How can spiders and silkworms structures and material influence architecture and design?

Word count: 4685

Content

Figures

Abstract

Material and structure are key elements to interior and design. We can learn about material and structure from nature. More specifically silk structures are created by spiders and silkworms. The research undertaken looked at how interdisciplinary architectural practices made use of a natural way to create structures and particularly silk as a material. Three case studies by interdisciplinary studios (Frei Otto - lightweight structures, Neri Oxman - Material Ecology, Tomás Saraceno - spiders' behaviour and art installations) were used to discuss the work and to extrapolate on the findings. Silk is a strong material and can be made into a bigger scale. Studying spiders web construction can help us progress with stronger and better structures. Working with both spider silk and silkworm silk can help advance future structures and materials. By working across the fields between architects, biologists, engineers and more, we can work together for a sustainable way of living.

Introduction

More architects and designers take inspiration from nature and nature's behaviour and how animals build and use their material. Spider web and silk are robust construction methods and strong materials. Silkworm's silk is also strong but not as strong as spider silk. However, both can analyse the space and repair a particular part instead of the whole web. Their silk is biodegradable, which makes it a very sustainable material.

This dissertation looks at three interdisciplinary architects and designers applying structure and material studies to their designs. The interdisciplinary studios are (Frei Otto - lightweight structures, Neri Oxman - Material Ecology, Tomás Saraceno - spiders' behaviour and art installations). Frei Otto looks at spiders' structures and takes inspiration into his tensile structures. It is done lightly to use less material, but it is still a solid way to build a strong structure like the spiders. He works naturally in harmony with nature. He started a new research group called "Biology and nature", which was relatively new at the time to mix disciplines. Neri Oxman has studied silkworms' behaviours and how they move and work. She found out that she could easily control the silkworms by controlling their climate. Oxman used that in two of her designs, Silk Pavilion I and Silk Pavilion II, to control where the silkworms would work to increase the density of the silk in certain places. Oxman's primary client is nature; she loke to grow, adapt, and respond to the environment. Tomás Saraceno has, with help from scanning equipment, studied spiders' behaviour. How do the spiders build their 3D webs to ensure it is a strong structure, and how do they improve it over time. He takes inspiration from this into his interior art installations. Making different spiders work on each other's web creates beautiful constructions. His work is suspended in the air, just like a spider web. They all co-exist or work in favour of nature in some way. We could learn and develop our structures and materials to look at how nature and these animals do it.

Firstly, looking into the structure and material that spiders and silkworms produce will help to get a better understanding. Secondly, looking closer at two of the designers research into spider web and silkworm web to see the benefits and properties of what they can bring into the world of design. Thirdly, introducing the case studies to see how they have done it in practice, learning how they put the ideas into a physical design. Finally, a discussion about what I found and compare the case studies and looking at future possibilities.

Silk, Structure strength

Silk is a natural material produced by spiders and silkworms. For the size that it is, the silk is strong. Studies have been looking into the strength of silk that comes from these insects and how well it would perform on a structural building scale; to decide if silk is a good building material or not.

Natural silk produced by spiders attracts future advanced structural uses and has environmental advantages alongside its properties and processing efficiency. The way spiders build their silk web helps enhance the robustness of its structure. A web is produced by the spider's dragline silk fibre which is the singular strand produced directly from the spider's finger-like spinnerets (Fig.2). (Porter, 2013) Cranford (2012) mentions *"...robustness arises from extreme localisation of failure at sacrificial elements..."*. Meaning if some parts of an aerial web were to break, the main structure of the web would still function. That is a method we could learn from and implement today's designs

This means the spider could rebuild the particular part instead of rebuilding the whole web. (Fig.1) represents an example of a local failure in an aerial web, where the spider can quickly repair it. Looking at the research that has been made, there is a future with possibilities for this material. A future of experimenting with the material and its structure could help modern designs to advance. Silkworms silk is also a naturally produced product commonly used as a fabric, but it is not as strong as a spider's dragline silk fibres. Non-natural silk has been reconstructed in the same way as natural silk, showing the potential to have similar strength and toughness depending on the appropriate size and molecular structure. On the other hand, artificial materials such as nylon have weaker properties and have environmental disadvantages. (Porter, 2013)

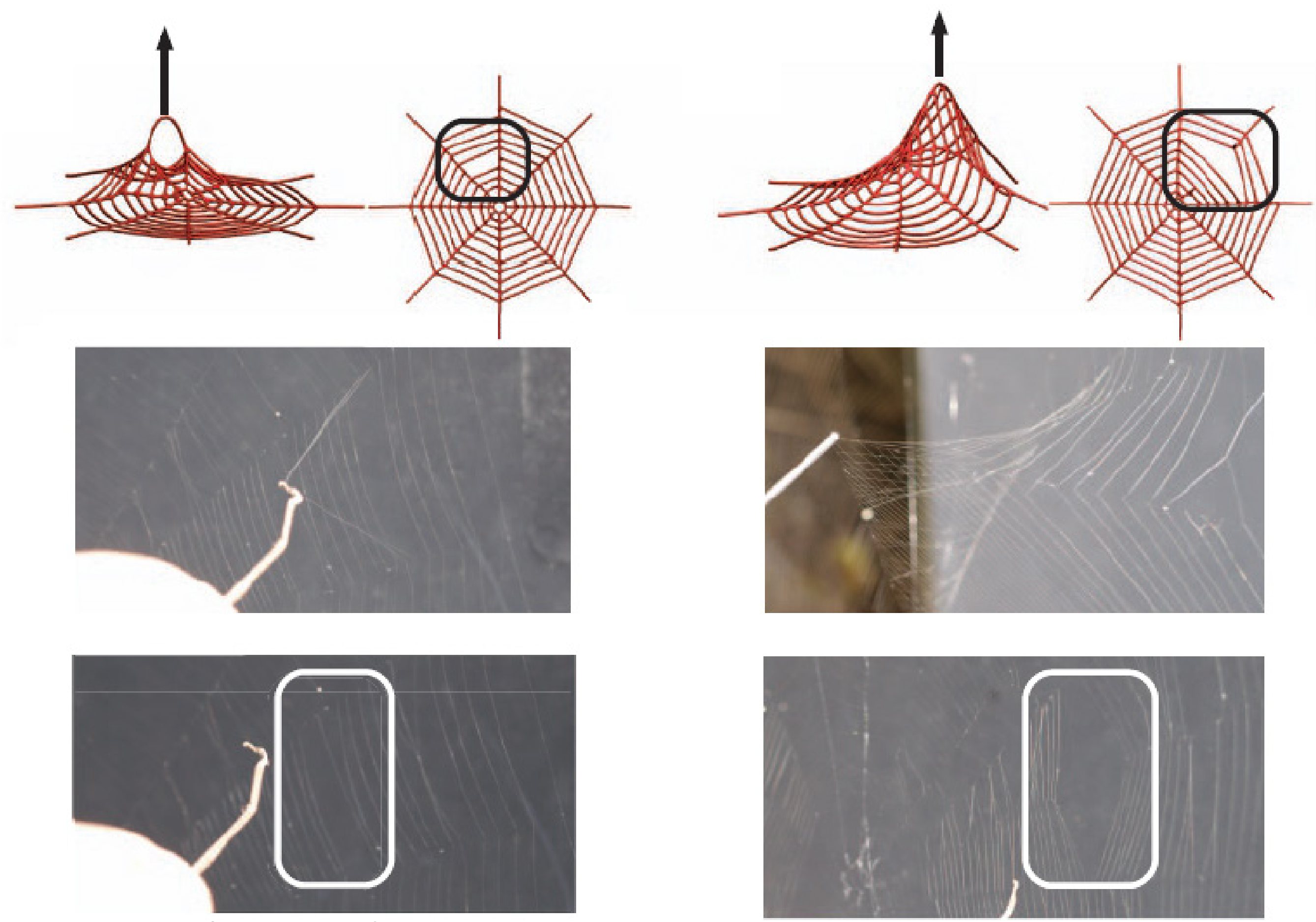


 Fig.1 Local failure (Cranford, 2012)

Silk as a material

Silk is a material produced by insects such as spiders, moths, and bees (Kapsali, 2016). Many designers have taken inspiration from their way of building nests or habitats. Their natural works and techniques have been studied and implemented in our architecture, design, and art. Looking closer at how insects create silk, the insects produce solutions of amino acids inside their bodies which then comes in contact with the air as it solidifies through oxygenation. (Kapsali 2016) The silk comes through microscopic holes and makes fine long continuous fibres (fig.2). For a long time, humans have tried to recreate silk as a material that started approximately 3000bce in China (Kapsali, 2016). Nowadays, we try to recreate it, but it is done in a less sustainable way and a much more comprehensive range of products. As mentioned previously, nylon is a type of plastic that doesn't biodegrade. At production, it releases a kind of greenhouse gas called nitrous oxide. Therefore, it contributes substantially to global warming (M, C. 2020). According to the research by Kapsali (2016), silk produced by insects is biodegradable, which makes it a sustainable material.

Kapsali's (2016) research suggests the remarkable properties of spider silk. One is its healing abilities used by humans to treat wounds. The spider's silk is also used for different purposes due to its nature of being; Sticky, strong, stretchy, and cement-like. With these properties, its functions can be used for a regular net/web, capture and wrap prey, or construct protective enclosures. (Fig.2) shows a close-up picture of a spider producing silk.

The dissertation will look at three different examples of interdisciplinary designers, all approaching various methods using spider webs or silkworms towards their designs, namely lightweight structures and general use of materials.

Fig.2 "An electron microscope image of finger-like spinnerets of a spider" (Das et al., 2015).

Tomás Saraceno, alongside MIT and Studio Tomás Engineers, Isabelle Su, Neosha Narayanan, Marcos A. Logrono, Kai Guo, Ally Bisshop, Roland Mühlethaler and Markus J. Buehler, closely studied the silk structure of spiders, using 3D scanners produced by image-processing algorithms to record a spider's movements. Neri Oxman did a similar study with silkworms showing their movement on various surface structures and how they create their nets in relation to different circumstances.

According to the research by Su et al. (2021), spiders are nature's engineers. We can learn a lot from how spiders build lightweight structures with little support. His study digs deeper into 3D spider webs that are more complex to describe and understand than the 2D web. The web is not only strong and lightweight, but it is a biodegradable and biocompatible material (Su et al., 2021). A spider monitors the web and detects any defects needing additional strength or repair. For future structures, materials and building systems, this could be a great way to achieve more sustainable and high-performing designs and working methods.

The spider works in a way where it builds the main geometric structure within the two first days after analysing the space. The arachnid would work in a non-linear way to reinforce the structure after those two days. The density of the web increases significantly more in the next two to four first days. (Fig.3) shows a diagram of the density, scan, and model through a period of days to show a better understanding of the way spiders build. They prove that the density increases more after the two first days. The scan also indicates that the fibre length median increases between day zero and two.

The spider web stretches in a significant way, enhancing the dragline's strength. When building in nature, spiders attach their web to moving objects such as trees, doors or even cars, testing the dragline's tensile strength, resilience and stretchiness. As the density of the web increases, so does its strength. (Su et al., 2021). Even in its early stages, the web avoids a cataclysmic collapse as the fibres are methodically well distributed. Slowly after this, the web is gradually reinforced, strengthening the silk structure further. (Su et al., 2021)

Fig.5 Rectangular FEM-Dice platforms (Oxman et al., 2013)

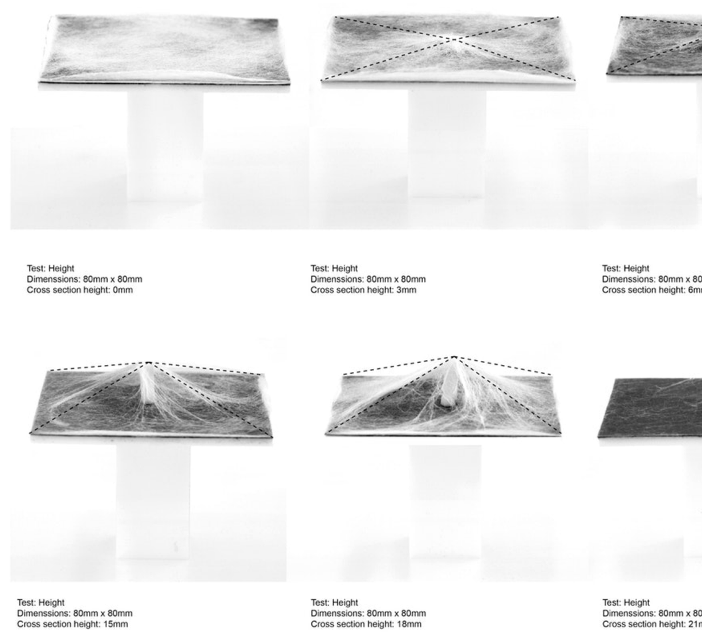


Fig.4 Silkworm templated response to height (Oxman, 2013)

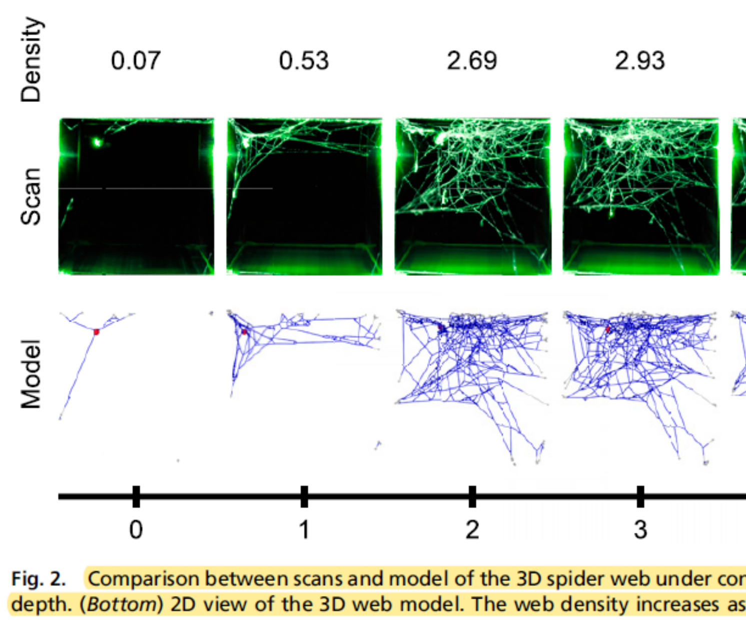
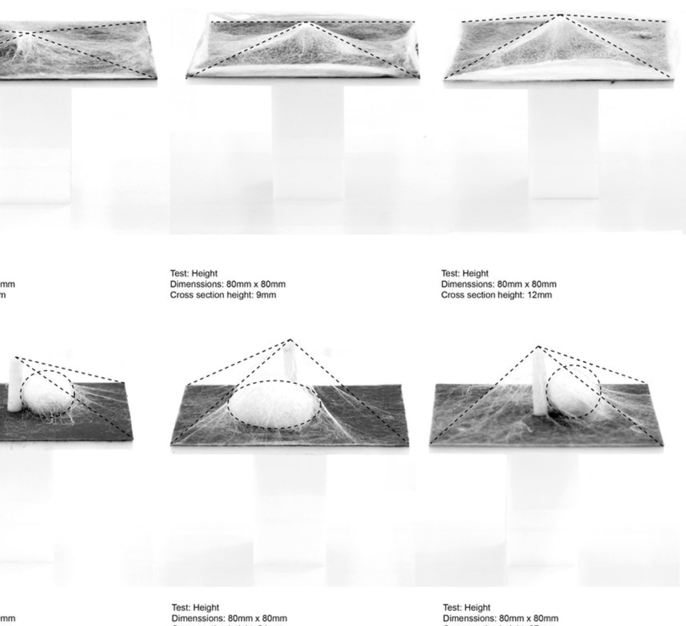
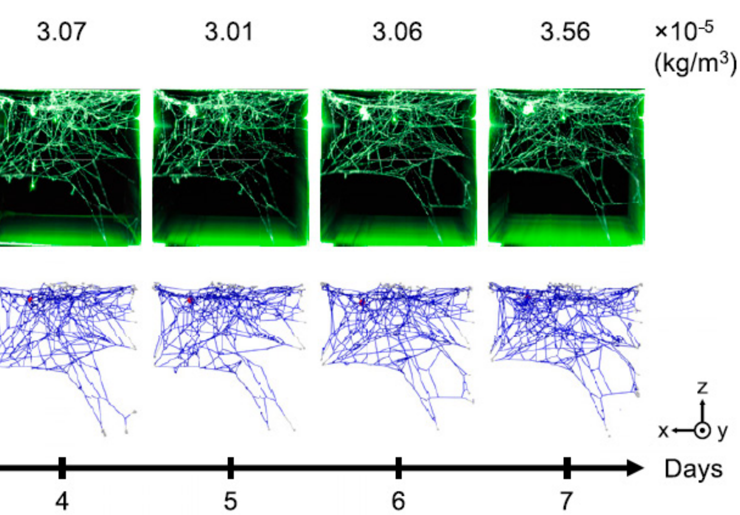


Fig.3 (Su et al., 2021)

Neri Oxman has studied the way silkworms build their three-dimensional cocoon. The way the silkworms work depends much on the light and the micro-climate in the environment around them. They tend to go towards colder and darker areas.





nstruction. (*Top*) Each scan image is an image superposition of all the scans over
the construction progresses.

In (fig.4), Oxman has made a study to see how silkworms work with height. Oxman could control the silkworm's movement by controlling the climate around them. The first experiment was on a flat surface with no vertical elements added to it. The silkworm did not make a 3-D cocoon structure as anticipated. The Bombyx mori silkworm was proven to spin silk flat with no vertical element to support it. (Oxman et al., 2013)

Oxman furthered her experiment following the flat surface by adding height into the equation. The heights used were as follows (all heights mentioned). Firstly, they discovered within the 21mm mark; a tent-like rectangular based pyramid structure would appear and only after that mark a cocoon would emerge. Anything below that height, a non-enclosed patch was spun. Later, the density of silk varied from the centre to the edge of the surface. This indicates that in the given timeframe, silkworms use an efficient method of creating a stable and robust structure using the least amount of energy. Finally, the edges became denser of the lower poles, which could indicate the ideal location for the cocoon to be placed. (Oxman et al., 2013)

(Fig.5) Shows the FEM-dice series, where they experimented with different 'dice-face' configurations, using poles as dots where they would be placed in various locations with varying heights of 10-15mm. The assumption was that the silkworms would reflect the placement of the poles in density and organisation. The variation in the membrane-tent-like structures static force hypothesis and the density assumptions were confirmed. (Oxman et al., 2013)

(Fig.6) variant represents the Polygonal FEM-Dice test. This study once again confirms the stress-strain and fibre structure relationship as per the previous studies. (Oxman et al., 2013)

(Fig.7) begins the 3-dimensional vault-like structures. The new constraints and shapes have varying sectional heights between 5-20mm and are represented in their fibre density and organisation. Edges are denser and have a stronger circle patch in the middle, indicating the silkworm's attempt to create a cocoon. It is only above 20mm when a cocoon begins to appear. (Oxman et al., 2013)

The final test (Fig.8) shows the Maltese cross. Gaps are introduced to the silkworm's circular movement. The sectional height from the previous test remains the same while combining the thrust-vault and flat-dice series. (Oxman et al., 2013)

In concluding these tests, the information gathered shows that spiders create a much more structural web in comparison to silkworms which produces a more fabric-like final product. Silkworms can be manoeuvred at will with light and climate, placing them where structure density would be improved. Spiders, being natural engineers, instinctively identify the weak spots of their structure and systematically look to reinforce them. Both insects' silks are biodegradable and have easily repairable properties, which can be a helpful feature for future designs. Oxman's study of silkworms can create more sustainable, easily fixable interiors. To summarise, combining the structural elements of a spider web and a silkworm sheeting outcome could be a way forward in building interior spaces.

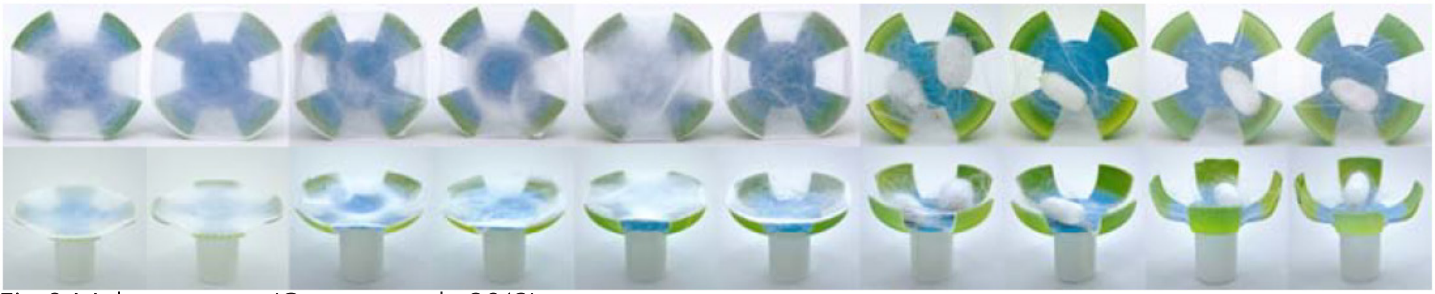


Fig.8 Maltese-cross (Oxman et al., 2013)

Fig.7 three-dimensional thrust vault spinning platforms (Oxman et al., 2013)

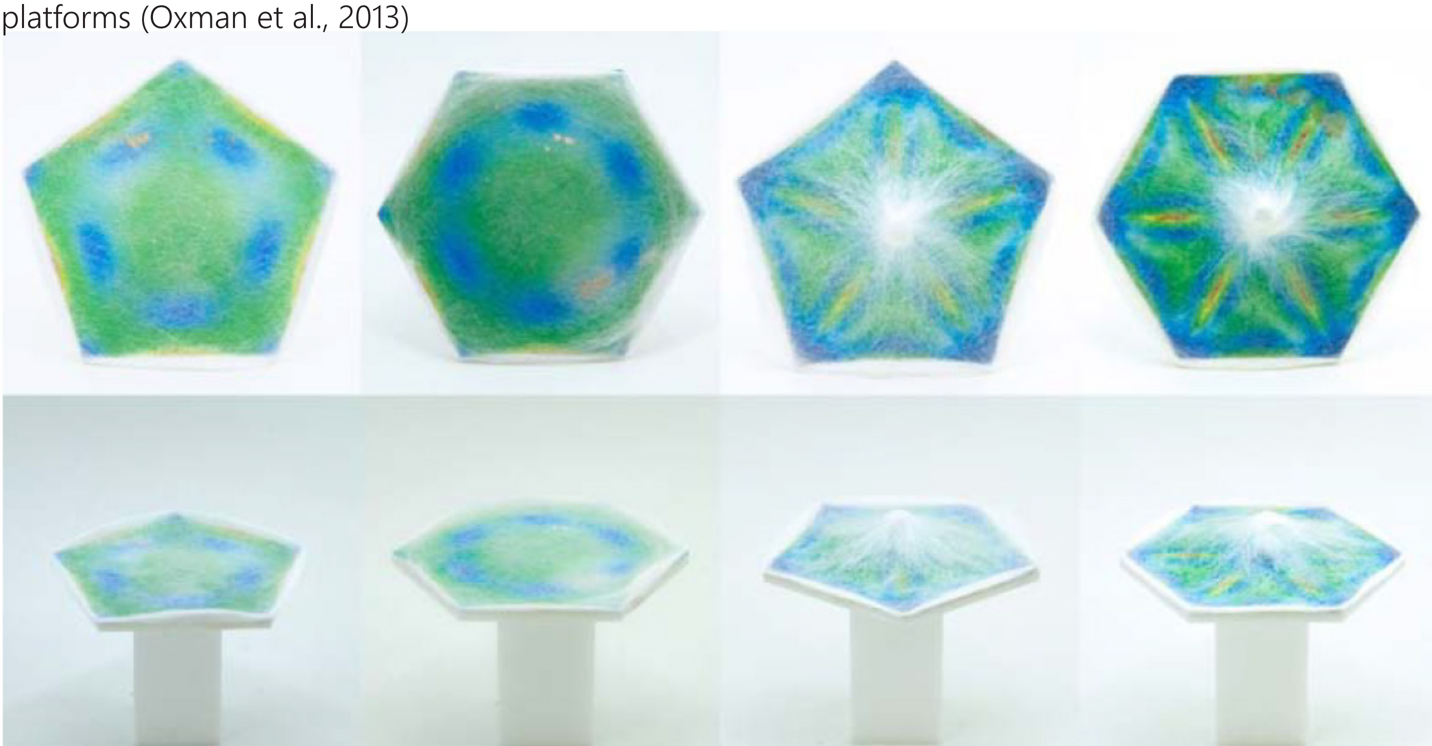


Fig.6 Polygonal FEM-Dice series (Oxman et al., 2013)

Spiderwebs - tension structures by Frei Otto

Fig.9 Picture of Frei Otto (Rawn, 2020)

Looking at spider webs to build structures is very interesting and has been done by Frei Otto (Fig.9) (1925-2015). It is done in a light way to use less materials, but it is still a strong way to build a strong structure, just like the spiders. It was not only inspiration from spider web but also skeletons and bubbles. (Skeletons, Soap Bubbles and Spider Webs -, 2015)

During world war two, Otto was a prisoner of war, and when he was out in the war, he started to look at how to create makeshift tents out of sheets and blankets. Even if it was a time of emergency and shortage of materials, he made it work, and this sat the base for the rest of his lives work. Otto said: *"My architecture is an architecture of survival"*. (PHILOSOPHY – Frei Otto: Spanning the Future, 2016)

The first project, the "German Pavilion, Expo '67" (Fig.10), was built over the German pavilion in Montreal. This was the first continuous tent structure that was in that big scale. The structure resembled the spider's web.

With the Munich Olympic Stadium (Fig.11), the

Figure.11 Munich Olympic Stadium (Rawn, 2020)

Figure.12 (Oh, What a Tangled Web . . ., 2019)

Fig.10 German Pavilion, Expo '67 (Rawn, 2020)

resemblance between the structure and the Grass spider's (genus Agelenopsis) spider web (fig.12) is apparent when you see it from above. The picture shows how the supporting structure works similarly to the grass by holding up the thin layer of fabric or silk. The strategy of getting shelter with the light structure is seen when you look at the design. When Otto was experimenting, he was using soap to find forms, and it was much physical model making to discover these natural shapes he was working with.

"For a peaceful society in harmony with nature" (Meissner & Möller, 2015). This is an interesting motto to have after going against the standard way of construction after the war. Experimenting with lightweight structures in a natural way was a new way of thinking. The way Otto was bringing together engineers, architects and biologists was something new at the time. The fields were so far from each other as you could imagine. Otto was one of the people that started a research group called "Biology and building" it was interdisciplinary between biologists, palaeontologists, and architects (Meissner & Möller, 2015).

Working across fields shows clearly in the designs of Otto how it improves to more sustainable designs—taking the knowledge from different fields and creating something inspired by nature. Otto and biologist Johann Gerhard Helmcke worked together, influencing Otto to think about objects from nature and combine Biology with Architecture. Thinking about natural structures, lightweight structures, and using less material emerged. They have an understanding of the natural world and its structural form. The built architectural structure is only a tiny part of something that includes all structures from molecular to plants and animal-built structures such as nets and webs. (Fabricius, 2016)

Otto has a deep interest in nature and questions how good the impact of human technology really is. The actions of our species are responsible for the impending danger that climate change is. (Fabricius, 2016) The interest and questions became one of the primary reasons for the search for alternative structures in nature. Otto and Helmcke saw the natural evolution of form and structure as evidence for theories. (Fabricius, 2016) In Otto's dissertation in 1953, he already suggested self-formation and natural structure. He mentions that the spider web is an appearance that one can not draw or explain. (Fabricius, 2016)

Helmcke took microscopic pictures, and the photographs he took made Otto see shapes that had formed themselves, such as bubbles, soap films, rubber membranes, and net structures. From that moment, Otto saw only such forms in all living organisms. (Fabricius, 2016) Interestingly, the way structures serve as pavilions in Otto's work is related to the bond with nature. Just like nature should not be used instrumentally, neither shall the architecture. In the 1970s-1980s, Otto and Helmcke were thinking about tomorrow's architecture. They became more concerned at this time due to the impact humans make on the natural world and climate. *"Their arguments for natural structures were now made in favour of global environmental concerns."* (Fabricius, 2016)

In (fig.13), the design of "Aviary at the Munich Zoo" shows the connection to nature well. A see-through net structure that connects the interior with the exterior. The representation of Otto's work shines through this web covering the Zoo.

Figure.13 Aviary at the Munich Zoo (Rawn, 2020)

Silk worms producing pavilions - Neri Oxman

"Everything flows, and nothing stays the same" -Heraclitus "Panta chorei kai ouden menei."

The natural evolution of architecture. (Antonelli et al., 2020)

The change affects everyone and everything, with different cycles, speeds, and scales. Most existing things like the examples in the book: glaciers, plankton, clouds, tigers, or dandelions go with the flow. They accept change and adapt to it. (Antonelli et al., 2020) Humans do not do the same, unfortunately. Most human beings try to control, resist, or peruse change, which many humans feel excellent or proud of. But manipulating the flow brings consequences not only for humankind but also for all species. The change is growing bigger and faster, and it is out of control. (Antonelli et al., 2020) Neri Oxman wants to take time and not hurry to achieve a better future. By working interdisciplinary and with different species like the silkworms, *"she engages change using change's own momentum."* (Antonelli et al., 2020)

The ways to find new innovative and natural organic designs are inspiring and in time. Oxman calls it Material ecology:
"An emerging field in design denoting informed relations between products, buildings, systems, and their environment. Defined as the study and design of products and processes integrating environmentally aware computational form-generation and digital fabrication, the field operates at the intersection of biology, material, science and engineering, and computer science, with emphasis on environmentally informed digital design and fabrication."
- (R. Oxman & Oxman, 2013)
Oxman wanted to go beyond the disciplinary boundaries like Tomás Saraceno already did when he studied spider-webs at the MIT Centre together with art, science, and Technology.

Oxman's primary client in all of this is nature. Grow, adapt, and respond to the environment. Also, work for the natural environment and not "only to benefit humans. Humans are equal to all living things. Look at how nature behaves, and the wish is to design with the mind-set "Difference over repetition." (Antonelli et al., 2020) Not using machines that make the same pattern or parts repeatedly—designing a behaviour instead of an exact form, as with controlling the silkworms but letting them work in their way. Following the natural cycle to decompose instead of being thrown away is an essential part of it. Focus on a designed decay to follow the ecosystem and fuel new growth. (Antonelli et al., 2020)

Neri Oxman has made two pavilions with help from silkworms. Silk pavilion I (fig.14-16) (Oxman, 2013) and (Silk pavilion II fig.17-19)(Oxman, 2020) are designed in slightly different ways. Silk pavilion I is intended to be a dome to represent the silkworm's cocoon; Silk pavilion II is made to spin clockwise and have light and heat to guide the silkworms to where they should apply silk. They both work in a way where a structure has been made, and biodegradable nylon has been applied as a start structure for the silkworms to work with. These projects are done to see how we can use silk from silkworms without boiling them to get their silk. To make one shirt, you need to boil 1000 silkworm cocoons. (Good night stories for rebel girls, 2021, 04.00). By not boiling them, we can save the silkworm and the environment and easily have the silkworms repair any part that needs fixing. For Silk pavilion I, 6,500 silkworms was used to create the three-meter vast dome with some help from a robot arm (Oxman, 2013).

Fig.14-16 Silk Pavilion I (Oxman 2013)

Fig.17-19 Silk Pavilion II (Oxman 2020)

Interior installments, Art - Tomás Saraceno

Tomás Saraceno grew up with a mother who studied biology, and this father was studying agriculture. Saraceno himself studied architecture at a university in Argentina. He got in contact with more artists when he was looking. Saraceno thought it was a good mix between disciplines. Already since he was young, he has been fascinated by spider webs and watching the stars with telescopes. In his old home in Italy, he sometimes enjoyed going up to the attic inhabited by others (spiders). (Virtual Studio Visits: Klaus Biesenbach in Conversation with Tomás Saraceno, 2021) That inspired his future work. As an example, in two of his pieces (Galaxies Forming along Filaments, like Droplets along the Strands of a Spider's Web. 2009) (Fig.21) and (14 Billions (Working Title). 2010) (Fig.22) he was inspired by The Black widow (Latrodectus mactans). Saraceno worked with arachnologists, engineers, and astrophysicists (Engelmann, 2016). By scanning and studying the spider web to reconstruct it. To build as an example (14 Billions (Working Title). 2010) was quite tricky. You need to have the proper tension between the threads to get the same as a spider's web.

His interest in the cosmic web created after the big bang is a big part of his work. He says that astronomers talk about the drops of water along streams of a spider web. That is because of curiosity about how and where we live. Not ignoring the spiders in a universe that he tried to understand. Two different ideas of the universe and to understand what we have on our planet. (Virtual Studio Visits: Klaus Biesenbach in Conversation with Tomás Saraceno, 2021)

Saraceno's work "Hybrid webs" (Fig.20)reflects his spider web studies and interest in the cosmic web. *"Spiders spin tiny universes. Formed of complex interwoven networks suspended in air..."* (Hybrid Webs ·, 2019). Each of the unique designs is a combination of different spiders working with each other's space to create these unique web patterns in one space. The spiders are the architects of the space they are given. The spiders chosen are both social and semi-social spiders that are fine with working on each other's construction. This is not seen as only an entangled arachnid webbed ecosystem but also" *human and more than human worlds*." (Hybrid Webs ·, 2019) The designs challenge gravity with the colliding silk and web types. The spiderweb all make different sounds so the spider can know when something is trapped or if another spider is interfering with the web. This is also considered with the sensory worlds, which merge together and connect. The encounters in the space represent the spiders becoming a good community," *a spatial condition of physical immersion in an environment where stories of co-existence between humans and other species materialise*." (Hybrid Webs ·, 2019)

" *Spiders, we now understand, have given us a model of which the present is a simulacrum, trough not just the technocratic, seemingly intangible future-present of life online but also the real-world urgency of environmental relationships and their fragility*." (David Toop, FilamentDrums: the Endless Instrument, in Cosmic Jive: The Spider Sessions, 2014)

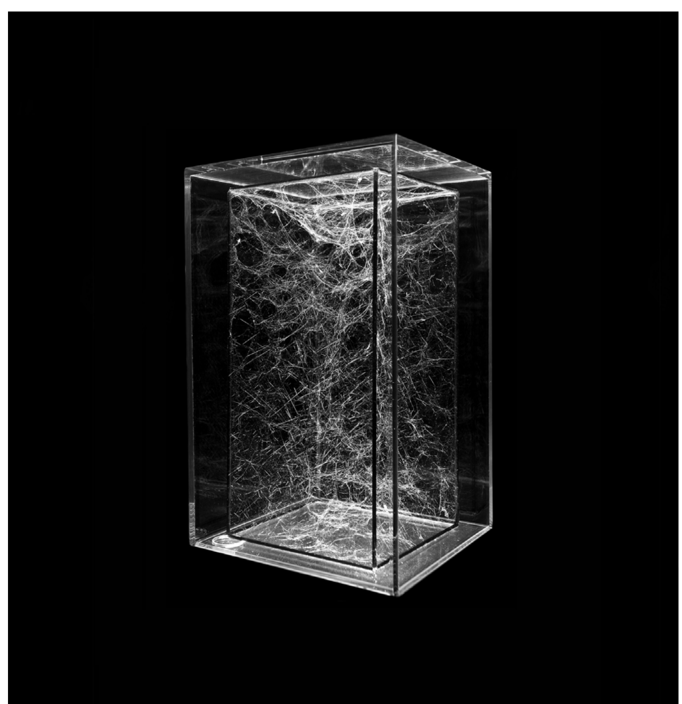


Fig.20 Hybrid Webs (Hybrid Webs ·, 2019)

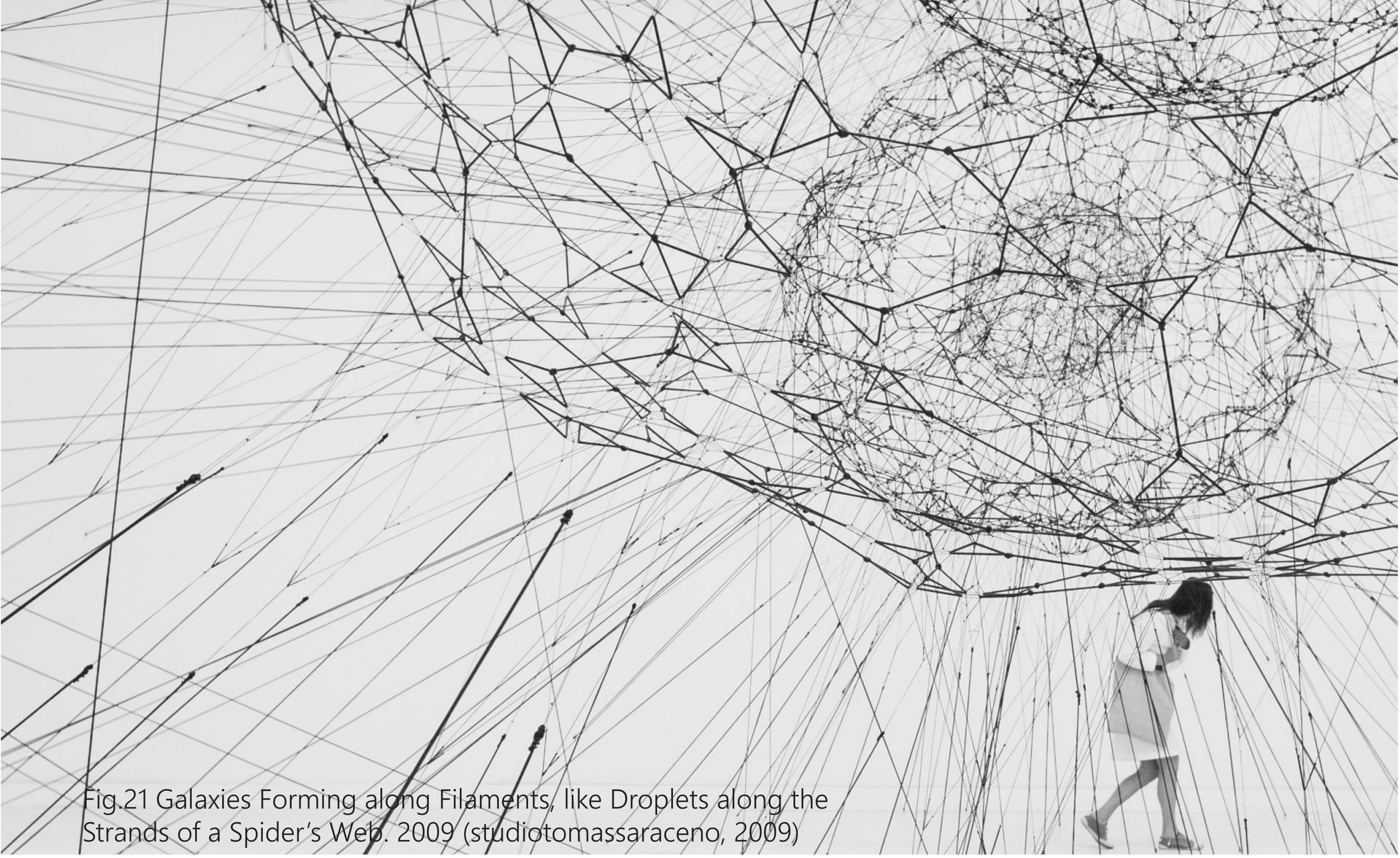


Fig.21 Galaxies Forming along Filaments, like Droplets along the Strands of a Spider's Web. 2009 (studiotomassaraceno, 2009)

Fig.22 14 Billions (working title) (studiotomassaraceno, 2010)

Discussion

All case studies are inspired by the natural forms and silk-producing insects in some way. They all have their unique way of representing it and bringing it into their designs. Co-existing or working in favour of and with nature or natural beings is a common thread, do well not only for humankind but to respect and help nature and all living things in nature. Grow, adapt, and respond to the environment. Studying the pattern and the strength more in depth could help us better understand the material and structure. Move forward with a more sustainable way of both construction and how to work with material and structures not to harm nature or the living beings in nature.

One question arises in the thought of what is best for the animals. Oxman and Saraceno work directly with the animals where Oxman controls them to build the way she wants them to. Saraceno makes the animals work inside the constraints and together with different arachnids. This could be an ethical question. But from the research, the understanding is that they want to find out what is best for the animals. As Oxman said to make one shirt, you need to boil 1000 silkworm cocoons. After all, it might be better to work alongside each other in a slower paste.

The three interdisciplinary practices have all been inspired by the shapes and forms of spiderwebs and silkworms' webs. The shapes have mostly inspired otto together with the lightweight material and tensile strength. His work clearly shows how the tensile structures look like something a spider could have built. Oxman and Saraceno have investigated silkworms and spiders' patterns and behaviour more in depth. This is clearly shown in their work with pavilions, art installations and exhibitions directly constructed with natural silk produced by the insects themselves. Oxman is controlling the silkworms more than Saraceno controls the spiders. Even if Saraceno make some spiders work together to see what their combined structures would look like, he let them work alone without controlling where they will build. It could be argued that Oxman is a combination of Otto and Saraceno, the way she controls the structure like Otto and how she uses the animal to produce the construction like Saraceno. Otto and Saraceno use silk math within their projects, where Oxman applies the movement of the silkworms more than the math.

To extrapolate on the findings in his dissertation, the thought of a future inspired by or created by insects could become a possibility. Silk as a material is solid and tough, and with the correct advancements in size and molecular structure, it could be used on a bigger scale. The way the web is constructed could help the architectural structures become more robust and avoid complete catastrophic failure. That could be achieved by knowing how the spider builds the web and only have local failure. As well as finding more innovative ways to construct structures.

We could learn much from the possibilities of self-repairing spaces and buildings for the interior spaces. Interior spaces could be ever-changing with sustainable and biodegradable materials. In today's society, there is a lot of waste, and we throw away way too many things we don't want or things that are broken. We could repair what is broken and make more robust constructions by taking inspiration from the spiders and silkworms—reinforcing the main structure and increasing the density of some areas that need to be stronger.

Advancing in today's technology to help us move forward sustainably by computing, we could find these natural patterns and structures that could be stronger, calculate how the insects create sustainable materials and how we can mimic them. Materials could be used without hurting the animals. Oxman uses this in her designs to create natural shapes.

Conclusion

Material and structure are key elements to interior and design. We have a lot to learn from spiders and silkworms, both from construction and material use. By studying the insects' behaviours and learning more about their silk as a material, we can advance in our constructions and material production. This works towards a more sustainable future by working with and for nature for humankind and all animals and nature. Spiders are natures engineers, and there is a lot to learn from them. Both spiders and silkworms' silk are biodegradable, and they can easily repair any broken parts. Architects or designers like Otto take inspiration from the shapes and starts the new thoughts working with biologists and collaborating over different disciplines. That is a significant first and important step for future thinking. Oxman's work with silk material and the studies of the movement of silkworms to create beautiful pavilions, demonstrating how we can use silk without boiling the cocoons. Saraceno explores how spiders move and construct their webs and implement this in his work. His research has taught us how 3D webs are built and what the spiders do to achieve a strong structure that is easy to reinforce. The research question has been answered by research and case studies. The case studies show how spiders and silkworms' structures and materials influence architecture and design. It offers an excellent future for continuing with this inspiration for more robust, strong, and self-repairing future designs.

Three case studies have only been studied; there are more to learn and understand to make it go forward in architecture and design. The research has shown that materials and structures of nature work well, and we should let them influence our architecture and design more. Working with nature gives us many sustainable opportunities; it might be more expensive and time-consuming at the start, but once we make nature and natural processes more common, it will become cheaper and faster. The way we live will change for a sustainable future more connected with nature.

References

Cranford, S. W. (2012, February 1). Nonlinear material behaviour of spider silk yields robust webs. Nature. https://www.nature.com/articles/nature10739)-?error=cookies_not_supported&code=1cf68485-d12f-44b0-a725-6115d5f6d911

Das, S., Bhowmick, M., Chattopadhyay, S. K., & Basak, S. (2015). Application of biomimicry in textiles. Current Science, 109(5), 893. https://doi.org/10.18520/cs/v109/i5/893-901

Engelmann, S. (2016). Social spiders and hybrid webs at Studio Tomás Saraceno. Cultural Geographies, 24(1), 161–169. https://doi.org/10.1177/1474474016647371

Fabricius, D. (2016). Architecture before architecture: Frei Otto's Deep History. Taylor & Francis. https://www.tandfonline.com/doi/full/10.1080/13602365.2016.1254667

Form and function: The significance of material properties in the design of tensile fabric structures. (2012, November 1). ScienceDirect. https://www.sciencedirect.com/science/article/pii/S0141029612002878

Good night stories for rebels. (Host). (2021, May 27). Get to know Neri Oxman. Good night stories for rebel girls. Castbox. https://castbox.fm/episode/Get-To-Know-Neri-Oxman-id3292375-id385986120?country=se

Hybrid Webs ·. (2019, July 10). STUDIO TOMÁS SARACENO. https://studiotomassaraceno.org/hybrid-webs/

Kapsali, V. (2016). Biomimetics for Designers: Applying Nature's Processes & Materials in the Real World by Veronika Kapsali (2016–09-15). Thames and Hudson Ltd.

M, C. (2020, April 7). Is Nylon Biodegradable. Social Sustainable. https://socialsustainable.org/biodegradable/is-nylon/

Meissner, I., & Möller, E. (2015). Frei Otto: forschen, bauen, inspirieren / a life of research, construction and inspiration (DETAIL Special) (bilingual edition). DETAIL.

Oxman, N. (2013). Silk Pavilion i. Oxman. https://oxman.com/projects/silk-pavilion-i

Oxman, N. (2020). Silk pavilion ii. Oxman. https://oxman.com/projects/silk-pavilion-ii

Oxman, N., Laucks, J., Kayser, M., David, C., Uribe, G., & Duro-Royo, J. (2013). Biological Computation for Digital Design and Fabrication. Biological Computation for Digital Design and Fabrication. https://neri.media.mit.edu/assets/pdf/278.pdf

Oxman, R., & Oxman, R. (2013). Theories of the digital in Architecture. Theories of the Digital in Architecture.

PHILOSOPHY – Frei Otto: Spanning the Future. (2016, April 22). [Video]. YouTube. https://www.youtube.com/watch?v=d4T9uHtPjNc

Porter, D. (2013, March 6). Spider Silk: Super Material or Thin Fibre? Wiley Online Library. https://onlinelibrary.wiley.com/doi/full/10.1002/adma.201204158

Rawn, E. (2020, May 31). Spotlight: Frei Otto. ArchDaily. https://www.archdaily.com/511689/happy-birthday-frei-otto

Skeletons, Soap Bubbles and Spider Webs -. (2015). World-Architects. https://www.world-architects.com/en/architecture-news/insight/skeletons-soap-bubbles-and-spider-webs

studiotomassaraceno. (2009). Galaxies Forming along Filaments, like Droplets along the Strands of a Spider's Web ·. STUDIO TOMÁS SARACENO. https://studiotomassaraceno.org/galaxies-forming-along-filaments-like-droplets-along-the-strands-of-a-spiders-web/

studiotomassaraceno. (2010). 14 Billions (Working Title) ·. STUDIO TOMÁS SARACENO. https://studiotomassaraceno.org/14-billions-working-title/

Su, I., Narayanan, N., Logrono, M. A., Guo, K., Bisshop, A., Mühlethaler, R., Saraceno, T., & Buehler, M. J. (2021). In situ three-dimensional spider web construction and mechanics. Proceedings of the National Academy of Sciences, 118(33), e2101296118. https://doi.org/10.1073/pnas.2101296118

Virtual Studio Visits: Klaus Biesenbach in Conversation with Tomás Saraceno. (2021, January 23). [Video]. YouTube. https://www.youtube.com/watch?v=MJmGhxfoUwg