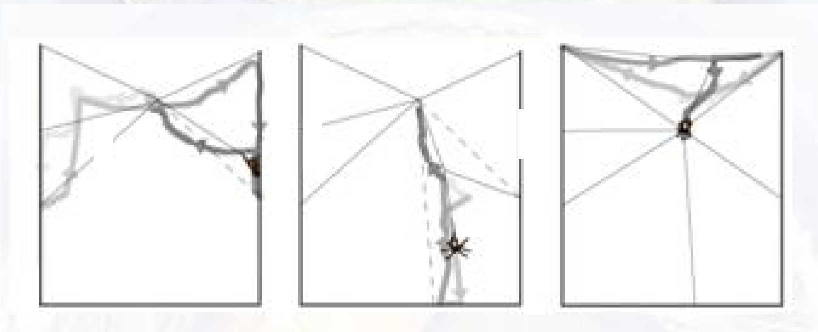

Fig.9 (shows the second phase in the web's constructional process) (20)

The finished Y shapes the initial three outspread strings of the web. More radial threads are then strung. More outspread strings are then hung. Taking after that, strings are included an "auxiliary spiral" from the middle outward.

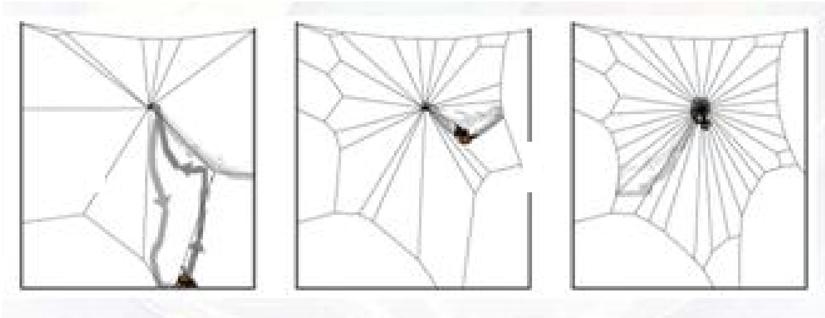

Fig.10 (shows the third phase in the web's constructional process) (21)

As such, the strings aren't sticky. But, now, sticky string is hung between the outspread lines, with the spider gobbling up the assistant winding as it lays the sticky winding.
The last development comprises of non-sticky system and outspread lines, plus sticky circular lines, in addition to sticky roundabout lines.

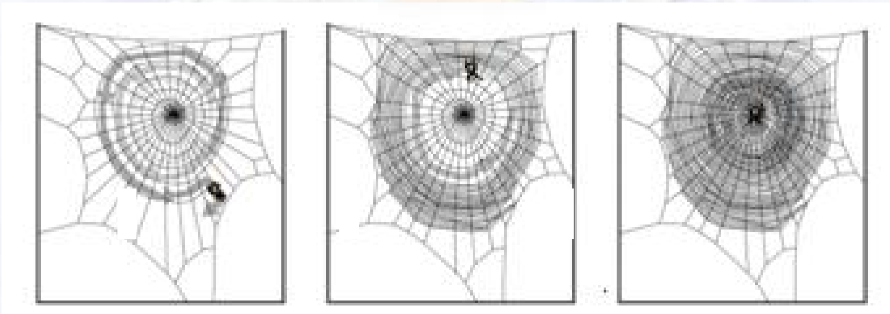

Fig.11 (shows the fourth phase in the web's constructional process) (22)

The spider then sits motionless in the center,holding up to feel vibrations on sticky silk, a declaration that prey is caught.
The spider proceeds onward the web by venturing on non-sticky outspread strings and the structure, while dodging the sticky round strings.
On the off chance that the web doesn't get excessively harmed, the spider may utilize it over and over, fixing it up a bit. A few spiders eat their web, except for the framework, each morning and re-turn it every night

6.2 The orb-web's structure

Based on a structural approach, the orb-web represents a cable structure with a high tension behavior and whose structural capacities is based on pre-stress for both form and load bearing manner.

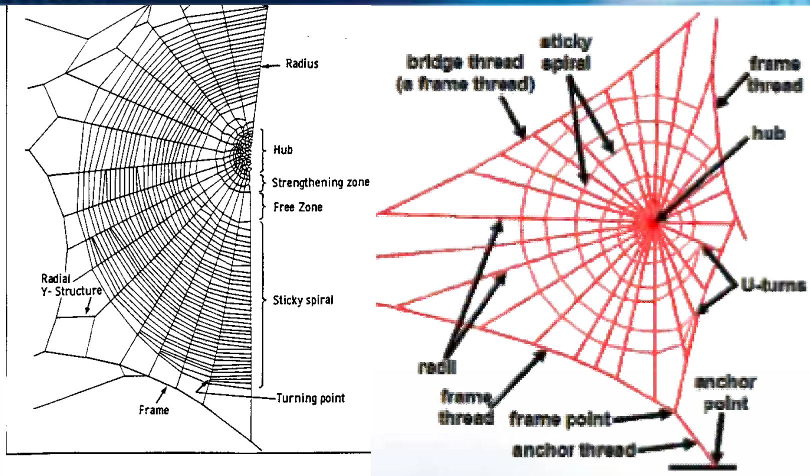

Fig.12 (shows the orb-web's structure) (23, 24)

7. Material analytical framework, mechanical properties of spider's silk

Spider silk represents a biological material with great mechanical properties. It includes high structural capacities, toughness, and strength-to-weight ratios five times corresponding to that of steel fibers.

The structure of spider silk is of particular interest at the molecular level due to its effects on the properties of the material, particularly its mechanical behavior.

Spider silk is famous for its mechanical strength. As an example, MA silk fibers of A. diadematus have strength in the range of high-tech fibrous materials.

Most importantly the toughness of spider silk is a lot higher than that of man-made fibers based on its low density, 1.3 $g.cm^{-3}$ compared to e.g., 7.8 $g.cm^{-3}$ of steel. (25)

8. From spider's silk structure to architectural lightweight structures

Lightweight structures effectively consolidate materials to accomplish a very low mass/span ratio, incorporation curvature for aesthetics.
They are highly material performative systems concerning the fact that materials are ideally utilized. In this manner no resources are squandered.

Physical quality of lightweight structures tend to focus on structural ingenuity and betterspecialized execution strategies and technical performance of structural members by use of lighter material substances or structural compositions.
The lightweight structures are directed towards the integration of material research and design strategies. (26)

9. Y-thread extended lightweight structure

A light weight structure designed by the authors as an experimental design proposal for a coverage system within the Faculty of Fine Arts campus

9.1 Project’s phases

9.1.1 First, biomimetic research

The research started with a biomimetic framework, capturing photos for the spider’s web and in order to analyze its structural morphology

Fig.13 (shows photos taken by the authors for the spider’s web as a primary phase, photos are taken by the authors)

9.1.2 Second, physical prototype

Physical prototype is presented for emulating the biological principles and structural capacities for the orb-web for analyzing and studying the correlation between the material’s behavior and structural performance.

Fig.14 (shows a mimicking process for the web’s structure)

9.1.3 Physical prototype for the campus and the lightweight structure

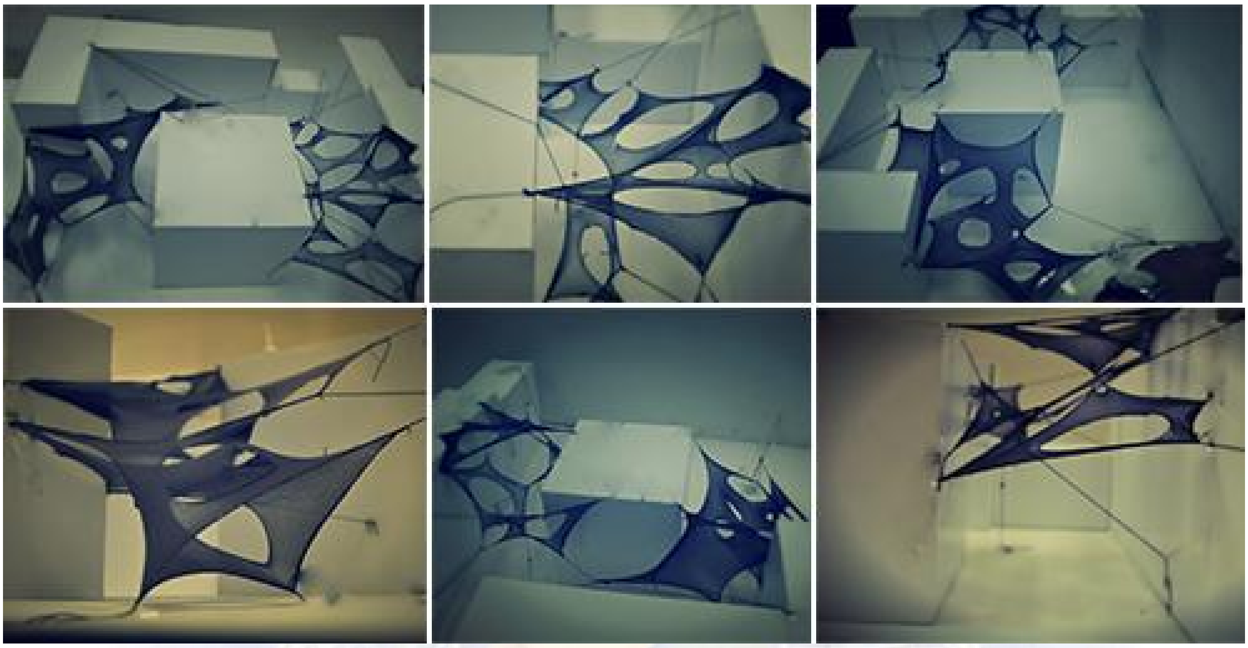

Fig.15(shows physical prototypes for the extended lightweight structure proposed by the authors)

9.1.4Third, 3D scanning for data acquisition from the physical model

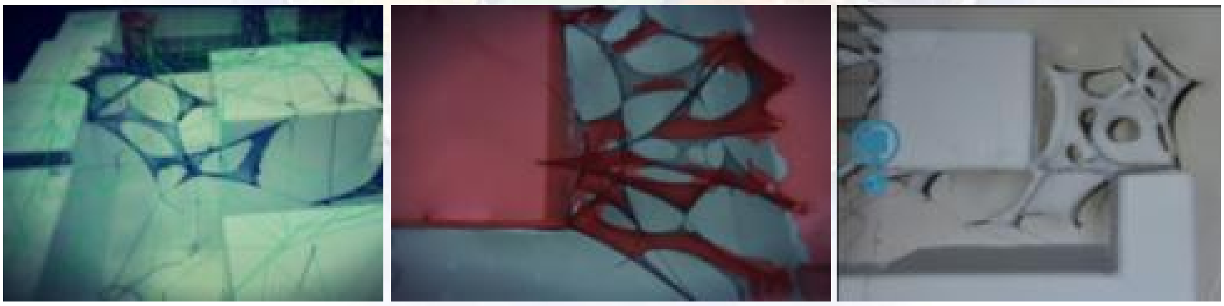

Fig.16 (shows 3D scanning procedures for the physical prototype)

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9.1.5 Fourth, Form simulation for computational model

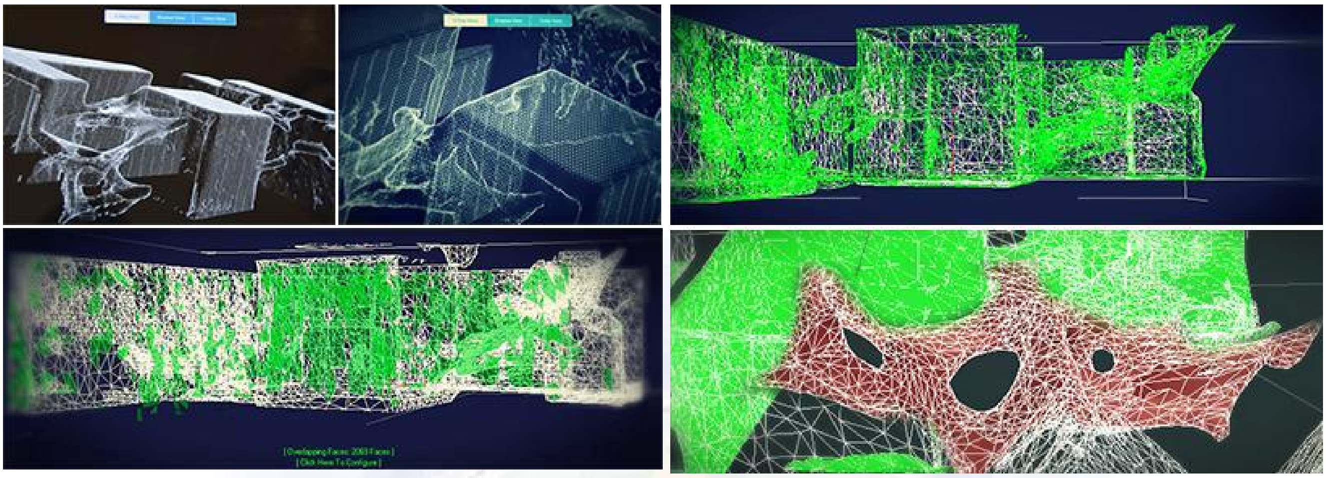

Fig.17(shows form simulation for the model)

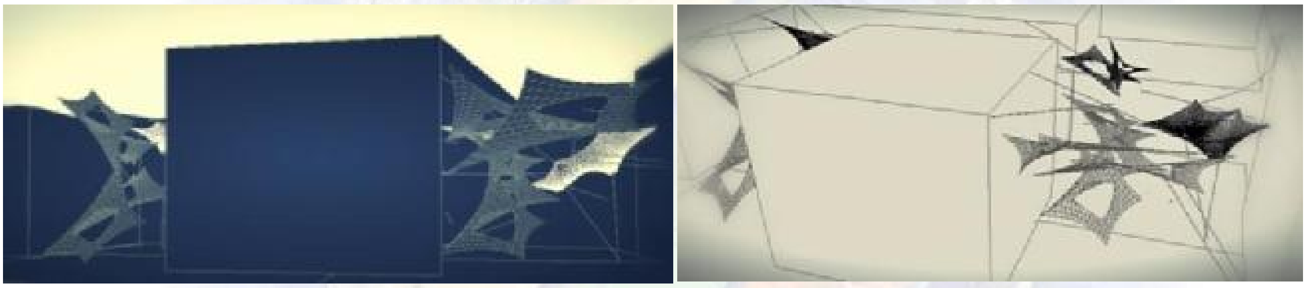

Fig.18(shows 3d models for the Campus)

9.1.6 Fifth, The Campus proposal

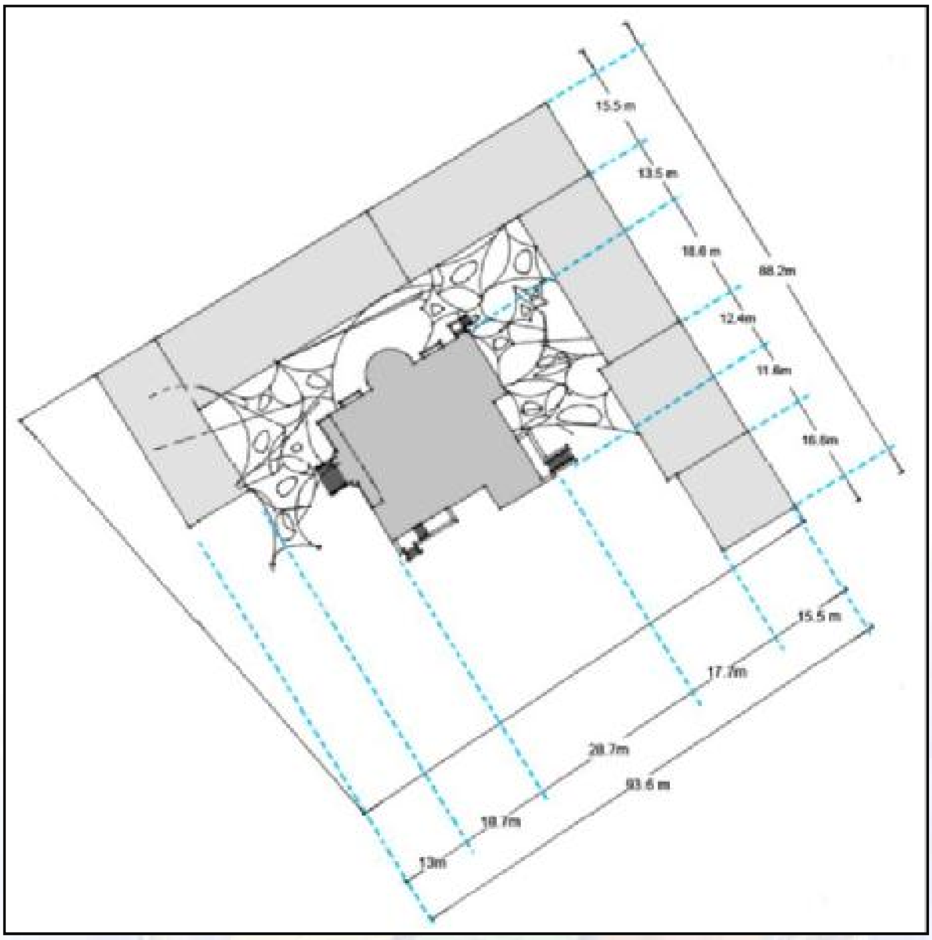

Fig.19 (shows a plan view for the extended lightweight structure)

Fig. 20 (shows a proposal for the extended lightweight structure)

10. Project proposed materials

As for the proposed project, Aluminum rods, steel cable and carbon fibers are the recommended materials to be used, while the carbon fibers can be replaced or combined by glass fibers, for their light weight and various uses and applications.

With the aid of a physical prototype and a 3dscanner, the researchers were able to create a three-dimensional simulation of this weightless form that is mainly inspired from the orb-web.

10.1 Light structures materials

10.1.1 Carbon Fibers

Carbon fibers represent a material with a high structural capacity. They are utilized in a manner where segments need to be mechanically robust while remaining lightweight.

Fig.21(shows carbon fibers as a light structural material for constructions) (27)

10.1.2 Glass fibers:

Glass fiber is the most overwhelming fiber utilized in the reinforced polymer industry and among the most flexible. Fibers produced using glass are fabricated in numerous assortments for particular uses. It regularly has a silica content of more prominent than 50 percent. (28)

Fig.22(shows a detailed view for glass fibers) (29)

10.1.3 Textile-Reinforced Concrete

The reinforcing material comprises mechanical materials made of high-strength carbon fibers. “Textile-Reinforced Concrete: Basics for an Innovative Technology” Throughout the most recent twelve years, eleven RWTH institutions in the fields of civil engineering, mechanical engineering, the natural sciences and architecture have led multidisciplinary research on the innovative material, concentrating on principal approaches additionally potential outcomes of applications.(30)

10.1.4 Future materials

Nature gives us a plenty of procedures in order to fabricate with fibers accomplishing particular objectives.Comprehending the structure, function relationships is key in producing and developing textile products which are adaptive, thermo-resistant, and self-healing, examples of which are plentiful in nature. The deep need for sustainability and ecological approaches requires not just emulating natural design but also the process (31)

11. Conclusion

It is obviously recognized that nature has evolved and optimized a large number of materials and structured surfaces with rather unique capacities.
And hence the authors have found that deep investigations and analysis for the ecological systems and behaviors concerning the spider's web morphology, its constructional principles and structural capacities, the silk material used have developed an extensive biomimetic framework and structural principles.

After deep studies for the constructional process of the spider's web, physical prototype, 3d scanning for form simulation and analysis, it can be widely noticed that the biologically-inspired tensile system has demonstrated high potentials with regard to elasticity as it is unaffected by extreme climatic conditions.
Its consolidate double curvature and high tension capacities provide structural stiffness. The curvature and tension keeps the layer from rippling under wind loads.

It permits wide choice of natural light transmissionconcerning edge treatment & building connections, Catenary edges result from the edge cable & fabric tension, also Gutters can be placed along building walls or at columns. Furthermore it can be re-located & re-used.
In terms of sustainability, it allows energy Savings through natural light transmission, in addition to material efficiency through utilizing a minimum amount of mass and materials due to minimal surfaces behavior.

And through further material analysis and comparing the mechanical properties of spider's silk fibers to that of carbon fibers in diverse terms concerning elasticity, strength, and stifness
Carbon fiber was found as an ideal proposed material to be used for the coverage system due to its high performative qualities (high strength to weight ratio) and the potential to generate differentiated material properties through fiber placement variation

12. Recommendations

The research emphasizes the notion of high integration between natural and biological systems, material analysis, and advanced computation design tools as it achieves high degrees of environmental coherence and performance, material efficiency and ecological construction principles.

Advanced computational design tools should be highly developed in order to develop novel fabrication methods for performative structural form findings.

It is highly recommended not to overload the existing structural system for the historical building, as it would affect its structural performance and would undergo several load-bearing problems.

Examining and evaluating the physical conditions for the structural system and its individual features before introducing any added structures to the site.

It’s highly recommended to optimize the material strengths and avoid wasting resources through material-efficient lightweight structures.

Buildings should employ passive heating system and day lighting depending on sun control and shading systems

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