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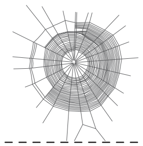

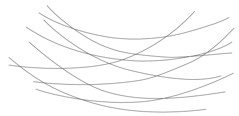

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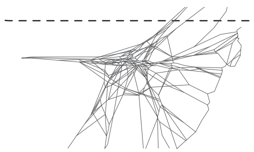
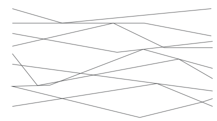




HOW?

BIOLOGICAL RESEARCH

ARCHITECTURAL INTERPRETATION

Chapter 01: INTRO

INTRODUCTION TO ZOMBIE SPIDERS

FIGURE 1_1: spider manipulated by wasps (*Source: Takasuga et al (2015))*

Host spider manipulation by parasitic wasps is a true example of a fascinating phenomenon: mind control in nature. This introduction will explain such host manipulation, its origin and its function.

This complex process happens through host manipulation (fig.1_1) where a parasitic agent chemically induces its host organism to generate alternative behaviour.

When a wasp successfully attacks a host spider at the hub of its orb-web, it temporarily paralyses it to lay an egg on the tip of the spider's abdomen. After that, the spider regains normal activity and during the next 7-14 days it builds apparently normal orbs to capture prey, while the wasp's egg hatches and the larva grows by sucking the spider's heamolymph (fig.1_2).

The parasitoid is able to turn the spider into an agent which modifies a normal orb-web structure (fig.1_3A) into a specific and more persistent 'cocoon web' (fig.1_3 C) (Eberhard, 2000). This structure will allow the wasp to pupate safely against the elements or enemies after the spider's death. The importance of having such a strong and durable support for the wasp's cocoon demonstrates the vulnerability of the wasp's pupae towards heavy rains.

It has not always been clear whether the parasitoid larva does really utilize the resting web-building behaviour or if its resemblance is suggested by a similar web-structure. However, recently researches have shown that during the manipulation process the larva recalls in the spider the same intrinsic web-building behaviour of the cocoon webs.

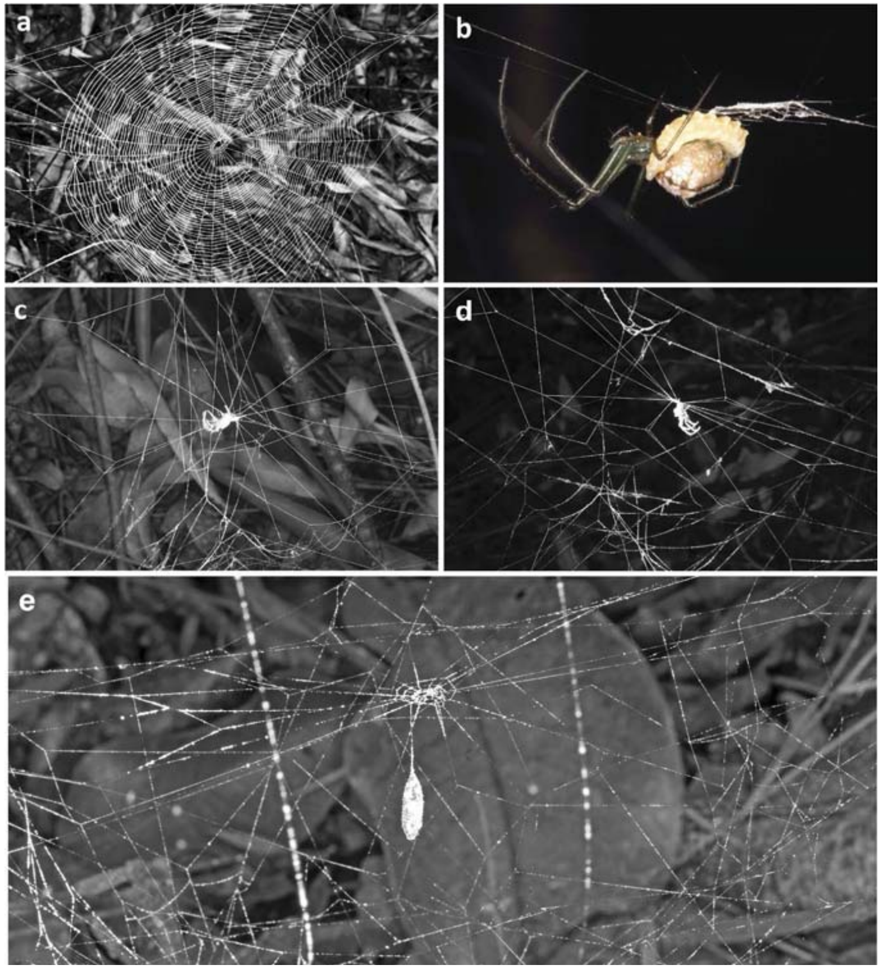


FIGURE 1_2: orb web to cocoon web transition. (*Source: Gonzaga et al(2015))*

Many parasites manipulate their host's behaviour but most of them, particularly insect parasitoids, induce only simple changes, such as movement from one habitat to another, eating more or less, or sleeping. To this respect the Hymenoepimecis's wasp manipulation of its spider host, Plesiometa Argyra, has been considered one of the most precise directed alterations of behaviour ever attributed to an insect parasitoid.

The behavioural change in the host spider can be understood in the web-building steps and its final cocoon web state. Furthermore, manipulated host mechanisms can be derived by comparing the functions between the unmanipulated (normal) webs and the manipulated end product (cocoon web).

According to a research paper by Takasuga et al. (2015), a specific ectoparasitoid (R. Nielseni) evokes resting web construction behaviour intrinsic to Cyclosa Argenteoabla and the Ecdysterioid-related components could be responsible for the manipulation.

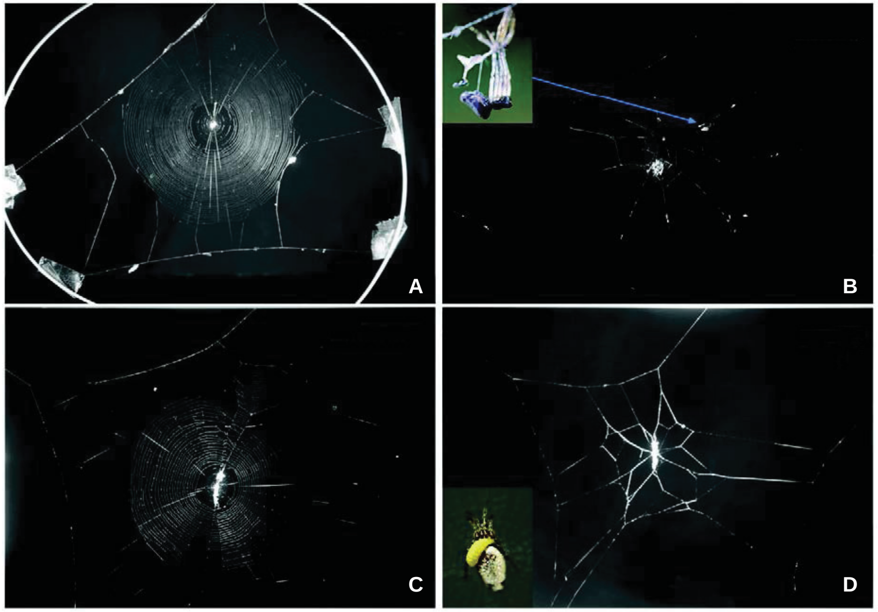


FIGURE 1_3: types of web constructed by orb-weaving spider Cyclosa Argenteoalba (*Source: Takasuga et al (2015))*

(A) Normal orb web.
(B) Resting web with a moulting spider (inset) somewhat away from the hub.
(C) Normal orb web constructed by a spider parasitized by the ectoparasitoid Reclinervellus nielseni on the eve of being manipulated by the wasp larva.
(D) Cocoon web constructed by the same spider as in C. Inset shows close-up of the parasitized spider.

To clarify the origin and function of cocoon webs and to understand the reason for the spider to invest time and energy in building such nets, spider web-building behaviour, resting and cocoon web structures were investigated, also including the silk tensile properties of both structures.

Scanning electron microscope images show that fibrous thread decorations on radii of resting webs (fig.1_4 A) and cocoon webs (fig.1_4 B) are very similar in structure. However, radii are laid down in greater numbers in the cocoon web than in the resting web.

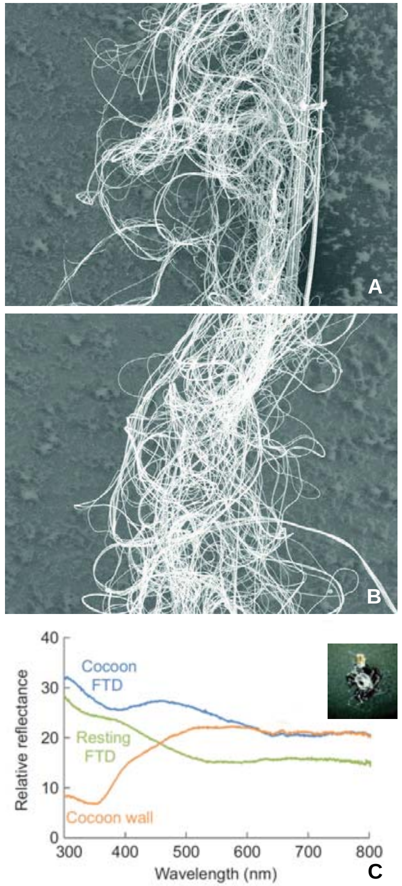
The breaking force (Mn) of radial and frame threads is notably higher in the cocoon web rather than in the other two web types while there is no difference between normal orb web and resting web in both radial or frame threads (fig.1_5 A). By looking at each thread type strength and diameter (fig.1_5 A,B), the Breaking Stress shows no relevant difference (fig. 1_5 C), pointing out that all threads consist of materials having same mechanical properties.

The Young's modulus of frame threads of orb and cocoon webs is highly different due to the cocoon radii being reinforced multiple times (fig.1_5 E) and this also applies as comparing radial threads of orb/resting webs and cocoon webs. (fig.1_5 D)

It has been understood that the sequence of behavioural manipulation is stereotypical in all parasitizes spiders. Manipulated spiders construct cocoon webs on the site of their original orb web. Behavioural manipulation begins with the spider retrieving the sticky spiral and then making repeated complex radial trips away from the hub and back whilst laying additional radii in both directions, without any laid threads being broken or reeled up.

Shuttling on the frame threads for reinforcement occurs during the same trip, resulting in multiple attachment points to the substrate. At the latter phase of manipulation, the spider repeatedly flaps its fourth leg-pair to spray fibrous threads onto radii.

Fibrous thread decorations are laid only on radii and never on the frame and all the spraying behaviour occur on the way back to the hub from the radial trips.



Properties of fibrous thread decorations in resting and cocoon webs.
Images of (A) resting and (B) cocoon webs indicating various numbers of radii as a central axis.
(C) Spectral properties of FTDs in resting and cocoon webs and of a cocoon wall with a piled thread sample on a hole in a polyfoam plate (see inset).

FIGURE 1_4: types of web constructed by orb-weaving spider Cyclosa Argenteoalba (*Source: Takasuga et al (2015))*

Though the spider decorates the radii on the radial trips away from the hub, it quickly reverses its steps and keeps decorating towards the hub. After every webbing bout, the spider always sits on the hub.

When cocoon web construction is finished, all spiders stay stationary on the hub and seem to patiently wait for the wasp larva to start ingesting them.

It takes the spider over ten hours on average from the withdrawal of the spiral web to the final resting of the spider at the centre of the hub web just before being killed. These cocoon webs are usually constructed in darkness, between sunset and sunrise, although it has been observed that other spiders construct it in the early morning or evening.

Understanding the mechanism of host manipulation is a very complex task. Eberhard (2010b) theorizes that larval effects can be strictly related either on cumulative or dose-dependent processes rather than many different factors singularly responsible for influencing the manipulated spider's behaviour.

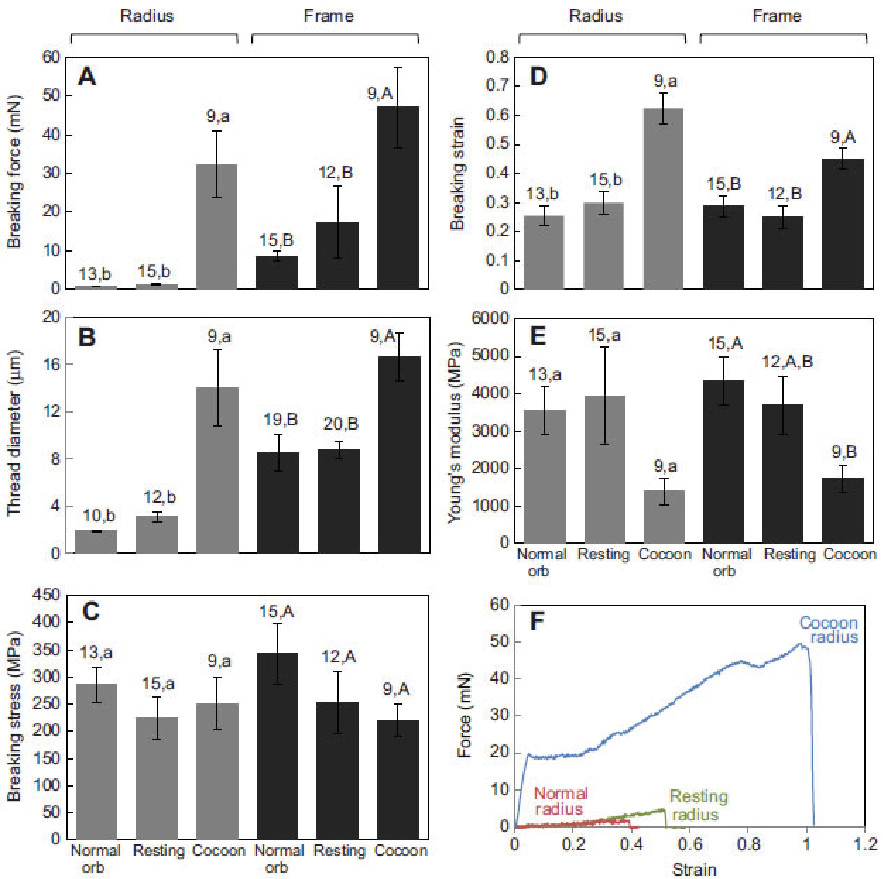


FIGURE 1_5: Mechanical properties of radial and frame threads in normal orb, resting and cocoon webs and typical examples of force-strain curves (*Source: Takasuga et al (2015)*)

(A) Breaking force
(B) Thread diameter
(C) Breaking stress
(D) Breaking strain
(E) Young's modulus
(F) Typical examples of force–strain curves of radii in three kinds of web. All bars represent the s.e. of means and
figures above each bar represent number of replicates (N). Different letters (small letter in radius and capital letter in frame) denote significant differences at the 5%.

This theory is supported by the fact that removing the parasitoid larva from the spider caused the spider to recover and get back to its normal web-building behaviour in the inverse steps previously used to build the cocoon webs during its manipulated behaviour.

The Polysphinctine larvae evokes a specific web construction that is exclusively limited to an exact life-history stage. The wasp larvae produce a signal molecule responsible for the beginning on the mind-controlled spider behaviour (Korenko and Pekár, 2011).

Another important feature of the R. Nielseni larvae which seems to be less frequent in the other two web constructions, resides in dragging the host spider to weave threads repeatedly, keeping the other building-web steps (such as retrieving sticky spiral webs and fibrous thread decorations construction) as normal.

The Reclinervellus Nielseni larvae is able to control the frequency of a particular independent resting web construction subdivision. Similarly, it is possible to have a case of another polysphinctine, the Hymenoepimecis argyraphaga larvae, which is able to force the spider to repeat some of the early steps of the orb-web construction, while neglecting the others. (Eberhards,2000, 2001).

The R. Nielseni larvae injects chemical components which correspond to the moulting hormone into host spiders, triggering the building process of the cocoon web. As the resting web construction is governed by ecdysteroids, the theory of the signal molecule triggering the process of the mind-controlled cocoon web syntax seems to be valid.

Similarly, the dose-dependent hypothesis, appears to be an equally valid theory; as the ecdysteroidal concentration gradient causes several behavioural responses in juvenile insects in a dose-dependent manner. Resting web construction consisting of several sequential building behaviours is likely to result from the same effect. The manipulative substance may react with the spider's endocrine system in a similar way, supporting the dose-dependent hypothesis.

Chapter 02: WHAT?

WHAT DO ZOMBIE SPIDERS TRANSFORM?

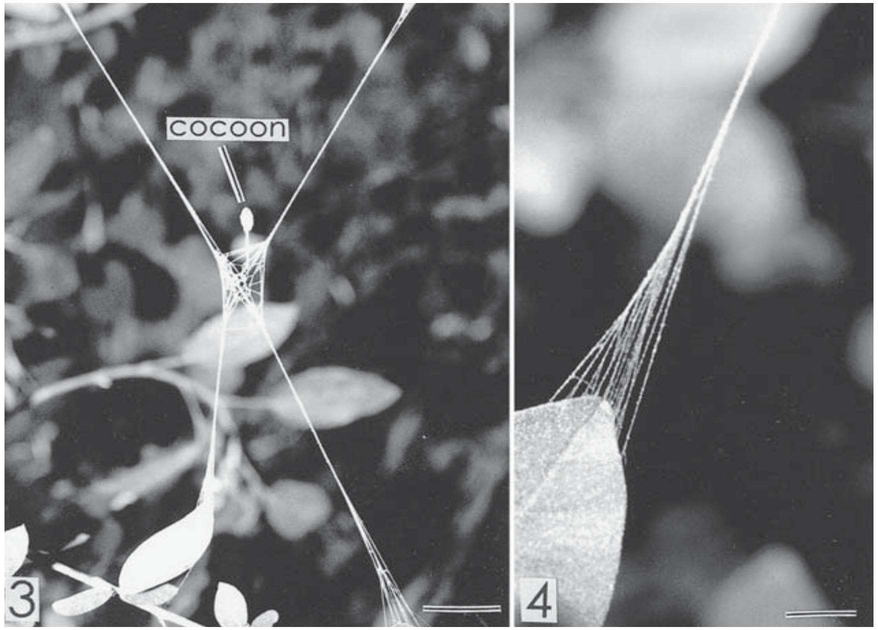


FIGURE 2_1: Typical cocoon web. (*Source:* William G. Eberhard)

After getting paralysed, zombie spiders begin to transform its normal webs into a “cocoon web” which is very different in terms of geometry, silk properties and function. These two types of webs serve for different ends of their masters, the spider or the lava. All the transformation strategies are aiming towards the goal of building a stronger, more durable support for the larva, and losing its original properties of a sticky orb web.
We will discuss these changes in the terms of geometry, function and silk properties among several species.

Manipulated Web Construction Behaviour

In the case of orb web spider Plesiometa argyra, after paralysation by the larva of the parasitoid wasp, Hymenoepimecis argyphaga Gauld, the spider repeats its early steps of a normal web construction routine, so that the first few threads of the orb web is reinforced multiple times, while the temporary and sticky spirals are missing, with the central portion of the orb web not being removed. (01 Eberhard WG (2000a))
The changes of two types of webs indicate that the cocoon web is elaborately designed for the hanging of the cocoon in high air, where sticky fibers with no structural benefits are no more produced by the manipulated spider.

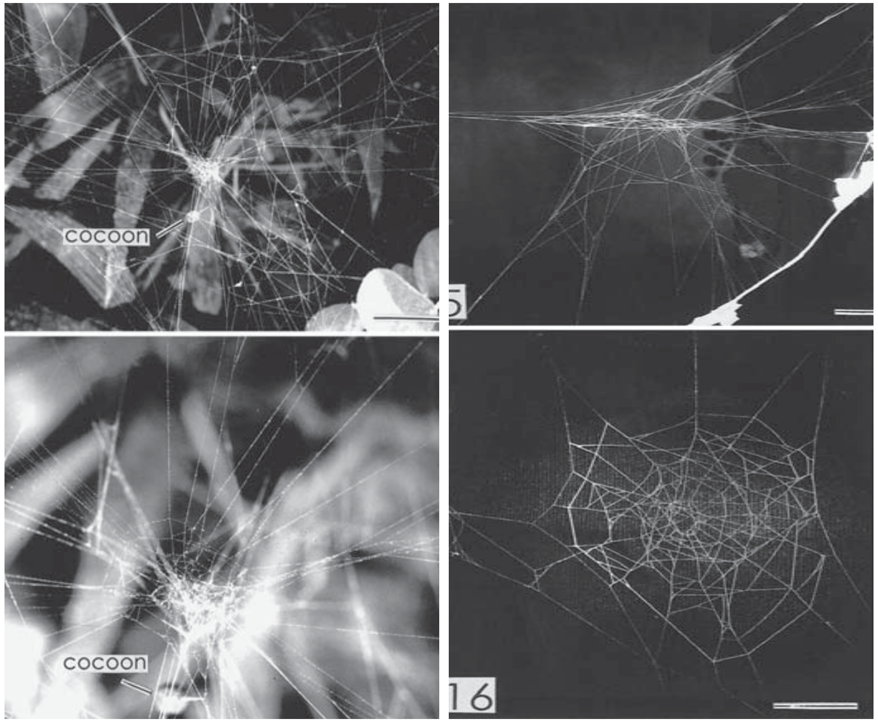


FIGURE 2_2: Complex cocoon webs and the experimental removal of the larva. (*Source:* William G. Eberhard)

Some cocoon webs have circular lines similar to those at the hubs of normal orbs. Anyways in no case the central portion of the hub is empty, as in normal orbs. Some have one or more frame lines connecting the radial lines. These frames were typically much shorter and nearer the hub than were the frame lines of normal orbs.

Experimental removal of the larva before it kills the spider was done by Prof. Eberhard’s team to see how the zombie spider will continue its zombie-mode construction under still prevalent but reduced chemical effect.

More complex 3-D cocoon-type web were recorded in the lab in Figure 2-2(15). And if the larva is removed earlier(5 days), the web will end up with something between orb-like normal web and cocoon-type web as shown in Figure 2-2(16), indicating the zombie spider is somehow recovering.

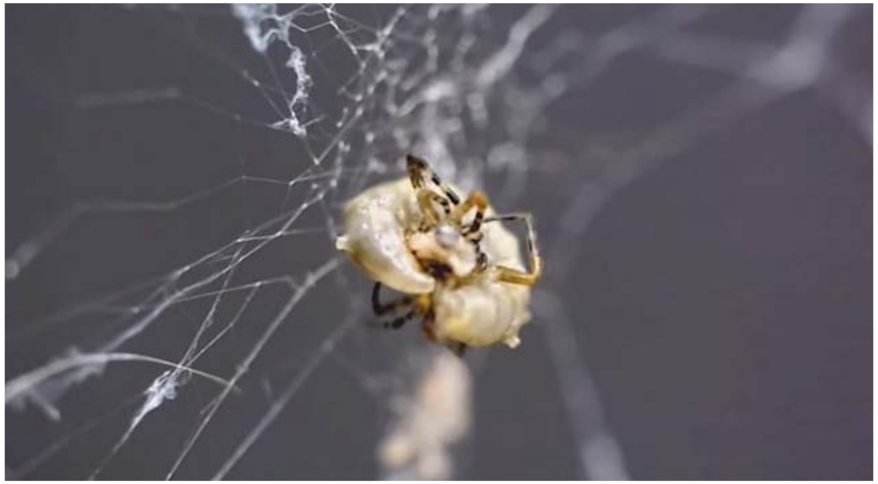


FIGURE 2_3: The larva sucks the spider's "blood." *(Source: Keizo Takasuka)*

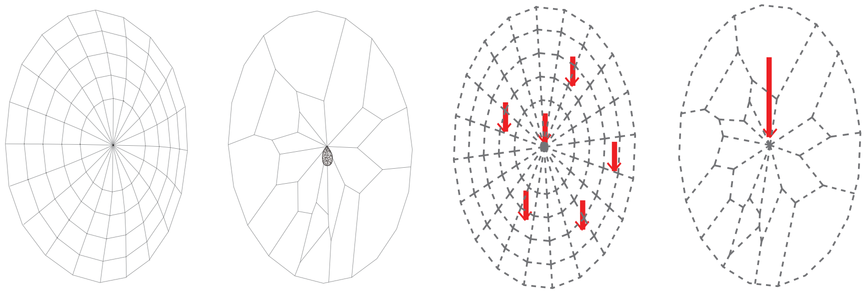


FIGURE 2_4: Diagrammatic representation of changing properties of function and load case. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

Manipulated Web Reconstruction Behaviour

In the case of spider Cyclosa argenteoalba manipulated by the larva of the parasitoid wasp Reclinervellus nielseni, similar behaviour is studied by Prof. Keizo Takasuka from University of Kobe in Japan.
Under normal circumstances, this species of spider spins two different types of web: a "normal orb web" that looks like a typical spider's web with a spiral of sticky threads that is used for catching prey, and a "resting web" which lacks the sticky spiral that is spun just before the spider moults its old exoskeleton.
After the larva hijacking the spider's nervous system, the spider is forced to transform its orb web into a cocoon web, which is similar to its resting web. The altered cocoon web is stronger, therefore more durable and perfect for the cocoon to be hanged in the air for the pupation of the larva, as suggested by the biologists.
The function of the transformed web therefore is fundamentally changed. It's not designed for catching preys any longer, so the sticky spirals are missing. The reduced web density of the layout will help protect the web from being destroyed by falling detritus or flying insects. The cocoon web is constructed with thicker silk so the web is more durable and robust. The load case of the webs is also changed from small dynamic impacts of preys to static concentrated load of the hanging cocoon.

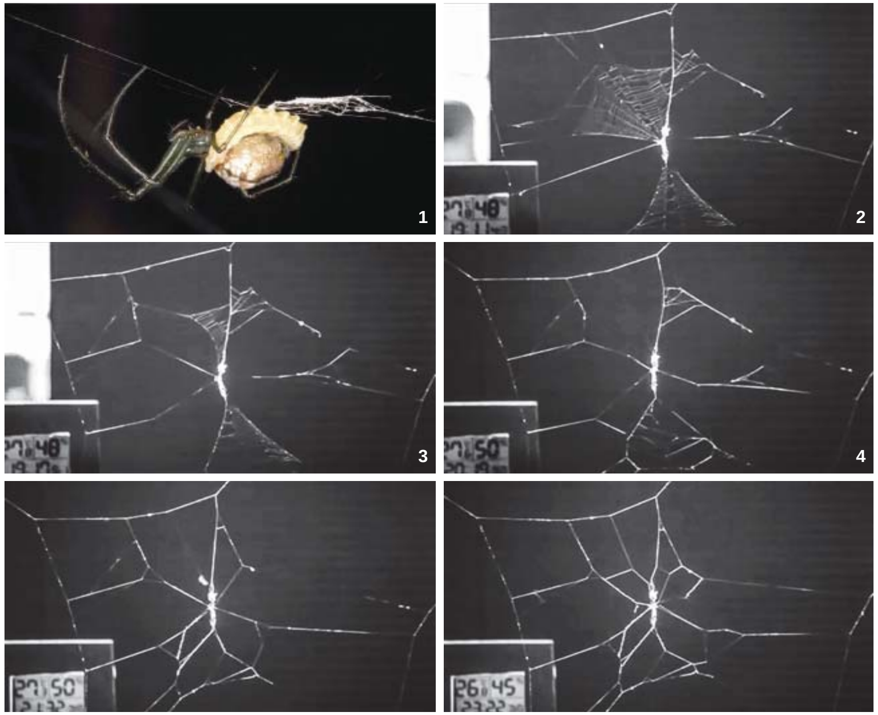


FIGURE 2_5: Reconstruction process screens hots (*Source:* William G. Eberhard)

The manipulated spider transforms the already built orb web into a voronoi-like cocoon web by lacing, gluing, adding, bundling, as well as relaxing fibers which will be further discussed in Chapter 4. The sticky spirals are all recycled as food for the larva later when the larva consumes the spider. That introduces also the idea of material efficiency in the prevalent Zombie Spider's webs.

Chapter 03: WHY?

WHY DO ZOMBIE SPIDERS TRANSFORM THEIR NET STRUCTURES?

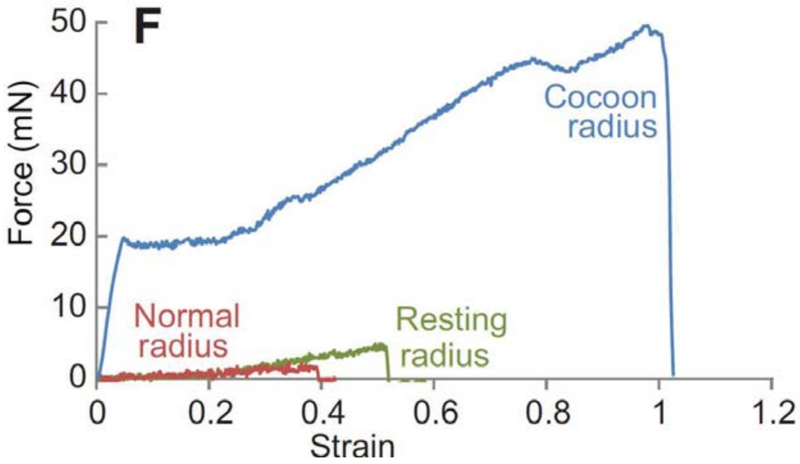


FIGURE 3_1: Silk properties of normal webs and cocoon webs. (*Source:* Keizo Takasuka)

The transformation of the normal orb web to the cocoon web is aiming towards the safety of the hanging cocoon. We will discuss the reasons behind from the perspective of material, structure and web configuration.

Material Properties

The material properties of silk used in both webs are almost of same stiffness. But as being reinforced multiple times, the threads in cocoon webs are much more thicker than the silk in normal orb web, so that the cocoon web is more robust than the normal web.
In the orb web failure is accepted and even planned, as the spider is constantly there to maintain and reconstruct the web when it's destroyed by insects' impact. In a cocoon web reconstruction is impossible.

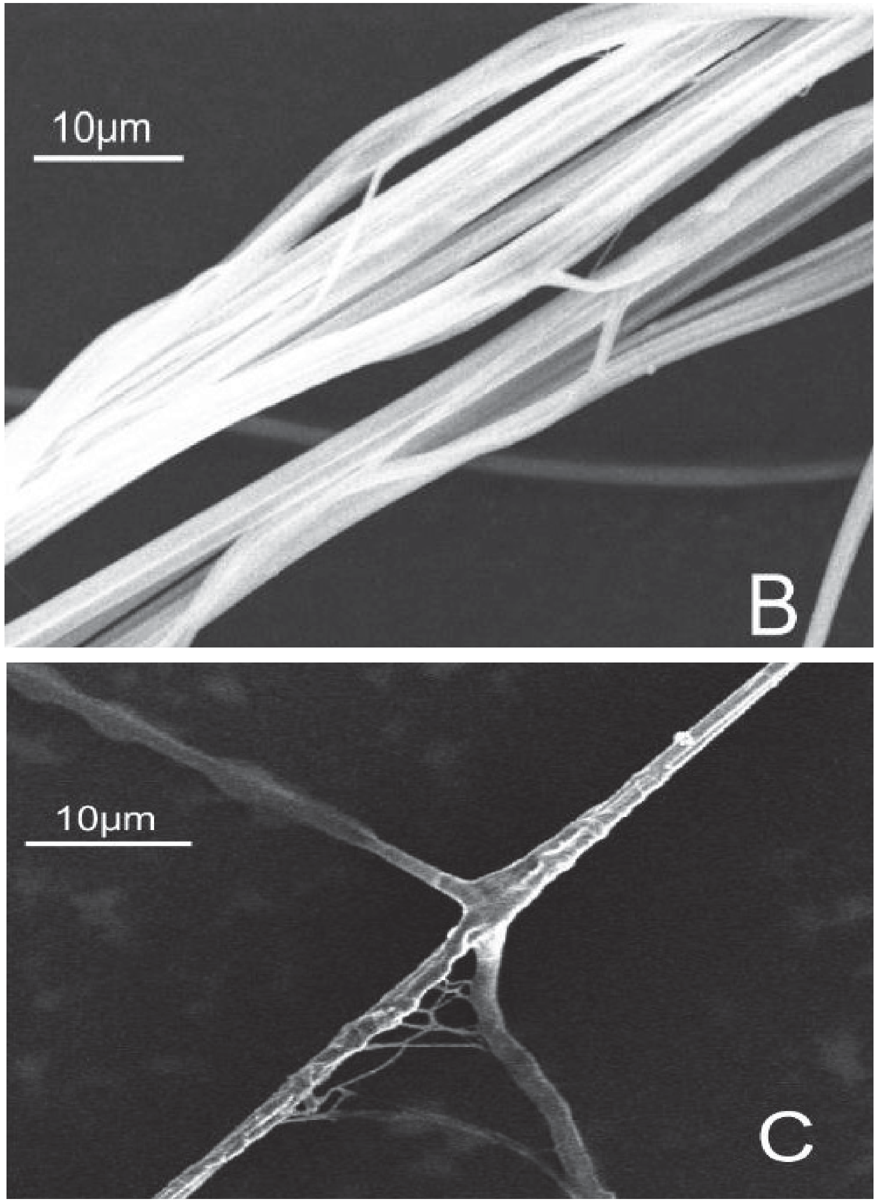


FIGURE 3_2: Spider Silk. (*Source: Takasuga et al (2015))*

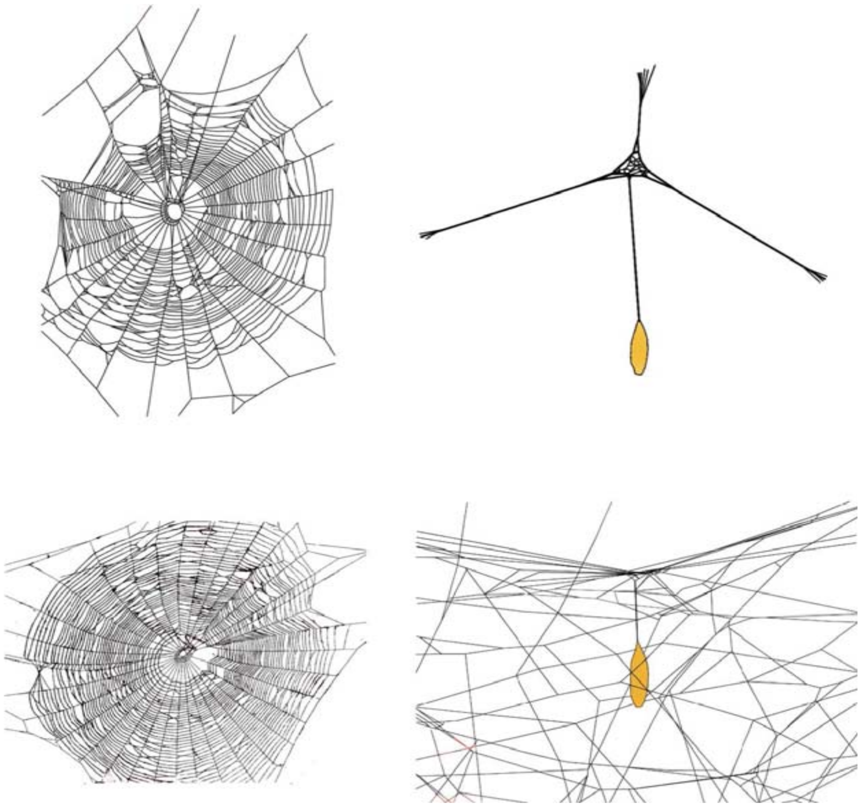


FIGURE 3_3: Different configurations of the cocoon web. *(Source: Marcelo O. Gonzaga)*

Compactness and Structure Efficiency

The density of the web configuration is significantly changed according to studies on multiple species. The most recognizable difference in the web layout is the missing of the sticky spirals and the voronoi-type layout of the radii. Some of these cocoon webs have relatively simple 2-D layout while others are very complex 3-D structures of elaborate design. But the laying of fibers should be carefully done by the manipulated spider because the material efficiency matters a lot in the construction process - the threads the zombie spider digests but doesn't lay out again mean extra food for the larva when it consumes the spider.

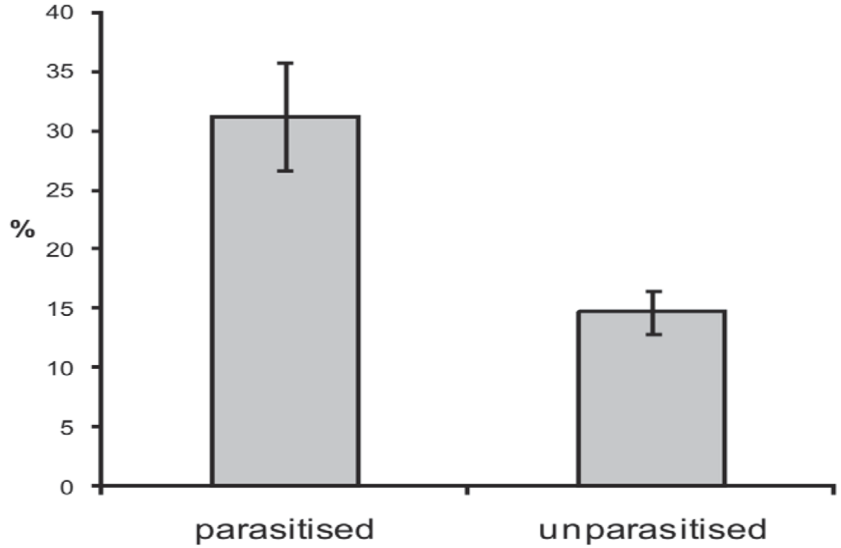


FIGURE 3_4: Comparison of the mean density of webs (*Source:* Stanislav Korenko)

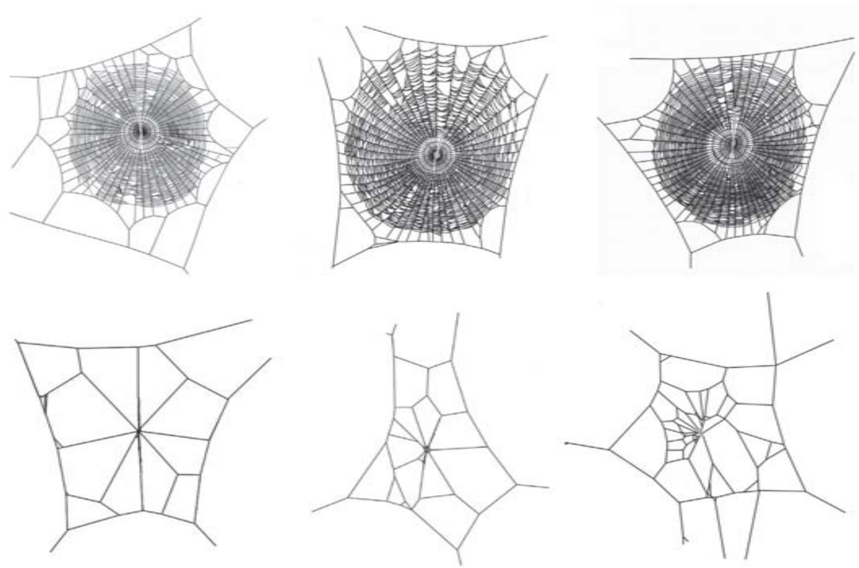


FIGURE 3_5: Compact layout of the cocoon webs. (*Source:* Marcelo O. Gonzaga)

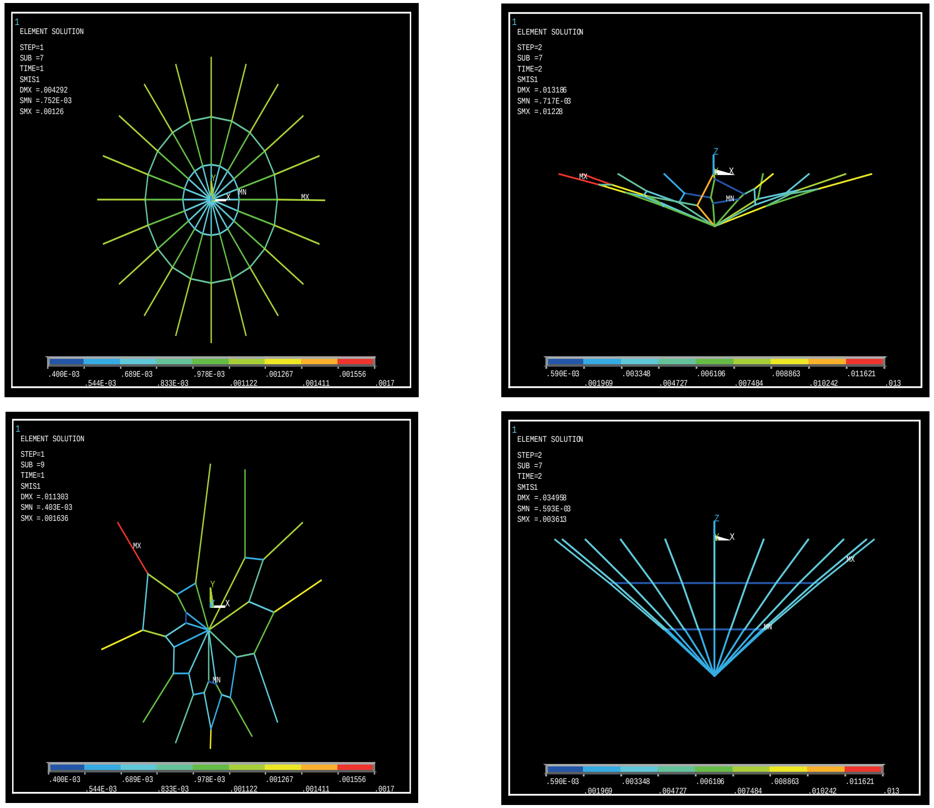


FIGURE 3_6: Structure analysis of two types of webs. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

If we assume that two types of webs are under same prestress, by simulating their structure behaviour in ANSYS, we can study the efficiency of normal orb webs and voronoi-type cocoon webs.

- comparison of maximum displacement

1. under self-weight: orb's max displacement is 75% of the cocoon web.
2. under concentrated load (hanging of a cocoon): orb's max displacement is 110% of the cocoon web.

- comparison of utilization(mean force density along each thread in web structures)

1. under self-weight: not much different
2. under concentrated load: spirals in the orb web become sag. Only needed threads remained in the web.

The simulation is somehow just telling part of the story because difference in "initial stress" is not concerned (same pretension is applied on both), which will even reveal bigger potential of the cocoon web because the initial tension is bigger in the case of cocoon web which will lead to smaller displacement and higher utilization of material.

(The script of ANSYS analysis is attached in Appendix(FIGURE 9_1))

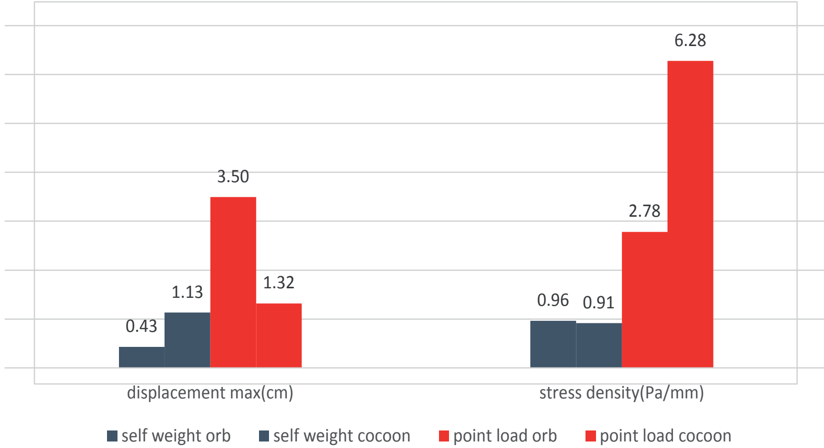


FIGURE 3_7: Maximum displacement and stress density of two types of webs. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

Chapter 04: HOW?

HOW DO THESE TRANSFORMATIONS HAPPEN?

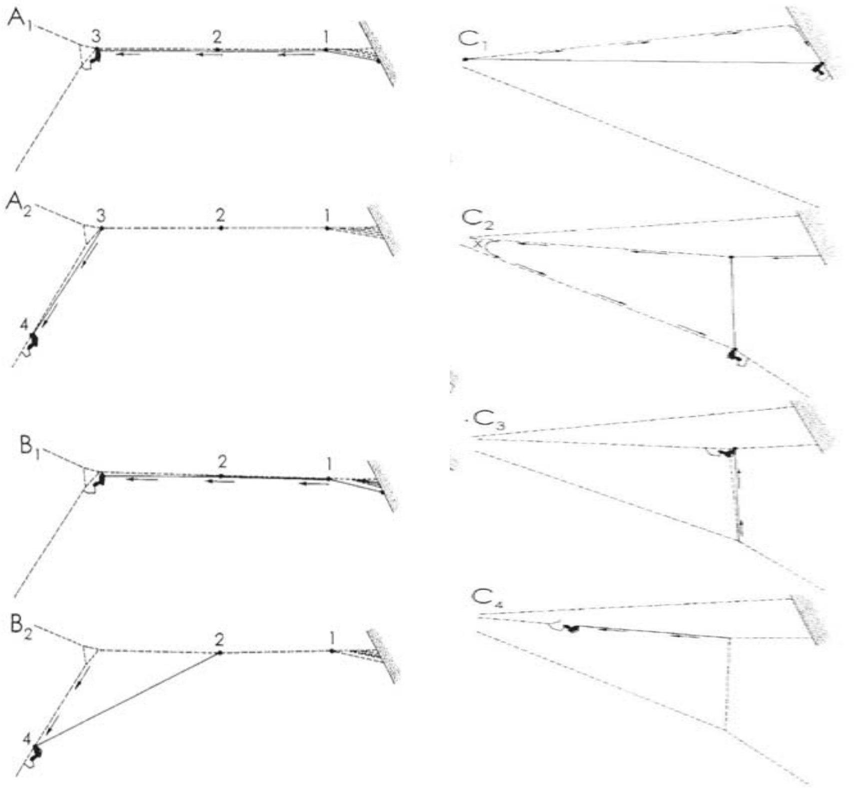


FIGURE 4_1: Construction sequence. (*Source: William G. Eberhard(1990)*

The most interesting but complex story consists in the transformation process of these two web types. We had a close look at the research materials from articles, images and videos. Based on our understanding of these researches we've were able to do some abstractions, which will be discussed in this chapter.

Prof. Eberhard has studied the silk-laying behaviour of zombie spiders analysed as the graph shown above (FIGURE 4_1). Diagrammatic representations of the sequences of behaviour during construction of a cocoon web (A1–A2, and B1–B2) and a frame line in a typical orb web (C1–C4) show us the different strategies the spider uses before and after getting paralysed. Stippling represents substrate, black spots represent points where the dragline was attached, and dashed lines represent lines laid earlier in the sequence (C1–C4 after Eberhard 1990). Cocoon web construction corresponds to the behavior in C1 and the first part of C2.

In order to pinpoint every move of the spider, we closely looked at one video captured transformation sequence and abstracted the key aspacts of the manipulated web transformation strategies.(FIGURE 4_2)

We also analysed the transformation process more abstracted step by step on from normal orb web into cocoon web. (FIGURE 4_3)

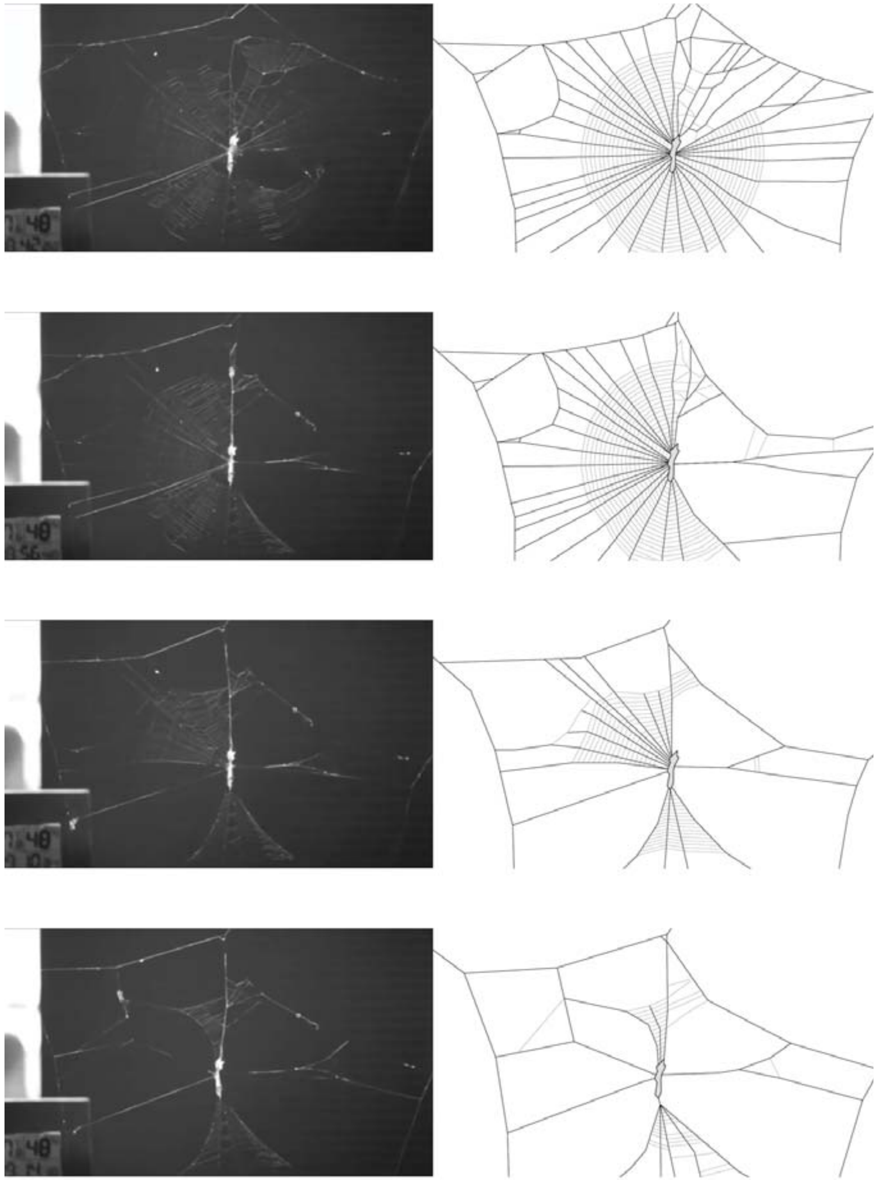


FIGURE 4_2: Transformation Process. (*Source: Takasuga et al (2015)*)

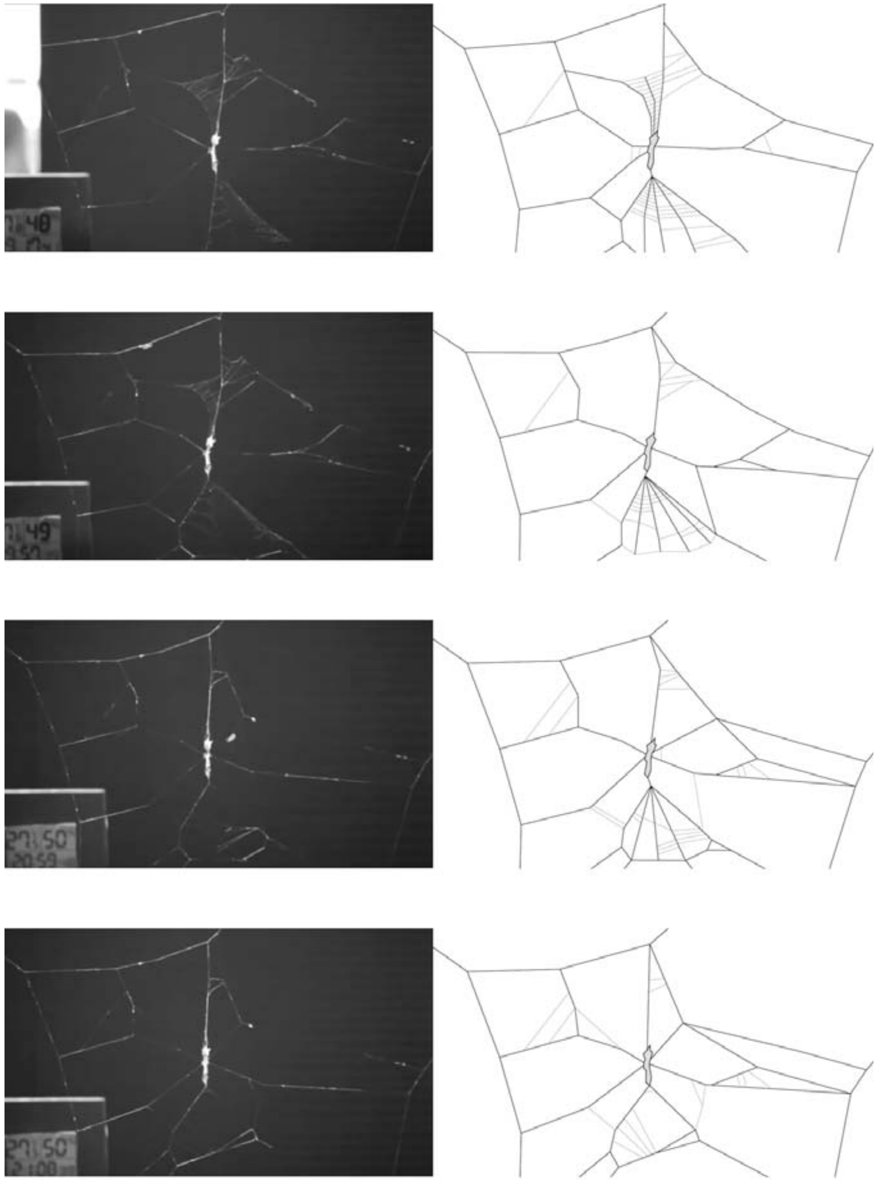


FIGURE 4_2: Transformation Process. (*Source: Takasuga et al (2015)*)

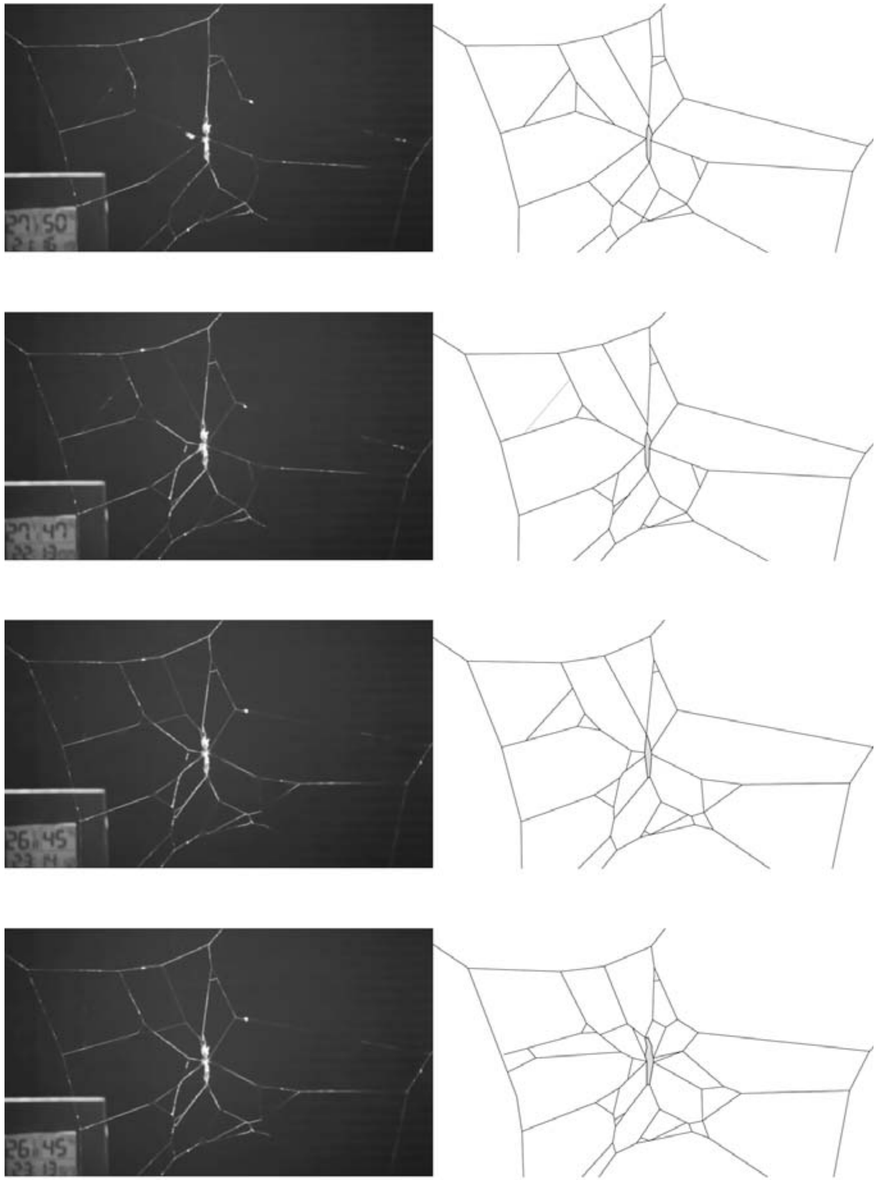


FIGURE 4_2: Transformation Process. (*Source: Takasuga et al (2015)*)

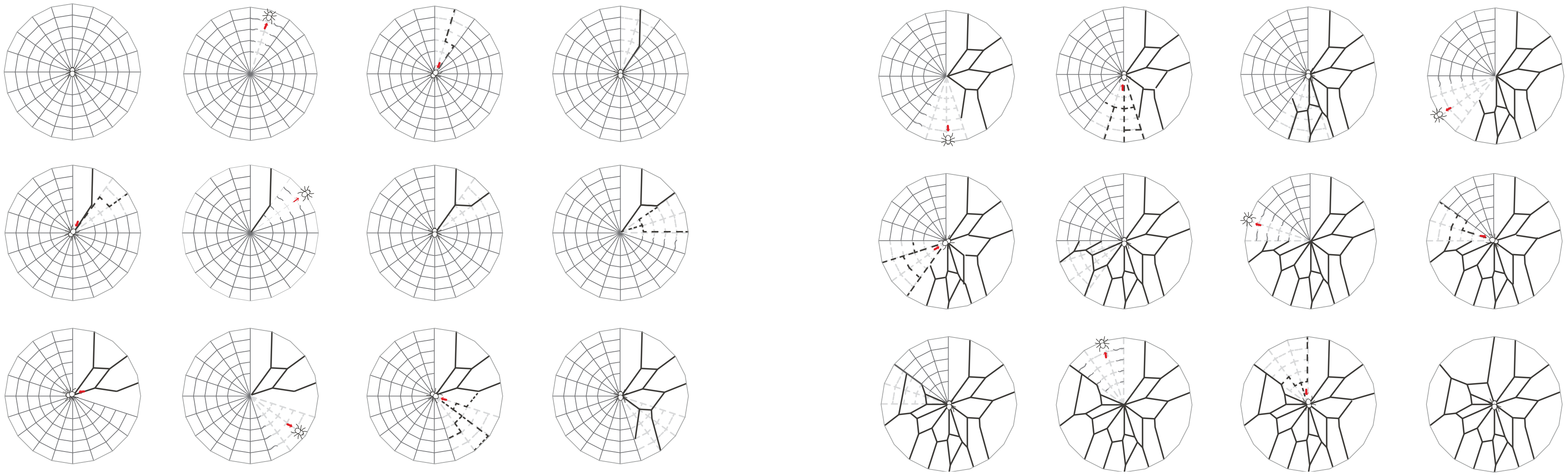


FIGURE 4_3: Transformation Abstraction.(*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

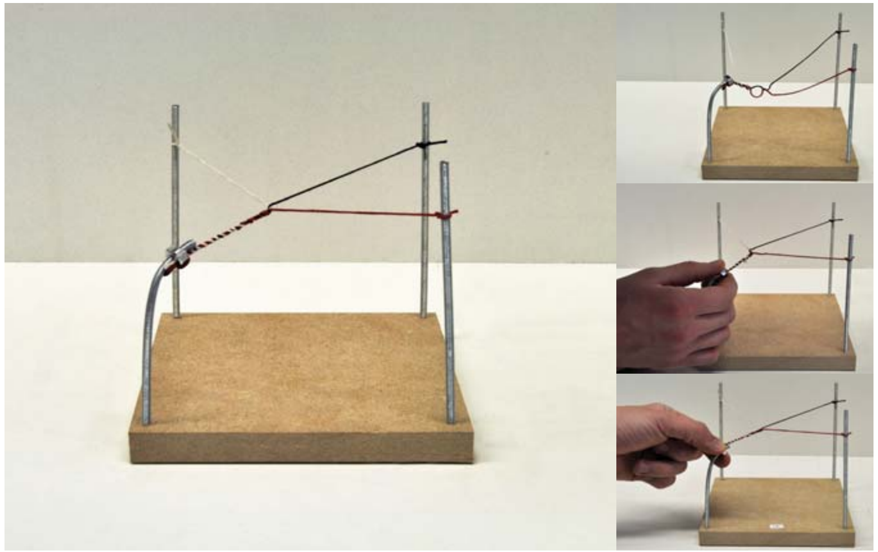


FIGURE 4_4: Winding. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

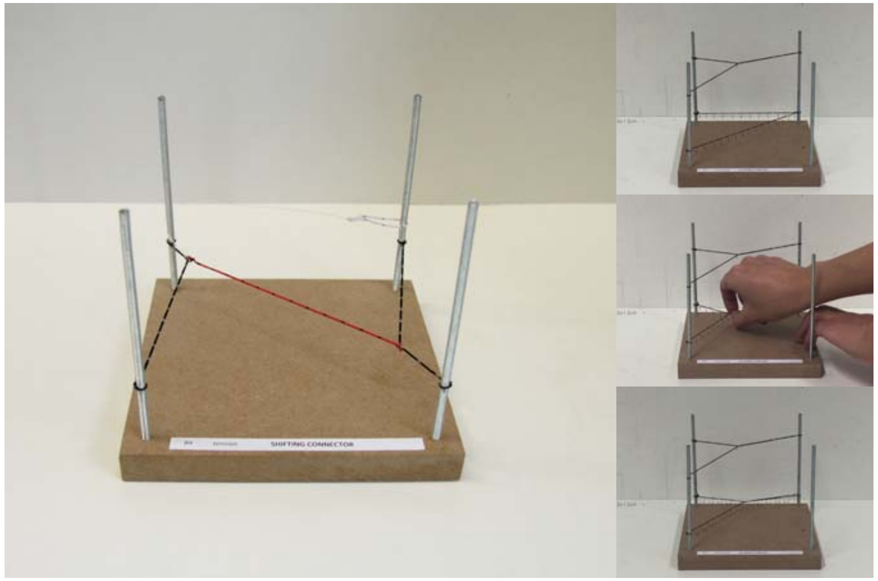


FIGURE 4_5: Connecting. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

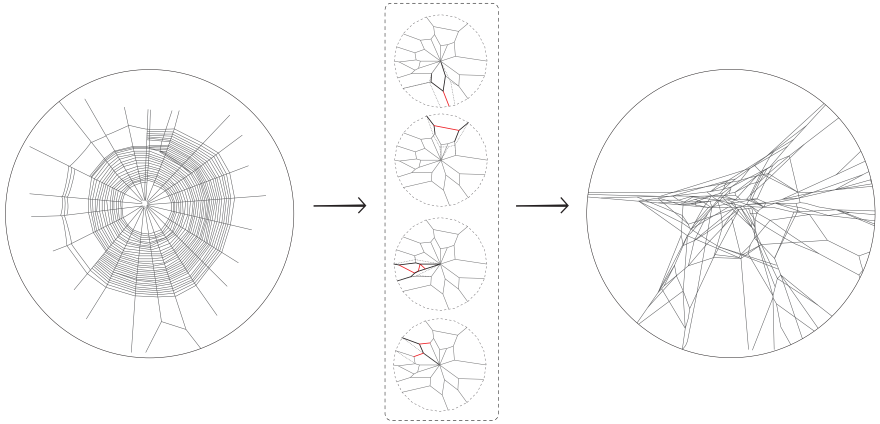


FIGURE 4_6: Conclusion of Transformation Strategies.(*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

Based on our study on the principles and strategies from our role model, we put our hands on small scale models to better understand local configurations of the web structures.* We chose two main strategies to look deep into, which are bundeling and connecting of fiber threads -- the most common and essential transformation process.(FIGURE 4_4/5)

What these strategies have in common is that they are both incrementally tensioning the resisting web structure during the transformation process. This potentially leads to a higher material efficiency or structural behaviour as we discuss in Chapter 3.

(Refer to appendix to see more models that were used for testing different transformation strategies (FIGURE 9_4).)*

Chapter 05: TRANSFER

TRANSFER OF IDENTIFIED STRATEGIES TO AN ARCHITECTURAL SCALE

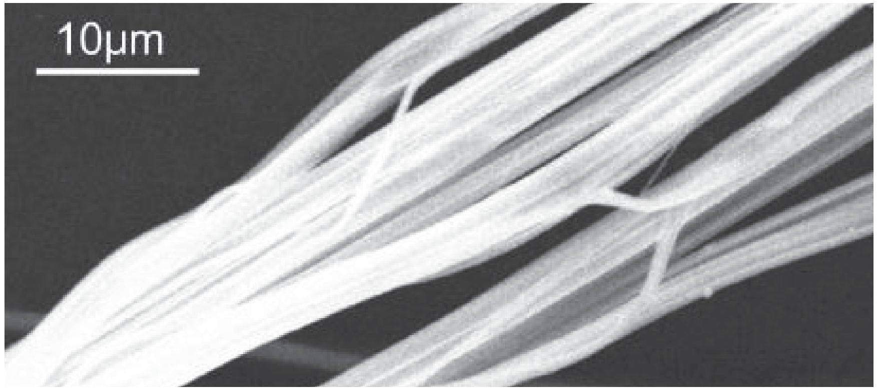


FIGURE 5_1: Spider Silk. (*Source: Takasuga et al (2015)*)

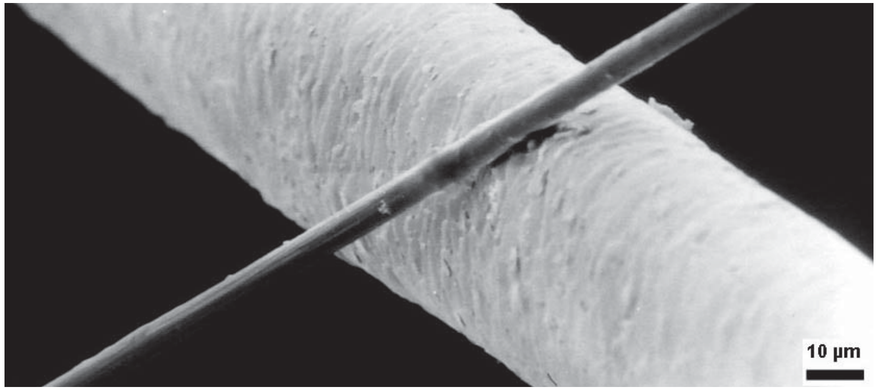


FIGURE 5_2: Carbon Fiber. (*Source: https://en.wikipedia.org/wiki/Carbon_fibers*

PREMISES OF TRANSFER

Considering the transfer from biological transformation strategies to architectural applications of such, it is essential to firstly discuss the variables and differences inbetween, to understand the feasibility and methodology of this undertaking:

1. Due to the fact that spider silk is a very elastic material (Young's Modulus 1-5 GPa)(FIGURE 5_1), whereas carbon fibres are more strong and stiff (Young's Modulus 30-50 GPa)(FIGURE 5_2)*, considerations need to be taken on how to deal with different material properties and behaviours. Transformation strategies need to be altered accordingly.

(Several material tests have been carried out to test carbon fiber properties and more specifically the joint behaviour. Refer to appendix to see more information(FIGURE 9_3))*

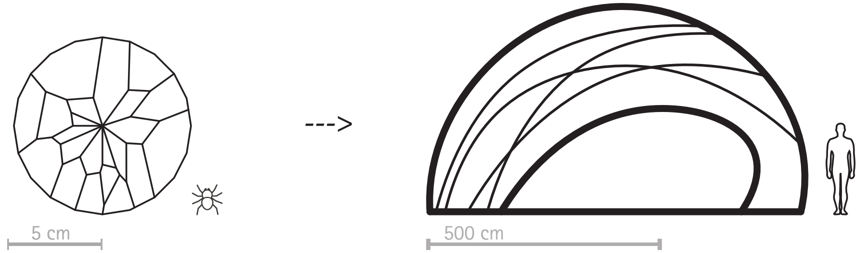


FIGURE 5_3: Different scale. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

2. An architectural structure, for instance a pavilion, has normally a diameter of approximately 6 meters, which is far more bigger than a typical spider web that has a diameter of normally not more than 20-40 centimetres. This indicates a huge difference regarding scale that does not only effect structural performance.

Taking these differences into consideration, the transfer from biological transformation strategies into architectural ones should concentrate on the methodology and transformation process, instead of just a superficial structural imitation which may probably not work when scaled up to architectural scales with different material usage.

Chapter 06: WHAT?

WHAT IS THE ARCHITECTURAL INTERPRETATION?

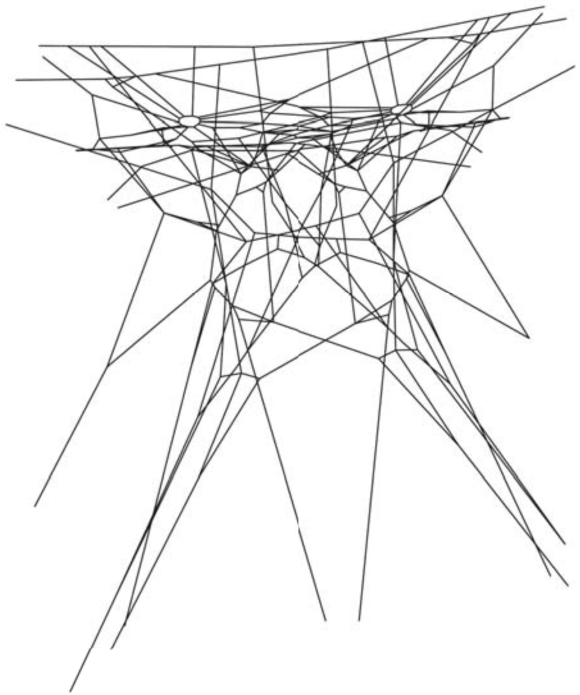


FIGURE 6_1: Resting Web of *L. mariana*. 3D reconstruction by the authors based on images in: Eberhard WG (2013)

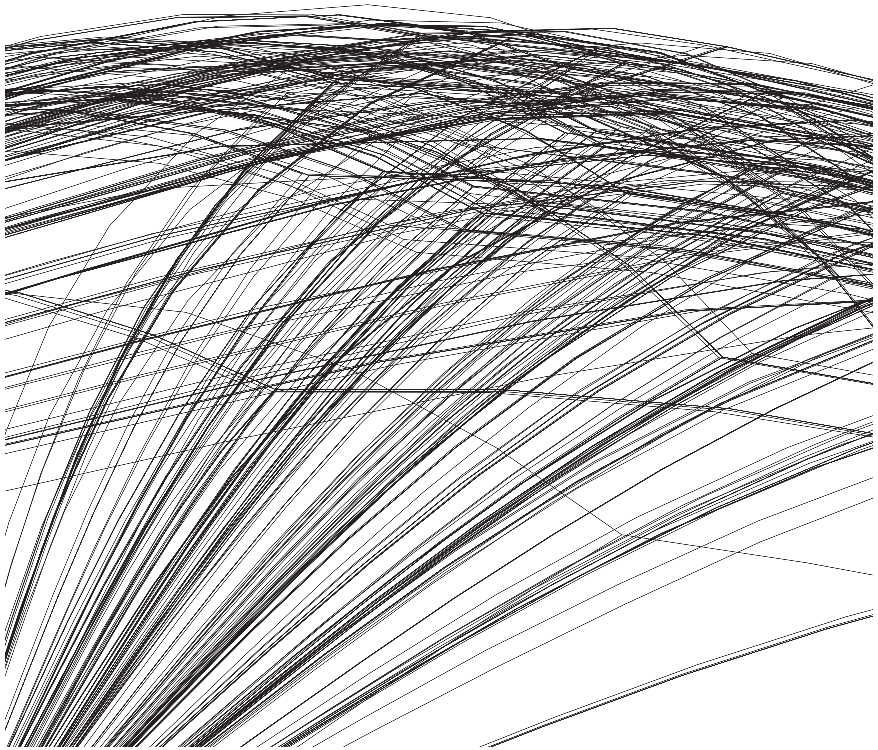


FIGURE 6_2: Study of a compression shell structure that employs the identified methods. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

Inspired by our Zombie-Spider rolemodels, we investigated possibilities to change existing fibrous structures. The most stunning part of Zombie Spiders transforming an Orb-Web into a cocoon web, is to see how much this transformation effects the whole behaviour of the structural system. It shows, that depending on how you (re-)organise threads in space, you can achieve various characteristics of the construction.

Thinking of fibrous structures in space not as a final stage of structural identity but as a system that is open for transformations and ada ptions opens up the possibilities of multiple scenarios of novel morphological concepts including optimization and ongoing structural change.

Depending on which material and fabrication process one wants to use, the structure can change from one kind to another one within a short time-period. The set-up can have multiple and flexible functions, and may adapt accordingly between them. This opens up multiple ways of how not only urban spaces can be used more effectively.

As we already discussed in Chapter 05, a very crucial part of adapting the *Zombie Spiders*' transformation process to an architectural scale is the material used.

The most unambiguous translation would be a fibrous structure that is composed out of fibers that are elastic up to a certain point. This means, that the structure can be fully transformed without changing the anchorings of the threads. The system plays with tension and looseness of the fibers which defines the structural behaviour inside of a dynamic, flexible up to a very static and stiff system. This could be interesting in constructions that need to somehow react to heavy environmental influences, changing loadcases and alternating functions. The elastic fibers allow for a back and forth change and continuous adaption. Their is no final state, but a possibility to change between a infinite number of configurations.

However, in our further investigations for technical applications we constrained ourselves to a specific setup with the used fibers being preimpregnated carbon rovings with an unmanned aerial vehicle (UAV) as transportation system and industrial robots for the exact placement of the fibers. At the one hand, this scenario is very specific and restricting, as the carbon fibers are going to cure within a certain timespan and are not open for transformations after they reached that final state. But at the other hand it comes very close to the most recent technical possibilities of how to work with fibrous systems in a big-scale fabrication scenario in the very near future. Even more, there is still the possibility to transform the morphology of the structure between the first placement of the fiber and the start of the curing process. And the impregnated carbon fibers make possible a shift from tension-only to compression structures as soon as they are cured.

Chapter 07: WHY?

WHY ARE THESE TRANSFORMATION STRATEGIES INTERESTING?

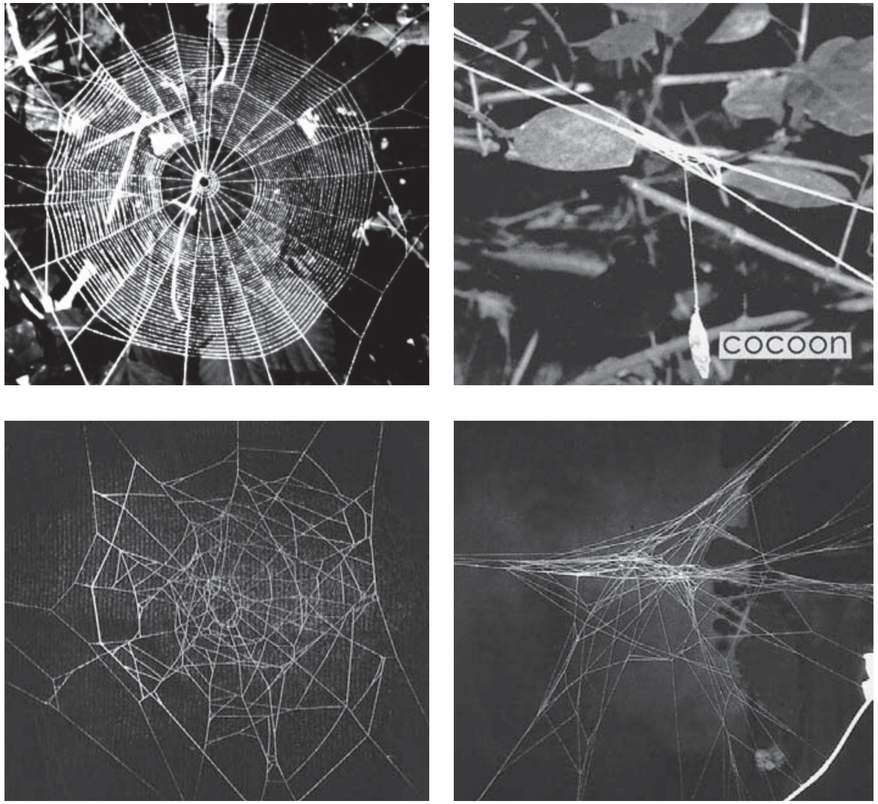


FIGURE 7_1: Orb-Like Webs (left) and transformed 'Cocoon-type Webs' (right) (*Source:* Eberhard WG (2001))

What we were most interested in terms of transformations of a carbon fibrous structure is the state change from a loosely put and undefined system of threads that are put into place by a somewhat unprecise UAV, to a defined and controlled form.

In all possible scenarios of how a drone could construct a fibrous construction one needs to deal with a maximum accuracy that is dependent on the fabrication space, but will not soon be below multiple centimetres, if not even a few decimetres. That means that whatever structure a drone is building, inaccuracy is either accepted and welcomed, or there is a system needed that is able to transform these loosely put threads into another, completely differently behaving structure.
Having the power of controlling the position of each of thousands of threads in 3D space is not only interesting in an aesthetic point of view. We reach the core of these possibilities as soon as we think about structural performance and material efficiency.

In the biological investigation we clearly identified these two factors as the main drivers for the transformative change from an orb web to a cocoon web. Even though these relationships are quite complex and hard to understand, we also had the chance of doing a structural analysis which seems to support this state of the art in biological research. The most apparent and logic way of describing the importance of this change and the reason why the cocoon web is behaving so much better in structural efficiency, is the logics of a tension equilibrium. An orb web has no use for a tension equilibrium, as it needs to most importantly deal with dynamic forces. The concept of dealing with an impact of a small flying animal on a spider web, is that some of the fibers will take most of the impulse-energy until

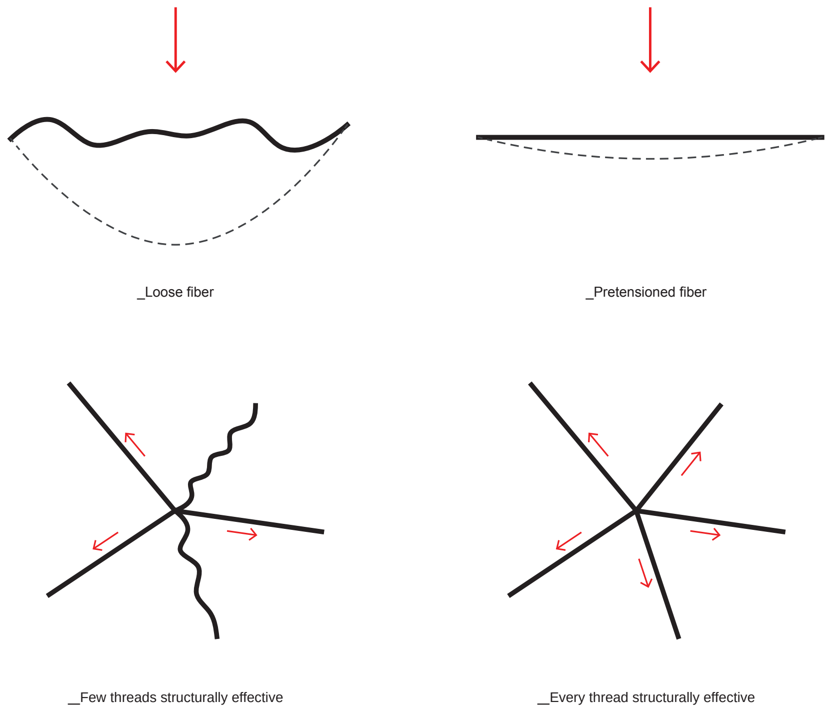


FIGURE 7_2: Pretension and Tension-Equilibrium. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

they break, and other loosely hanging threads get only tensioned after this impact and tore the other threads apart. If you have the possibility of repairing a net, this is a very efficient method to deal with dynamic forces.

But in a cocoon web this need is turned around into the opposite direction. Here the system's value is derived from its ability to hold up a static load (the wasp's cocoon) and all dynamic impacts are reduced to a minimum.

Concerning the material efficiency in a static load-case scenario of a fibrous system it is very important that all forces are distributed to all the thousands of fibers in a homogeneous way. Dealing with a static load that is X times higher than the material strength of the single threads in the system, a scenario where only minor amount of fibers is structurally effective at the first place will result in the failure of these, and incrementally of the whole structure.

To avoid this failure spiders have developed strategies of creating a tension equilibrium in the cocoon web. Threads that are only loosely hanging in space are tensioned with very simple techniques like the concept of bundling two fibers together in order to make both of them more tensioned.

We see a lot of potential in the application of similar bundling techniques with carbon fibers, because also there the tension equilibrium in the structure is of crucial importance.

Chapter 08: HOW?

HOW CAN FIBROUS MORPHOLOGIES BE TRANSFORMED?

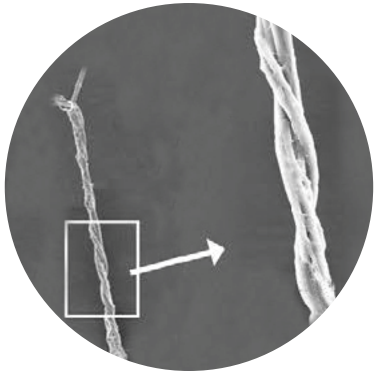


FIGURE 8_1(left): Winding of Spider Silk Threads. (*Source: 26 Thomas Hesselberg, Fritz Vollrath (2012)*)
FIGURE 8_2(right): Bundling with Additional Material. (*Source: 29 Kullmann Ernst, Stern Horst (1975)*)

Looking into the microscopic images of how spiders in nature actually bundle two silk threads together, we discovered that in some species fibers are winded (FIGURE 8_1) and in other species fibers are glued biologically (FIGURE 8_2). A common feature among most of the spiders is that they use bundling strategy to tension the existing fibers and control the position of joints, thus transforming the whole web structure's morphology.

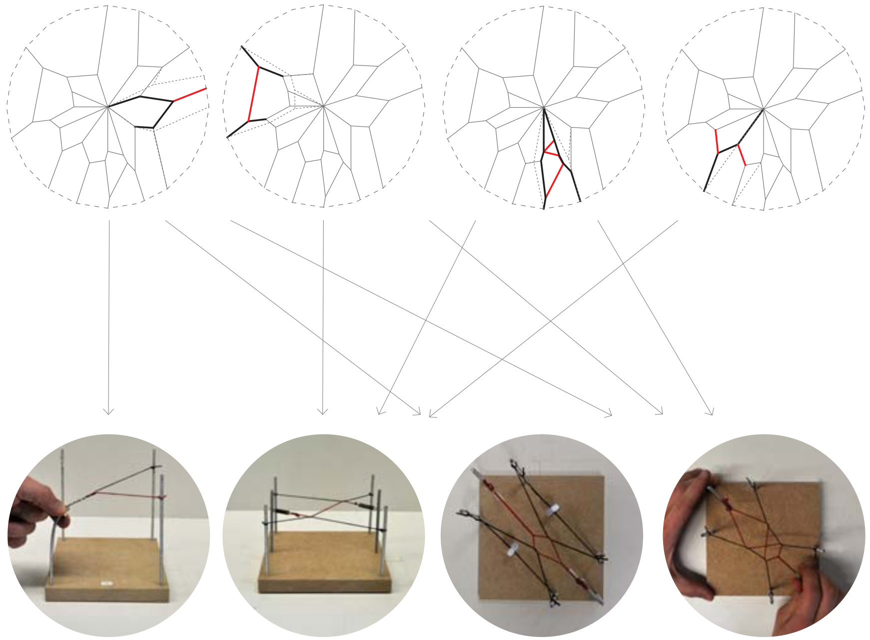


FIGURE 6_3: Main Transformation Strategies. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner*)

As discussed in Chapter 4, we can conclude that *Zombie Spiders* control the tension in their net-structure mainly by bundling two fibers, connecting two fibers and combinations of these two strategies. We abstracted three typical transformation strategies shown as below:

1. BUNDLING.
Basically two fibers are bundled together into one stronger fiber, thus the two slack fibers get more tensioned and much stiffer. This is the preliminary transformation strategy. When we turn that into architecture, considering the bundling technique, we choose winding two or more fibers together to tension the system and reach a similar effect.

2. CONNECTING.
If two fibers in space are far away or when there is a need of stabilizing the structure, *Zombie Spiders* also connect two fibers with an additional fiber. In architectural scale, we add additional fibers as well, to connect two distanced fibers.

3. BUNDLING + CONNECTING
In spider net structures combinations of bundling and connecting strategies are most commonly observed. These transformations form a certain geometrical pattern and have a great potential in architectural scales.

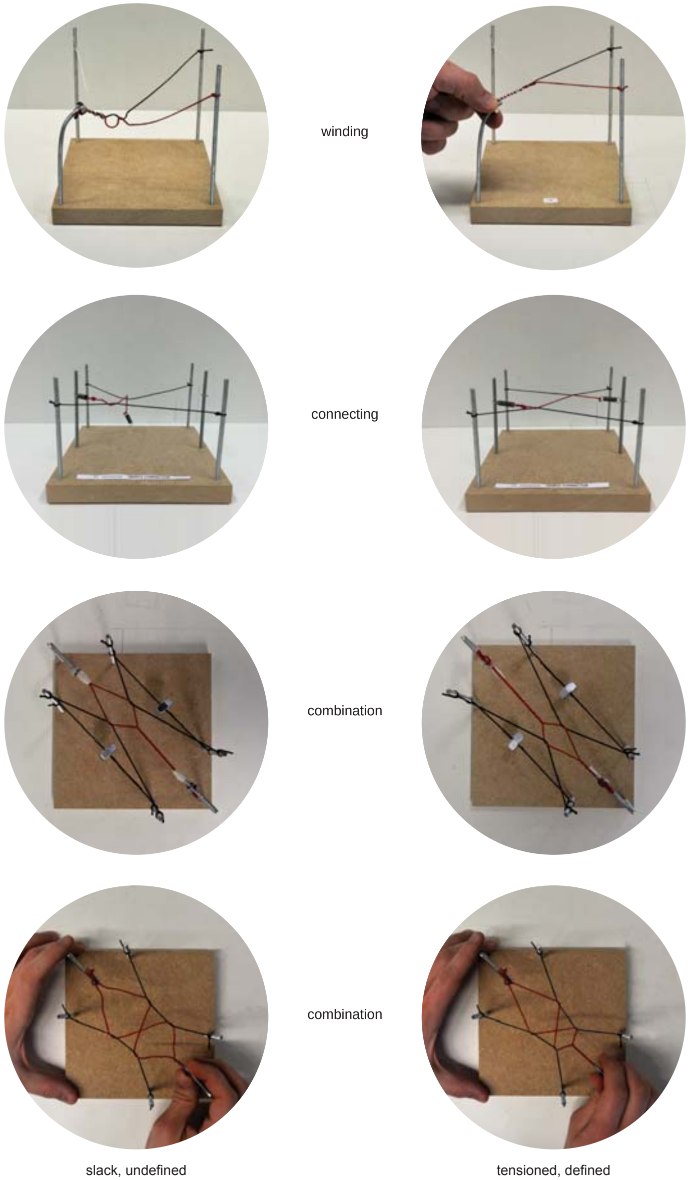


FIGURE 8_4: Main Transformation Strategies. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

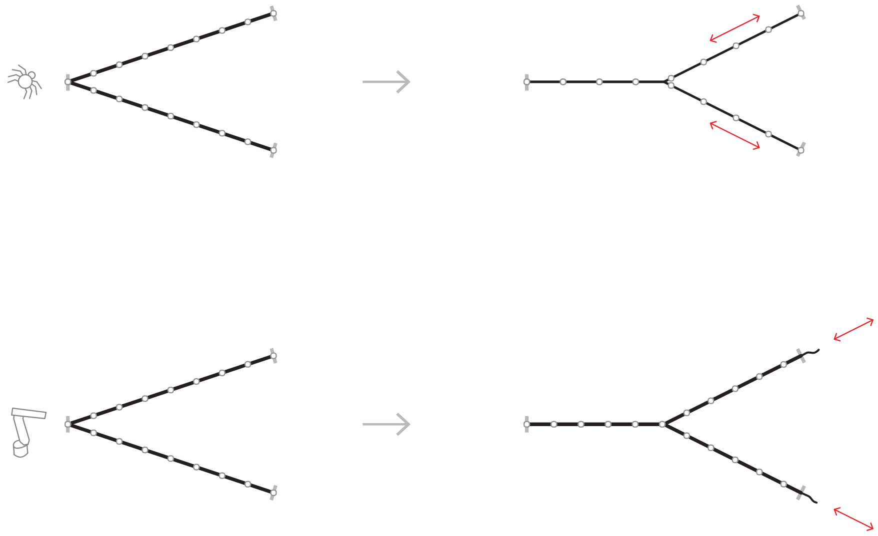


FIGURE 8_5: Stretching and Feeding. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

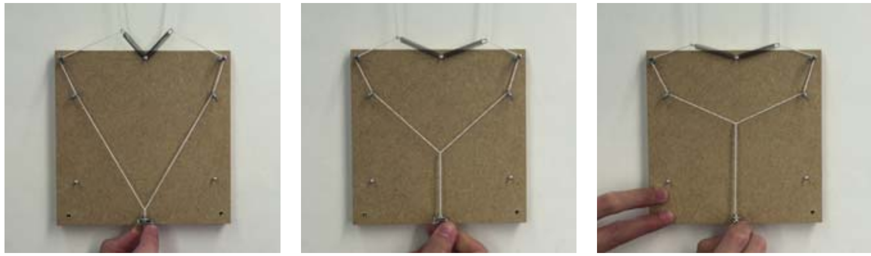
WINDING AS BUNDLING TECHNIQUE

Given the fact that bundling is a very important strategy to transform the *Zombie Spider's* net-structure, we believed that the bundling strategy should also be the main transformation method of this project.

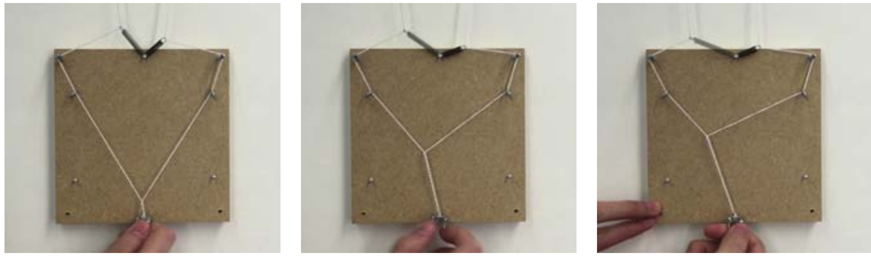
But considering the different fibrous material properties between silk and carbon fiber, it is not a simple copy-paste transfer, since spider silk can get deformed after bundling due to its elasticity, whereas carbon fibers do not allow such deformation.

Trying to bring the bundling techniques of the spider into an architectural scale we therefore needed a way to compensate the elastic behaviour at the anchor points of the threads.

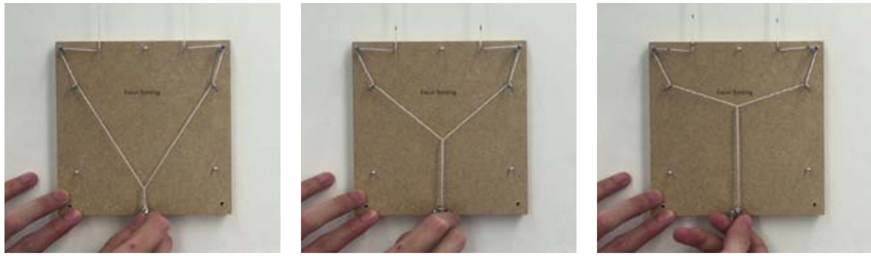
That means that while two fibers get tensioned, we also need to feed fibers to guarantee a controlled winding process. During these studies, we found that by controlling the feeding speed and feeding force, we can actually control the winding direction, thus controlling the position of winding joint in space as a spider would do by moving along the threads.



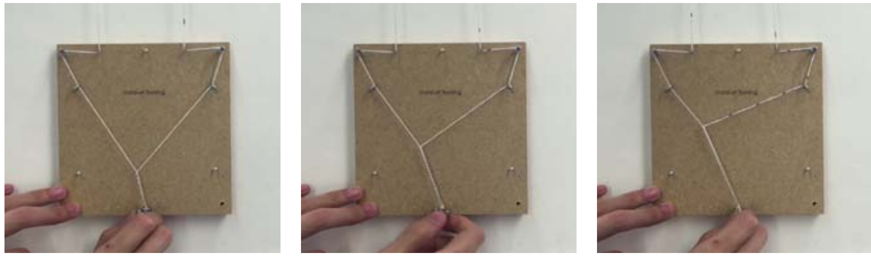
Equal Force Feeding



Unequal Force Feeding



Equal Speed Feeding



Unequal Speed Feeding

FIGURE 8_6: Different Feeding Options. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

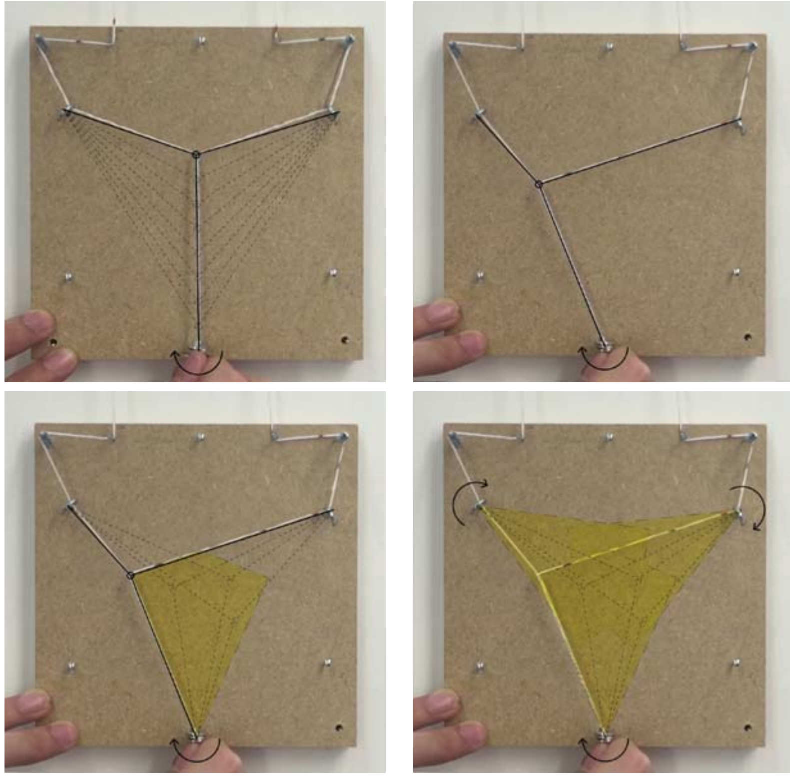


FIGURE 8_7: Controlling Position by Feeding. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

Position Controlling

We discovered that by controlling the feeding speed and force we can actually control the position of the winding point. This offers a big potential in global design and a bottom-up transformation. *

(Using this winding methodology, we created different setup to explore the potential of position controlling. Refer to appendix to see more information(FIGURE 9_5))*

Chapter 09: Appendix

ANSYS SCRIPT

```
!orb_web, deadlload
finish
/clear,nostart
/prep7
et,1,link10
keyopt, 1, 3, 0
pi = 3.1415926
deadld = 2e-3*9.8    ! 2g, cocoon weight
dd = 2e-6
AREA = 1/4*pi*dd*dd
ISTRAN = 0.999                          ! initial strain
!Q0 = 2.58e-6             ! unit load of the cable(N/m)
!QF = 5                             ! concentrated load(N)
H0 = 1e-2              ! pre tension under self weight
r,1,AREA,ISTRAN                         ! real constant
!mp,ex,1,1.5e9
mp,ex,1,H0/(ISTRAN*AREA) ! Fake Youngs Modulus
mp,nuxy,1,0.3                          ! Possion ratio
!mp,dens,1,Q0/AREA /(1-ISTRAIN)
!conversion density (N/m^3)
mp,dens,1,1.31*9.8e3


! ----------nodes----------
ua = 2*pi/20
*do,i,1,20
n, i, 0.0033*cos(ua*(i-1)), 0.0033*sin(ua*(i-1))
n, i+20, 0.0067*cos(ua*(i-1)), 0.0067*sin(ua*(i-1))
n, i+40, 0.01*cos(ua*(i-1)), 0.01*sin(ua*(i-1))
*enddo
n,61,  !!!!!!!!!!!!!!


!  ----------element
et, 1, link10
allsel
type,1
mat,1
real,1

*do,i,1,19
e,i,i+1
*enddo
e,20,1

*do,i,21,39
e,i,i+1
*enddo
e,40,21

*do,i,1,20
e,61,i
e,i,i+20
e,i+20,i+40
*enddo

! ----------solve----------
acel,,,-1
*do,i,41,6
d,i,ux,0
d,i,uy,0
d,i,uz,0
*enddo

ERR0 = 1/200
PASS1 = 1
*dowhile,PASS1
/solu
antype,0
nlgeom,on
sstif,on
nsubst,20
outres,all,all
solve
fini


! redefine stiffness and loading
/prep7
mp, ex, 1, 3500e6 !!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!

r,1,AREA,H0/(3500e6*AREA)
/solu
nlgeom, on
nsubst, 20
outres, all, all
time,1
solve
time,2
f,61,fz,-deadld
solve

/post1
set,last,last
plesol,smisc,1
```

```
!cocoon_web, dead_load
finish
/clear,nostart
/prep7
et,1,link10
pi = 3.1415926
deadld = 2e-3*9.8    ! 2g, cocoon weight
!small E for form finding
dd = 14e-6
AREA = 1/4*pi*dd*dd
ISTRAN = 0.999
!Q0 = 2.58e-6
!QF = 5
H0 = 1e-2
r,1,area,ISTRAN
!mp,ex,1,1.5e9
mp,ex,1,H0/(ISTRAN*AREA)
mp,nuxy,1,0.3
!mp,dens,1,Q0/AREA/(1-ISTRAIN)
mp,dens,1,1.31*9.8e3
n, 1, 0.0022, -0.001
n, 2, 0.0013, -0.001
n, 3, 0.0022, -0.0016
n, 4, 0.0029, -0.004
n, 5, 0.0016, 0.0005
n, 6, 0.0, 0.0
n, 7, 0.0026, 0.0019
n, 8, 0.004, 0.0029
n, 9, 0.0014, 0.002
n, 10, 0.0015, 0.0047
n, 11, -0.0009, -0.0027
n, 12, -0.0012, -0.0017
n, 13, -0.0001, -0.0026
n, 14, -0.0022, -0.0021
n, 15, -0.0029, -0.004
n, 16, -0.0036, -0.0007
n, 17, -0.0047, -0.0015
n, 18, -0.0028, -0.0006
n, 19, -0.0023, -0.001
n, 20, -0.0005, 0.0016
n, 21, 0.0, 0.0049
n, 22, -0.002, 0.0014
n, 23, -0.0031, 0.0019
n, 24, -0.004, 0.0029
n, 25, -0.0017, 0.0007
n, 26, 0.0001, -0.0044
n, 27, 0.0, -0.0049
n, 28, 0.0, -0.0021
n, 29, 0.0013, -0.0031
n, 30, 0.0018, -0.0045
n, 31, 0.001, -0.0027
n, 32, 0.0008, -0.0023
n, 33, 0.0032, 0.0003
n, 34, 0.0048, 0.0009
n, 35, -0.0016, 0.0
n, 36, -0.0015, -0.0047
! ----------element----------
et, 1, link10
allsel
type,1
mat,1
real,1

e,1,2
e,1,3
e,3,4
e,5,6
e,5,7
e,7,8
e,7,9
e,6,9
e,9,10
e,11,12
e,11,13
e,6,12
e,12,14
e,14,15
e,16,17
e,16,18
e,18,19
e,6,19
e,20,21
e,20,22
e,22,23
e,23,24
e,22,25
e,6,25
e,26,27
e,13,26
e,13,28
e,6,28
e,29,30
e,29,31
e,31,32
e,6,32
e,2,6
e,2,29
e,26,31
e,28,32
e,5,33
e,33,34
e,16,23
e,6,20
e,6,35
e,18,35
e,14,19
e,11,36
e,1,33
e,25,35
! ----------solve----------
acel,,,-1
d,24,all
d,17,all
d,15,all
d,36,all
d,27,all
d,30,all
d,4,all
d,34,all
d,8,all
d,10,all
d,21,all

ERR0 = 1/200
PASS1 = 1
*dowhile,PASS1
/solu
antype,0
nlgeom,on
sstif,on
nsubst,20
outres,all,all
solve
fini

! redefine stiffness and loading
/prep7
mp, ex, 1, 1500e6
r,1,AREA,H0/(1500e6*AREA)
/solu
nlgeom, on
nsubst, 20
outres, all, all
time,1
solve
time,2
f,6,fz,-deadld
solve

/post1
set,last,last
plesol,smisc,1
```

FIGURE 9_1: ANSYS script. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner*)

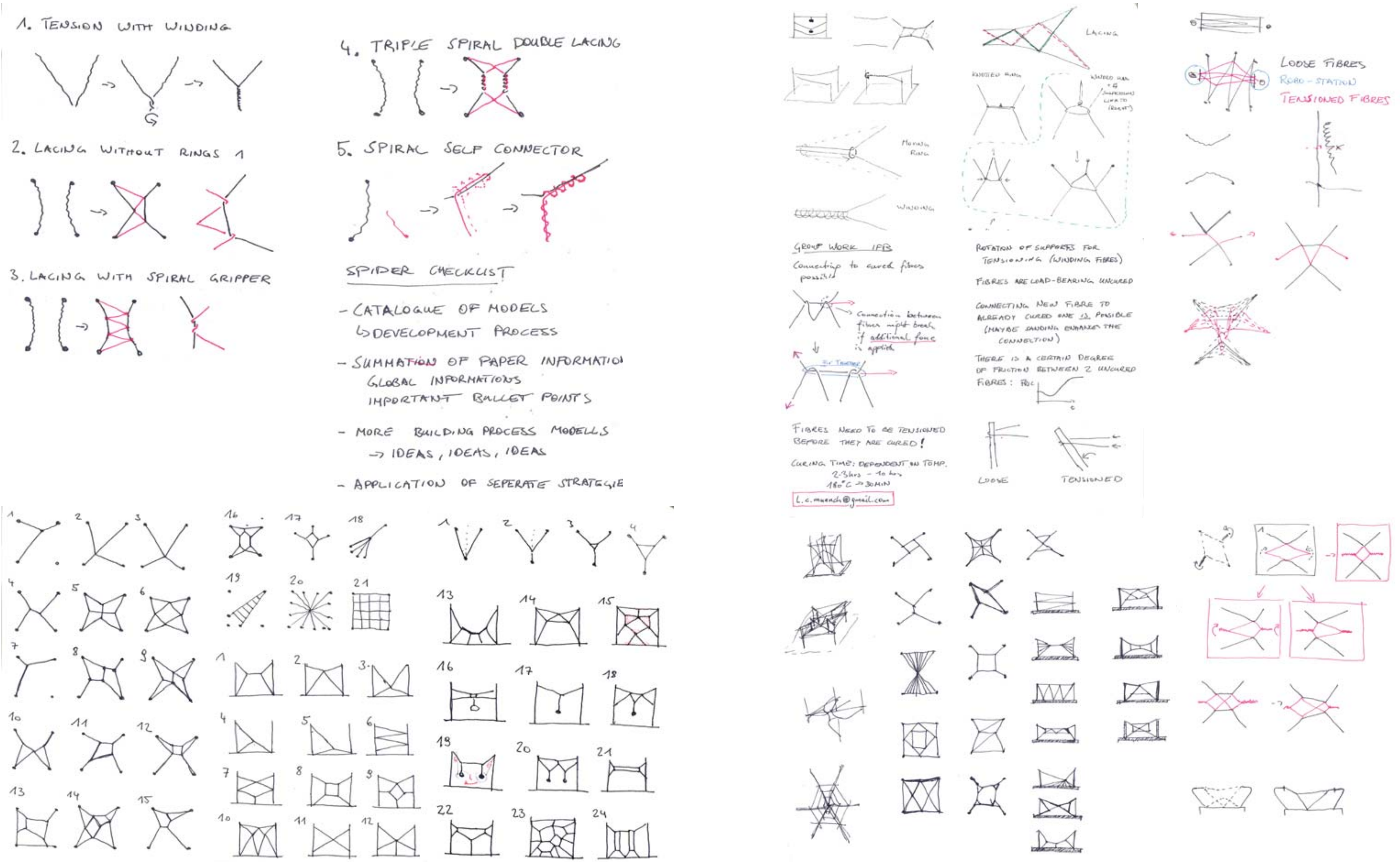
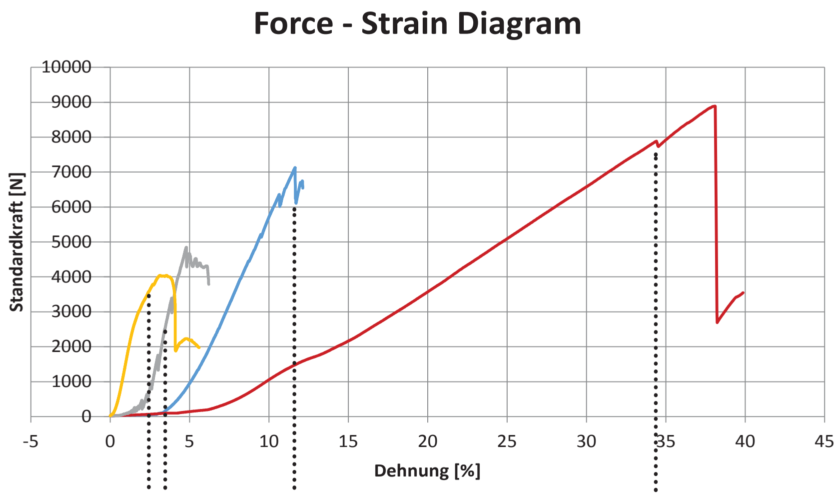


FIGURE 9_2: Sketches. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner*)



Test 1
2 fibers wound together

Test 2
2 fibers wound together (with fork)

Test 3
2 straight fibers

failure at ends

axial tension test

FIGURE 9_3: Carbon Fiber Axial Tension Test. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

A: COMPARISON

B: TENSIONING

C: CONNECTING

D: CONNECTOR

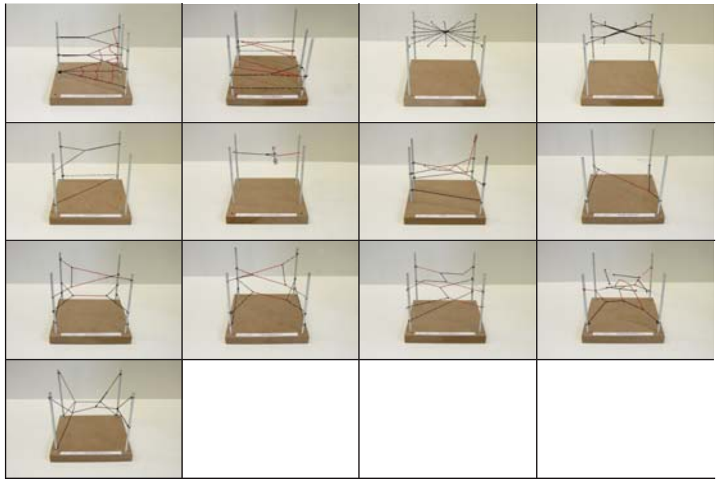


FIGURE 9_4: Exploration of local web configuration. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

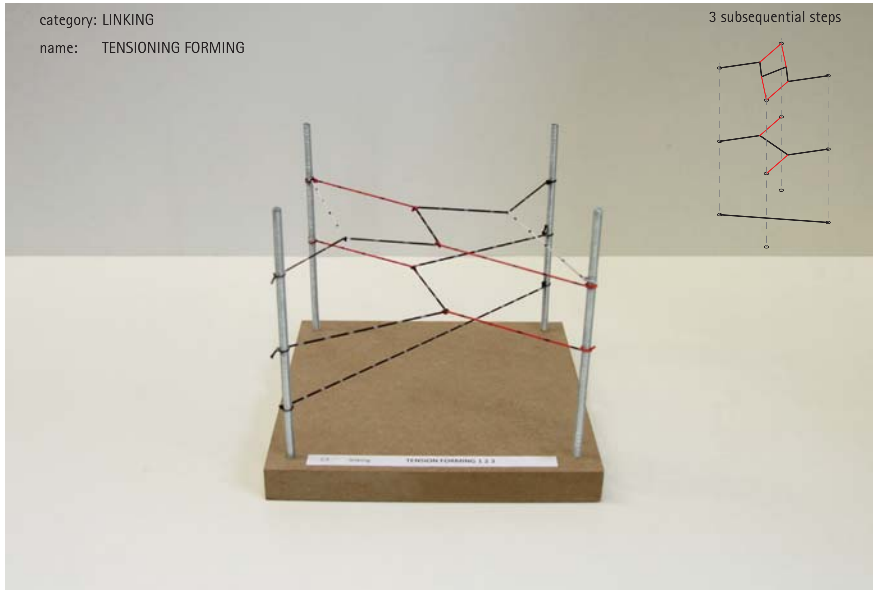
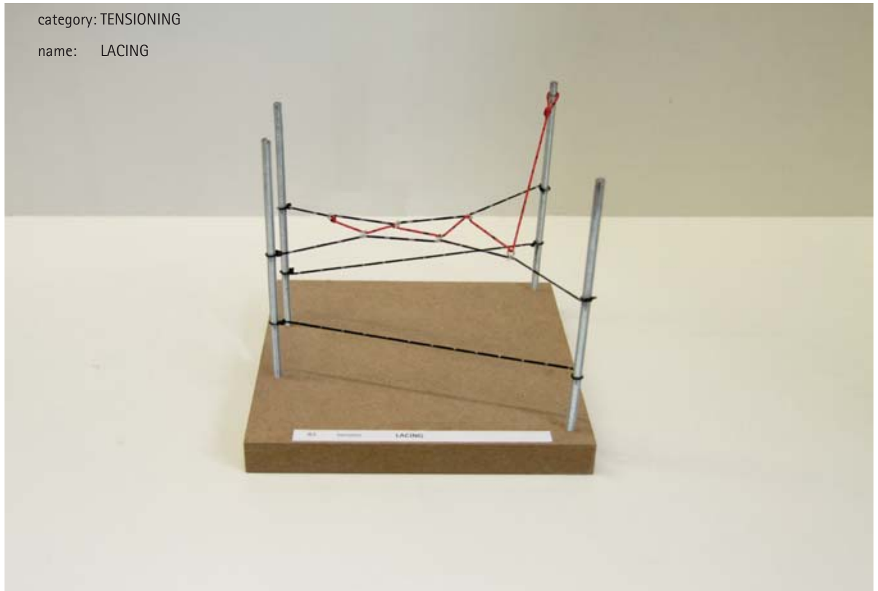


FIGURE 9_4: Exploration of local web configuration. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*



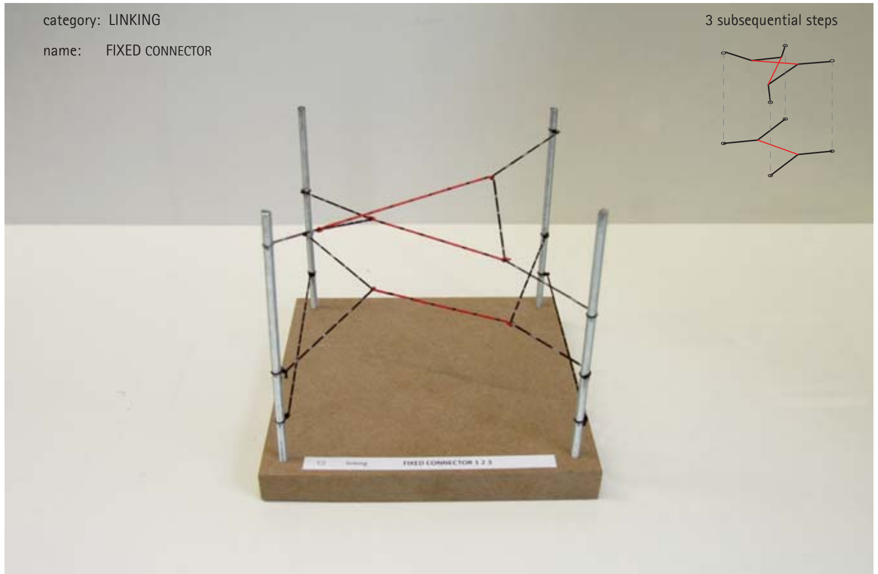
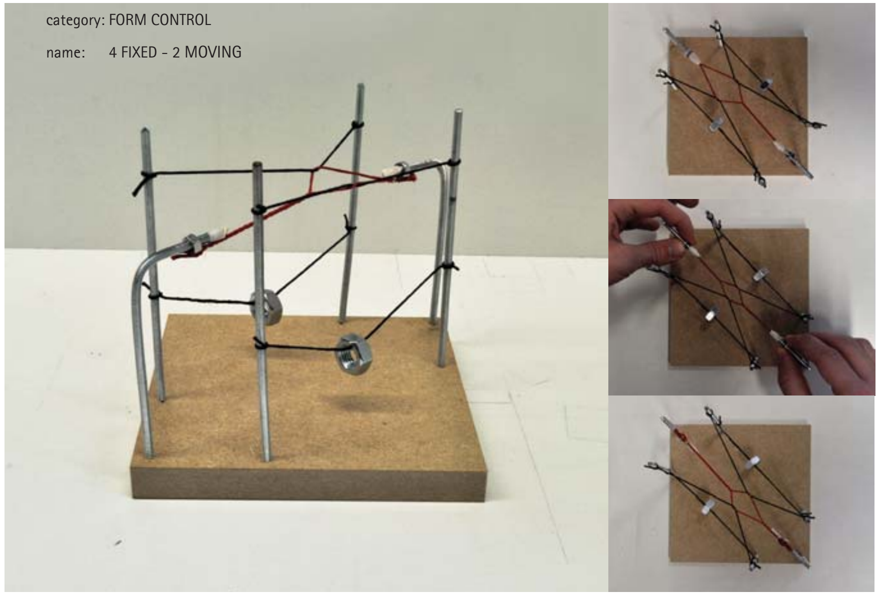


FIGURE 9_4: Exploration of local web configuration. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*



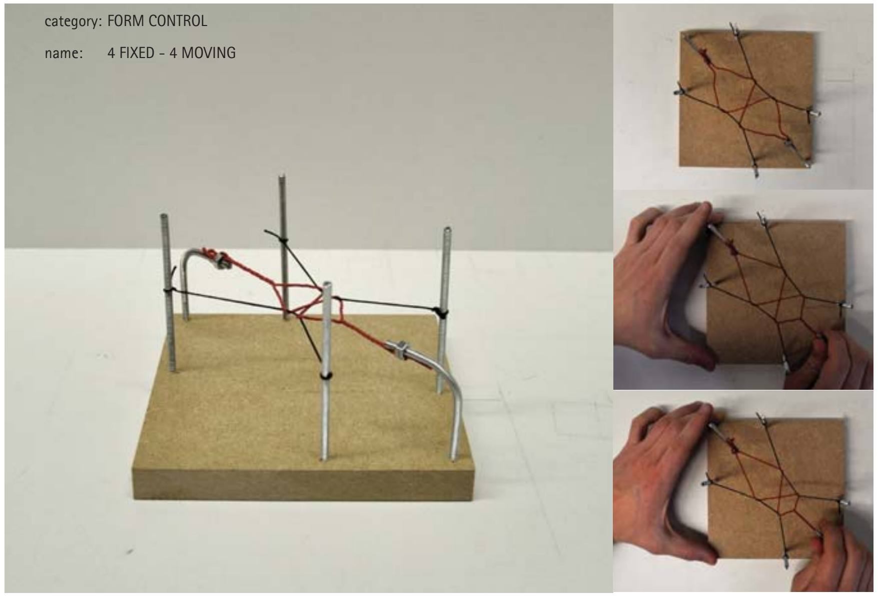


FIGURE 9_4: Exploration of local web configurations. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

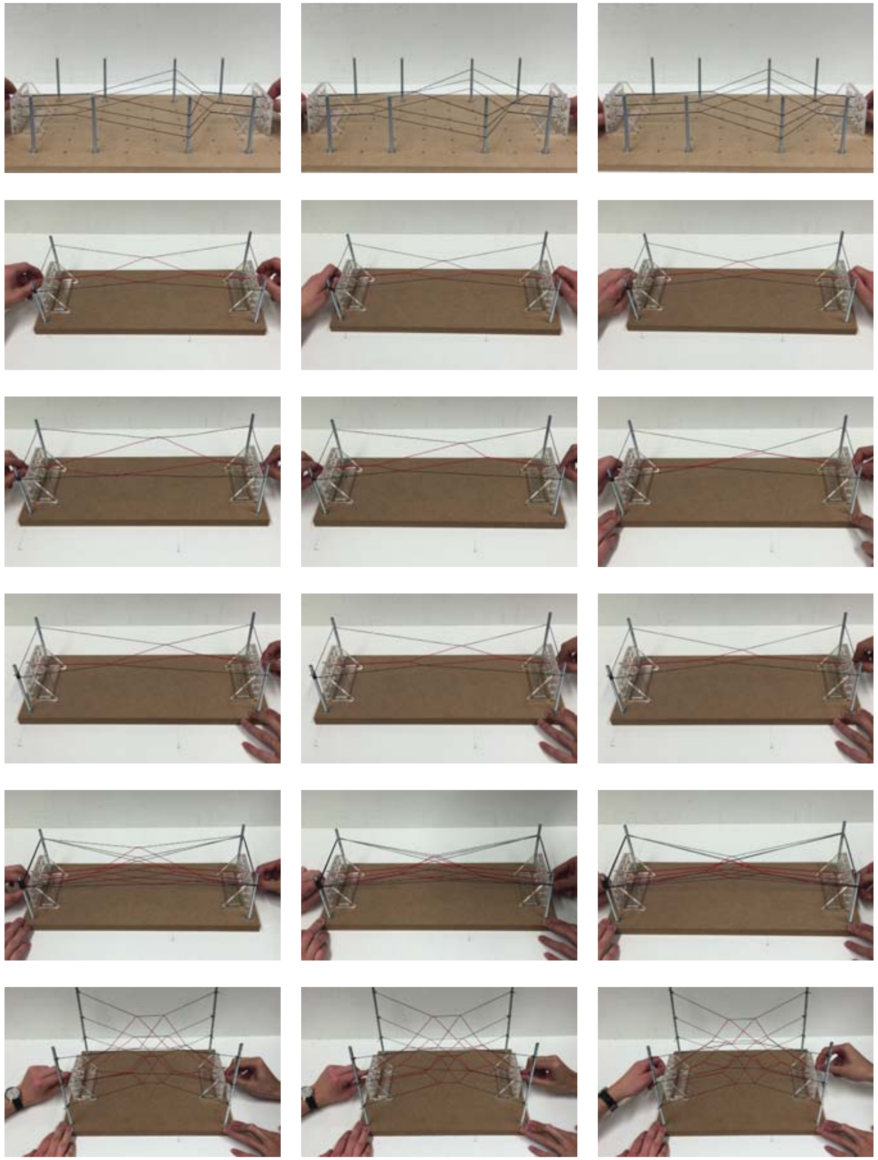


FIGURE 9_5: Exploration of Winding System. (*Source: Jingcheng Chen, Dominga Garufi, Dongyuan Liu, Hans Jakob Wagner)*

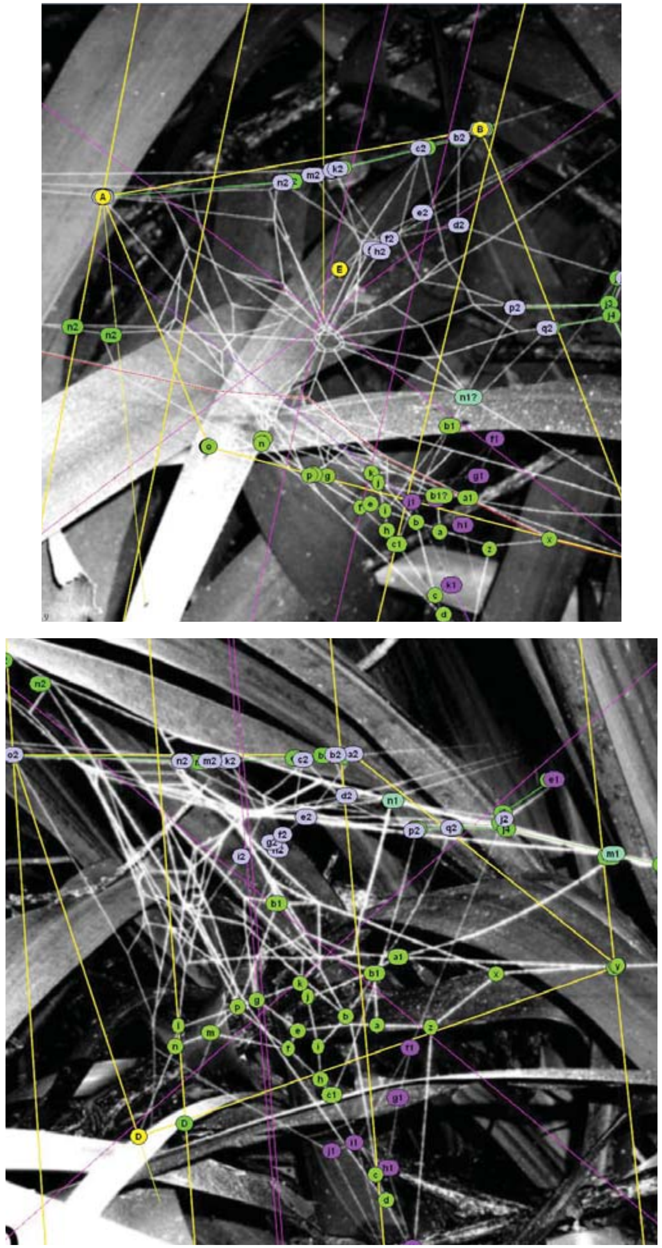


FIGURE 9_6: Reconstruction process of a 3D model of the resting web of L. mariana based on two images taken in the field by Eberhard WG (2013)

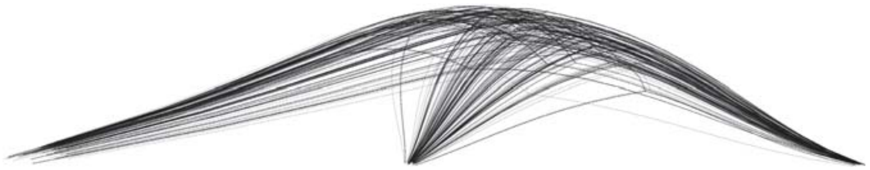


FIGURE 9_7: Speculative Design 1 Using transformation techniques to controlably create connection points of threads onto inflatable formwork (*Source:* Dongyuan, Garufi, Jingcheng, Wagner)

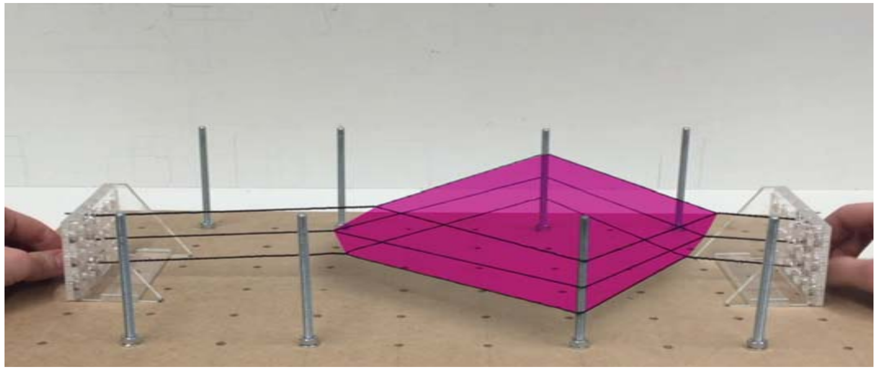


FIGURE 9_8: Speculative Design 2 Scaffolding structure that is controlled by developed transformation strategies (*Source:* Dongyuan,

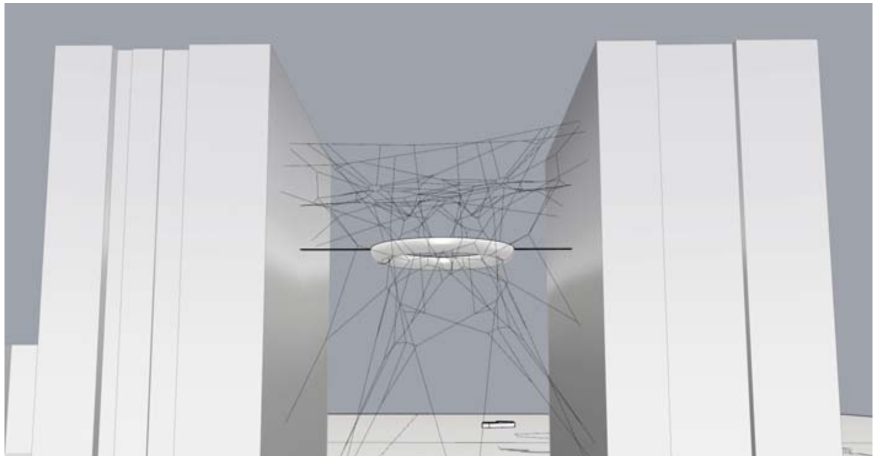


FIGURE 9_9: Speculative Design 3 Using transformation techniques to create network of structural threads, being tensioned and connected by developed transformation strategies (*Source:* Dongyuan, Garufi, Jingcheng, Wagner)

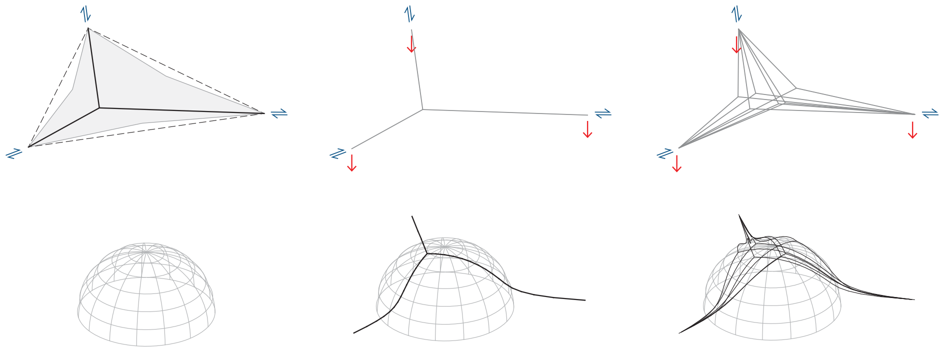


FIGURE 9_10: Speculative Design 1 Using transformation techniques to controlably create connection points of threads onto inflatable formwork (*Source:* Dongyuan, Garufi, Jingcheng, Wagner)

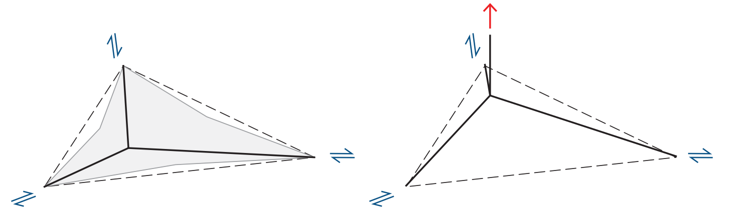


FIGURE 9_11: Speculative Design 3 Using transformation techniques to controlably create connection points in a 3 Dimensional Fabrication Space (*Source:* Dongyuan, Garufi, Jingcheng, Wagner)

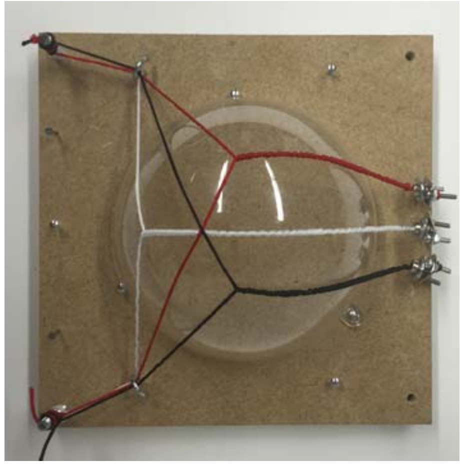


FIGURE 9_12: Speculative Design 1 Using transformation techniques to controlably create connection points of threads onto inflatable formwork (*Source:* Dongyuan, Garufi, Jingcheng, Wagner)

FIGURE 9_13: Polysphinctine Wasp Flacopimpla barathrica sp. (*Source:* NR Fritzen (2014))

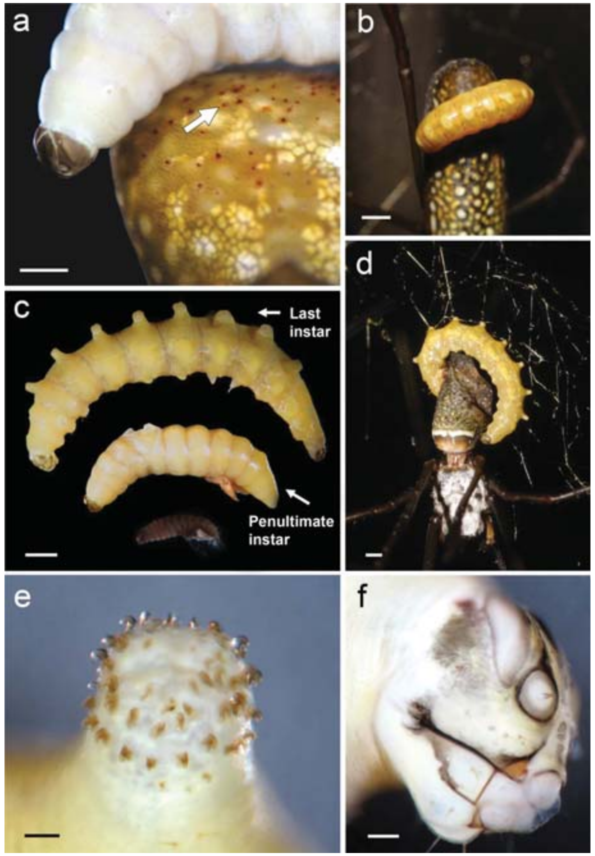


FIGURE 9_14: Immature stages of H. bicolor and their effects on their hosts. (*Source:* Gonzaga, Eberhard, Sobczak, Penteado-Dias (2010))

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