RESEARCH RESEARCH RESEARCH RESEARCH RESEARCH RESEARCH RESEARCH RESEARCH RESEARCH RESEARCH

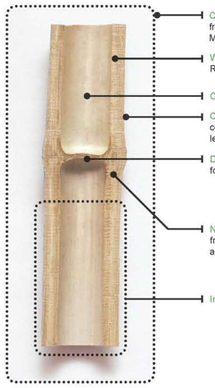
The process of studying a material is a daunting task. This is so in the sense that in order for any discovery to be made or learned, one must ignore application and program. Instead, one must make broad strokes to better understand the material; quite often with much failure. Research in this method can only be accomplished through a sense of “discipline and play” or “reason and passion”. Passion and play are usually easily acquired; the challenge for research is to apply a discipline or reason to your action. Over the last year I have focused on studying bamboo, and have developed a set of rules that can be applied to a building system.

The method was not apparent in the beginning. I began working in a very erratic fashion; yet, this paved a route to a clearer method of research allowing me to define certain parameters based on material properties. The properties of bamboo, described in the composition column, naturally coincided with modes of bundling, splitting, weaving, and tensegrity. By mapping out these modes in conjunction with parameters such as scale and connection details new methods can be derived.

Parametric design is commonly used in computer programming technologies to model complex surfaces and volumes based on a set of programmatic data. However, if examining the structure and theory of a parametric model a reduction of tools can be made. Because the material I have chosen to work with lends itself to such a low level of technology, I can eliminate technology in terms of designing with bamboo. Instead, by understanding what inputs and parameters are acceptable to the material, an honest output can be derived.

My studies have lead me to a naturally flexible and dynamic system, that rely on the properties of the material.

BAMBOO_COMPOSITION



Culm: The primary vertical stem of bamboo. The culm grows from a shoot, the base being the full diameter of the bamboo. Most culms are tubular in section.

Wall: The portion of the material that is unsupported. Referred to in thickness.

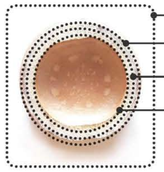
Cavity: The hollow portion of the culm

Cuticle: Outer skin or periphery of the culm. The cuticle contains a dense concentration vascular fibers that run the length of the culm.

Diaphragm: The tissue that crosses the interior of the culm found at the node.

Node: the joints that segment the culm at a varying frequency. The nodes encircle the culm and can be identified as raised concentration of material.

Internode: the hollow length of bamboo between the nodes.



Dendrocalamus Strictus

Periphery: greatest concentration fibers. on the cellular level, cells vary in diameter, the smallest diameter on the outside.

Middle Layer: larger diameter, less strong.

Inner Wall: usually soft to the touch, this layer is more pulpy and has little strength.

Other Terms

Paracheyma: the silica based lignin that binds the vascular bundles in the culm.

Lignification: the natural hardening of the culm that occurs 5 years after virgin growth.

Rhizomes: root system that supports the growth of the culm.

Monopodial rhizome: often referred to as running bamboo. Monopodial rhizome, spreads in all directions, running to better soil conditions. This type can be identified by an vertical indentation in the internode.

Sympodial rhizome: referred to as clumping bamboo. Clumping types grow confined to a 5 foot diameter and offer the best material for building.

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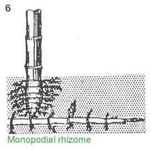

Monopodial rhizome

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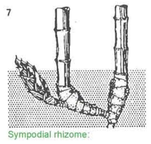


Sympodial rhizome:

*taken from “IL 31 Bambus- Bamboo”

Scientific Classification

Kingdom: Plantae

(unranked): Angiosperms

(unranked): Monocots

(unranked): Commelinids

Order: Poales

Family: Poaceae

Subfamily: Bambusoideae

Supertribe: Bambusodae

Tribe: Bambuseae

*Around 92 genera and 5,000 species

Material Properties:

Specific gravity:
0.575 to 0.655 Kg/cm²

Average weight:
0.025 Kg per Meter

Static Bending:
a. Fiber stress at elastic limit : 390 to 100 Kg/cm²
b. Modulus of rupture: 610 to 1600 Kg/cm²
c. Modulus of elasticity: 1.5 to 2 X 10^5 Kg/cm²

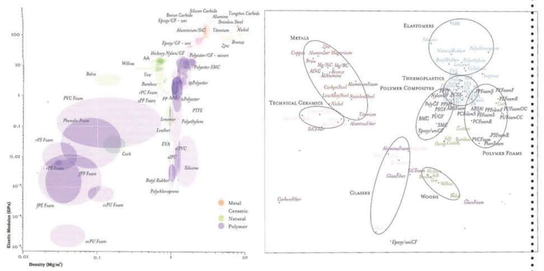
Ultimate crushing stress:
320 to 720 Kg/cm²

Average tensile stress at yield:
1400 to 2800 Kg/cm²

Ultimate compressive stress:
794 to 864 Kg/cm²

Safe Working Stress:
a. Tension: 160 to 350 Kg/cm²
b. Compression: 105 Kg/cm²
c. Shear: 115 to 180 Kg/cm²

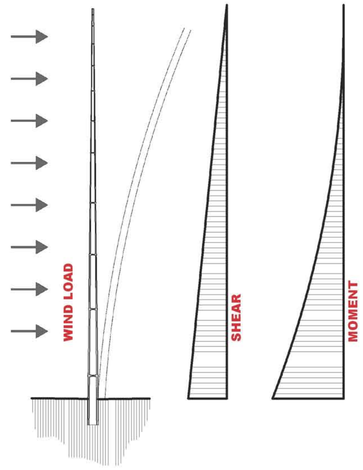
*taken from “Bamboo and Wood stave Technology” T.N. Lipangile 1990 Teknicus



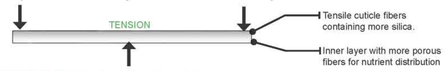
*taken from” Materials and Design”

BAMBOO_FORCES

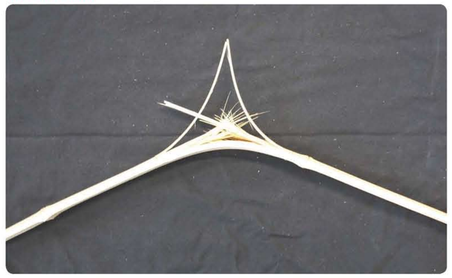
BENDING



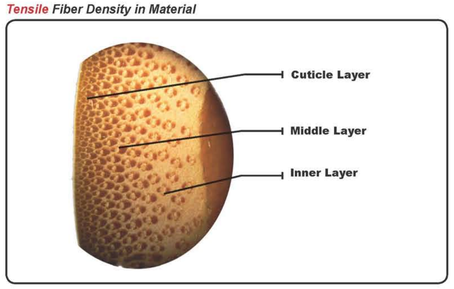
***Response** to Natural Occurring Conditions*
(Modulus of Elasticity due to wind loads on culm)



***Tensile Failure** in Bending Material*



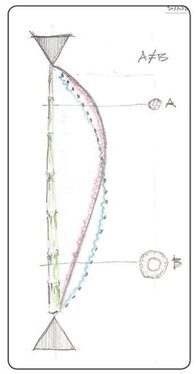
***Tensile** Fiber Density in Material*



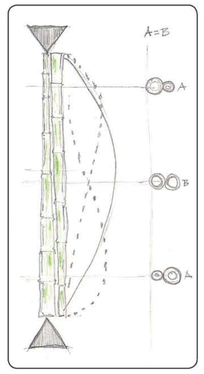
***Testing** Woven Bundles*

BAMBOO_LOADING

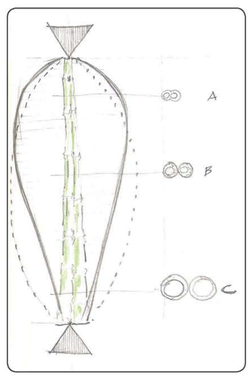
BUCKLING



SINGLE CULM
Considering the cross section of bamboo and its conical tubular form, when loading, the material bends in an catenary curve. There are really three ways to arrange the material, to compensate for this cross section.



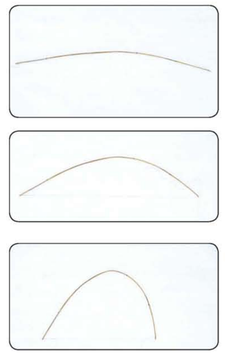
DOUBLE CULM OPPOSING
If loading the 2 culms, by opposing the tapper, the catenary form is lost and the system tends to break in the center where both culms match each other in weakness.



DOUBLE CULM REGULAR TAPER
By purely bundling without opposition either one catenary form is created or, a planer element is created.

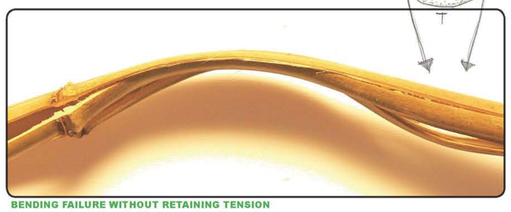
***Testing** Woven Bundles*

BAMBOO_FORM



COMPRESSION STAYS AND FABRIC
Adding a composite material to these systems allows for an enclosure of space and architectural elements to appear.

CATENARY FORM
Form condition by axial loading.



BENDING FAILURE WITHOUT RETAINING TENSION
By not responding to the materials cross section with a continuos line of tension, the material splits or fractures increasing failure in a system.

SPIRAL THROUGH SPACE
Bending the material causes the culm to warp three dimensionally as the sun lignifies the strands of fibers.

CATENARY FORM IN GRIDSHELL
Building a gridshell reveals a catenary form.

WOVEN BAMBOO STRANDS
Laser cut bamboo woven into a friction fit joint.

BAMBOO_INPUT

MATERIAL

FORM

LOADING CONDITION

CATENARY FORM

MATERIAL SECTION

MATERIAL LOADING CONDITION

MATERIAL FAILURE

FORCE

BAMBOO_PARAMETERS

MODES

CONNECTIONS

SCALE

BUNDLING

SPLITTING

WEAVING

TENSEGRITY

SLEEVING LASHING

SLEEVING

SPLICING

FRICTION

RATTAN

JOINERY

KERFING

CASTING

AMPLITUDE

FREQUENCY

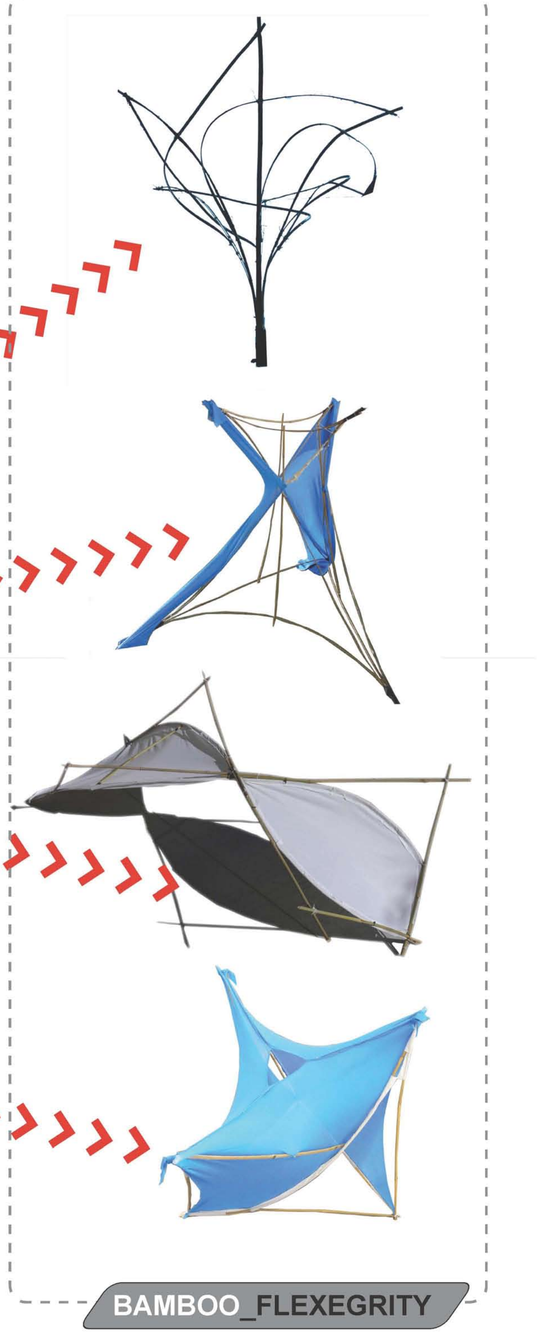
PROPORTION

BALANCE

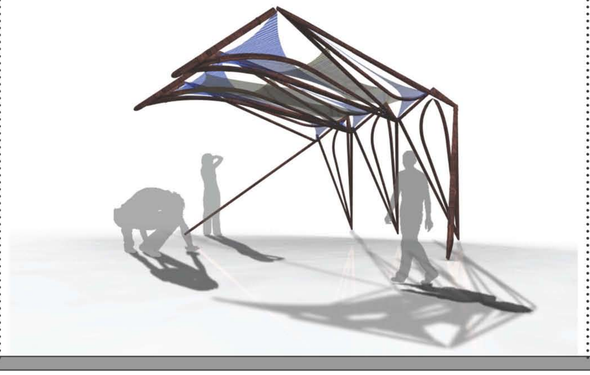
ORIENTATION

BOUNDARY

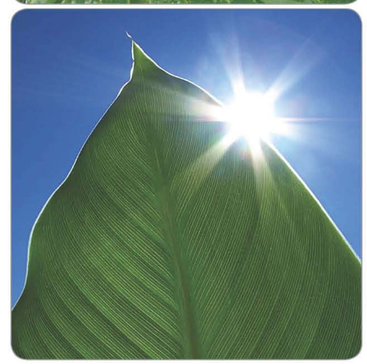
BAMBOO_OUTPUT



BAMBOO_FLEXEGRITY



OUTSIDE_FORCES



EXTERIOR FORCES:
After paremetric design is completed based on material properties. external forces cand be applies to further develop the design.

Considering biomimicry, I like to think of how natural systems react to seasons, climate, and human sprawl.

CATENARY FORM:

1. The theoretical curve generated by gravitational force on hanging elements.

2. Bamboo is not a true centenary form due to its tapering cross section. its form is closer to a n equiangular spiral.

3. The form appears when loading in an axial manner.

MATERIAL FAILURE:

Bamboo tends to fail at the nodal joints. the celular structure is less regular and therefor force is concentrated in these areas.

When bamboo fails in the region of the internode, the results are spectacular. Fibers of the material go into great stress and splinter violently.

MODE:

1. a manner of acting or doing; method; way: modern modes of transportation.

2. a designated condition or status, as for performing a task or responding to a problem: a machine in the automatic mode.

3. appearance, form, or disposition taken by a thing, or by one of its essential properties or attributes.

MODE:

1. the act or state of connecting.

2. the state of being connected: the connection between cause and effect.

3. anything that connects; connecting part; link; bond: an electrical connection.

SCALE:

1. either pan or tray of a balance

2. a beam that is supported freely in the center and has two pans of equal weight suspended from its ends —usually used in plural

3. an instrument or machine for weighing

PARAMETRIC MANIFESTATIONS

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Capstone Chairs:
Álvaro Malo
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FLEXE_GRITY

DEFINITION:

A structure in which its integrity is based on the flexure of the material.

Synergy between surface tension and bending. Occurs in anisotropic materials when applying force with isotropic material.

Flexegrity is a portmanteau of flexure and integrity.

FLEXURE:
Behavior of a slender structural element subjected to an external load applied perpendicular to an axis of the element.

The movement of the diaphragm and colon in the digestive tract.

INTEGRITY:
Consistency of actions, values, methods, measures, principles, expectations and outcome.

ANISOTROPIC:
The property of being directionally dependent. Bamboo is an Anisotropic material because of the directionality of the fibers in the culm.

ISOTROPIC:
Which means homogeneity in all directions.

METHOD:

Because bamboo is comprised of linear elements that travel the length of the culm, elements must be added to the material to compensate for its anisotropic qualities. If the material were to only be loaded at its ends simple tensegrity structures could be made that appreciate the material qualities. However, once a system that is bundled enters a buckled condition, the flexure of the material occurs.

Originally the basic form of flexegrity was derived from material failure. So rather than working with the materials strengths, I chose to work with its weaknesses. From this I was able to comprehend and develop multiple connection and detailing conditions.

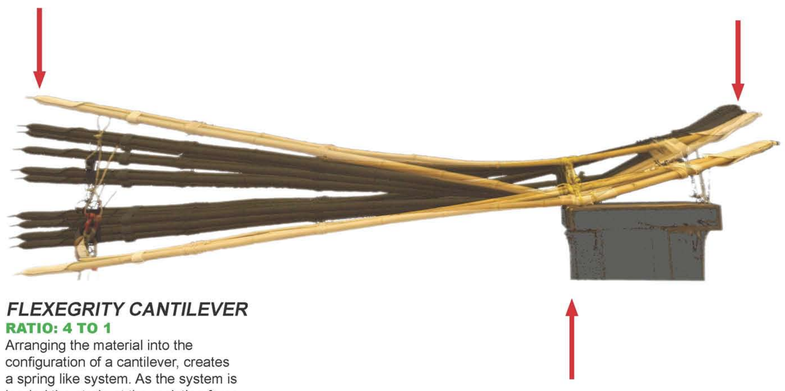
The system is derived at the simplest terms with three elements. Two anisotropic materials placing bending moment on another. This creates in a sense a two dimensional diaphragm that can be arrayed to further define space while maintaining and allowing movement.

COMPOSITE:

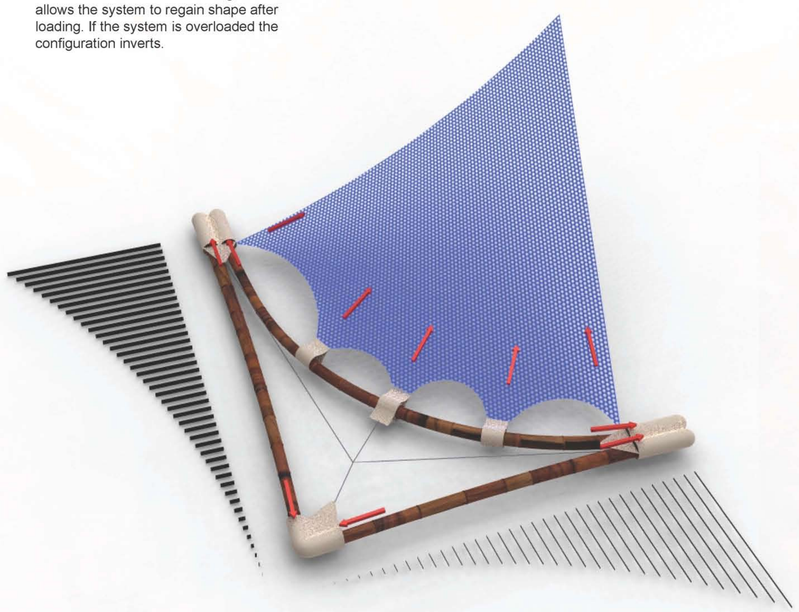
Considering bamboo and its properties, a few good choices can be made in terms of material connection details. As noted before we can see that as far as mechanical attributes bamboo is similar to leather, and it is as dense but less elastic. Therefore leather, rawhide, or similar material would be a good choice for a terminating connection.

When loading the material with surface tension, I chose nylon rip stop for its isotropic properties in the weave of the fabric. Nylon in itself is comprised of synthetic lines similar to the properties of bamboo.

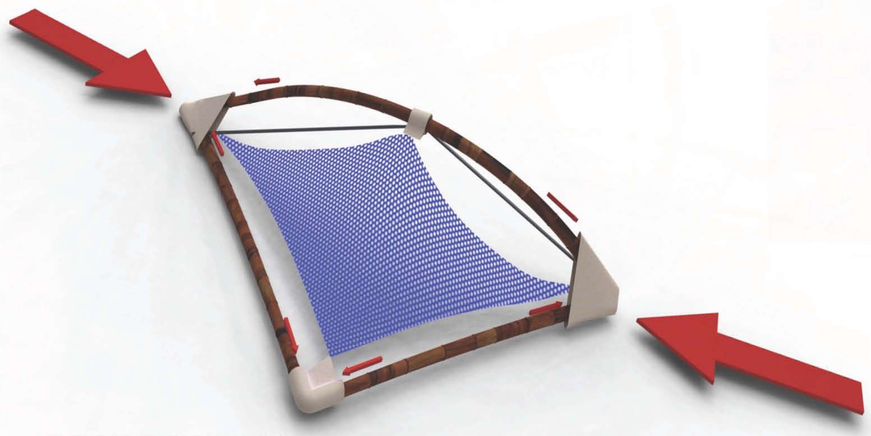
FLEXEGRITY_DIAGRAM



FLEXEGRITY CANTILEVER
RATIO: 4 TO 1
Arranging the material into the configuration of a cantilever, creates a spring like system. As the system is loaded the strain at the resisting force allows the system to regain shape after loading. If the system is overloaded the configuration inverts.

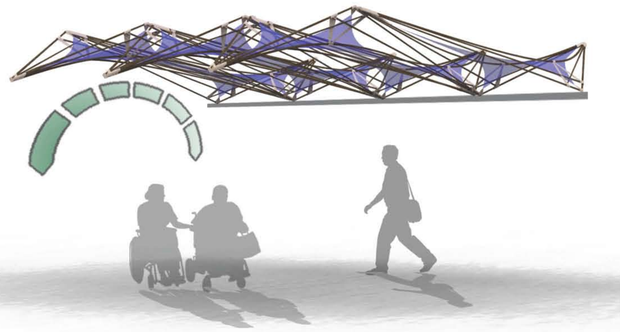


FLEXEGRITY IN MOMENT
LOADED BY SURFACE TENSION
If loading the system with surface tension, ie stretching a fabric element in the system, generates most moment in the the straight culms.

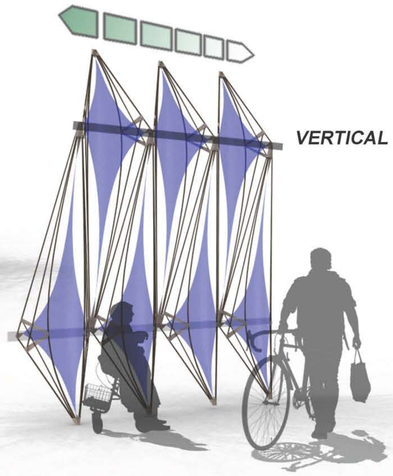


FLEXEGRITY IN BUCKLING
RESISTED BY SURFACE TENSION
If deformation is resisted by surface tension, failure is most apparent in the point loaded area on the curved culm. This can be corrected by sleeving the system

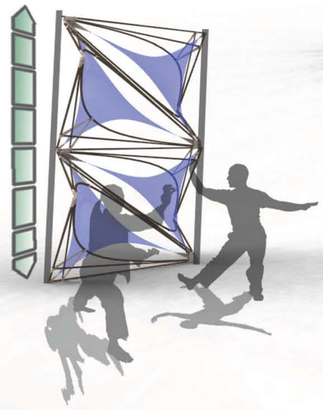
FLEXEGRITY_CONFIGURATIONS



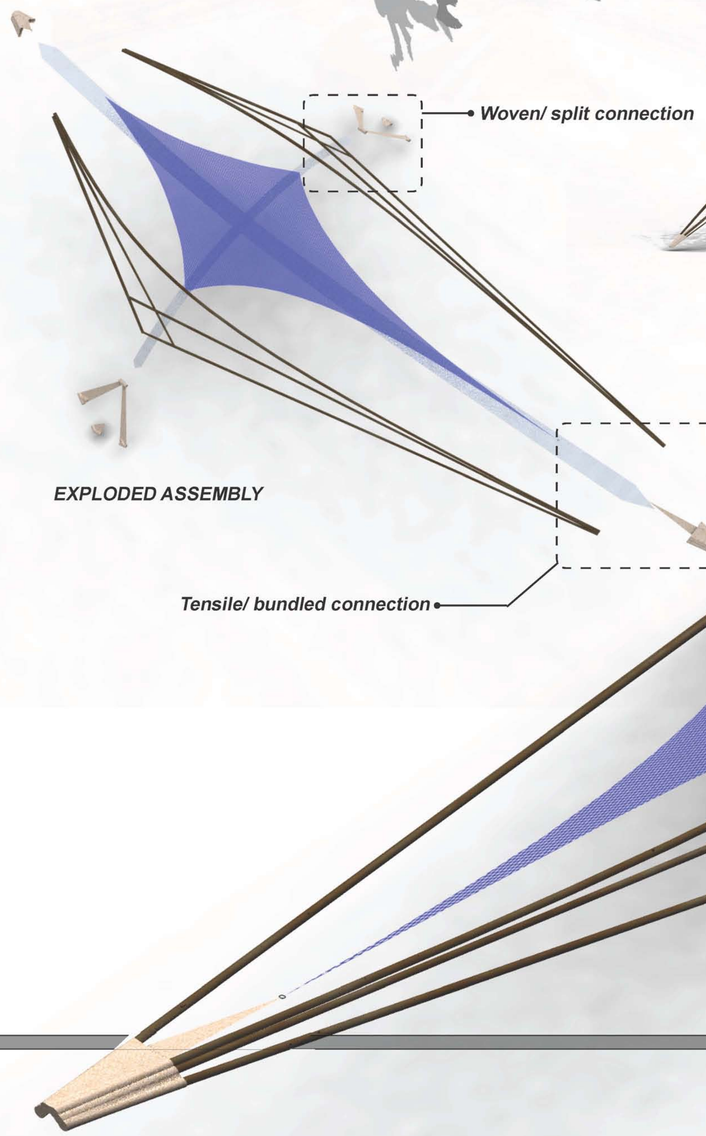
OVERHEAD SHADE STRUCTURE



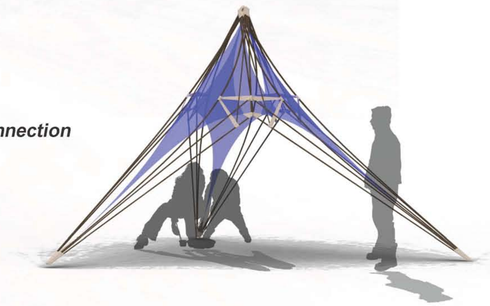
VERTICAL WALL STRUCTURE



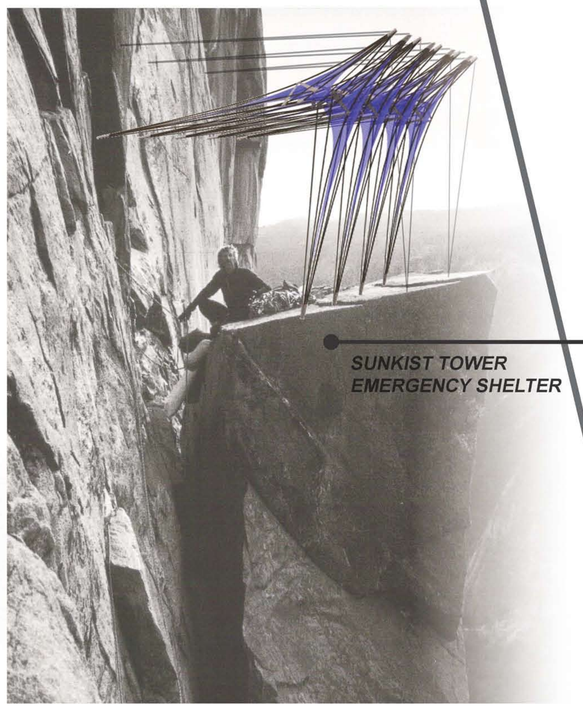
HORIZONTAL WALL STRUCTURE



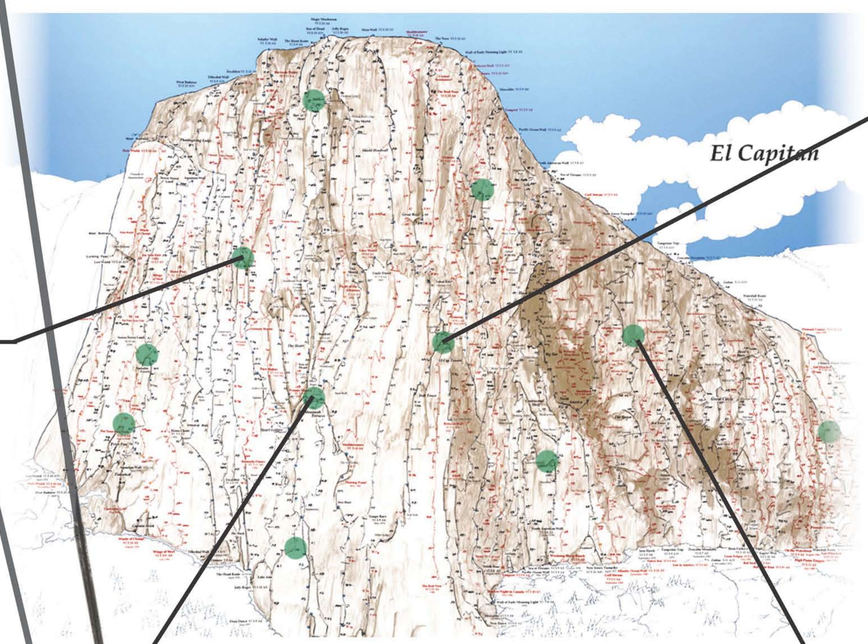
EXPLODED ASSEMBLY



ARRAYED SHELTER



SUNKIST TOWER
EMERGENCY SHELTER

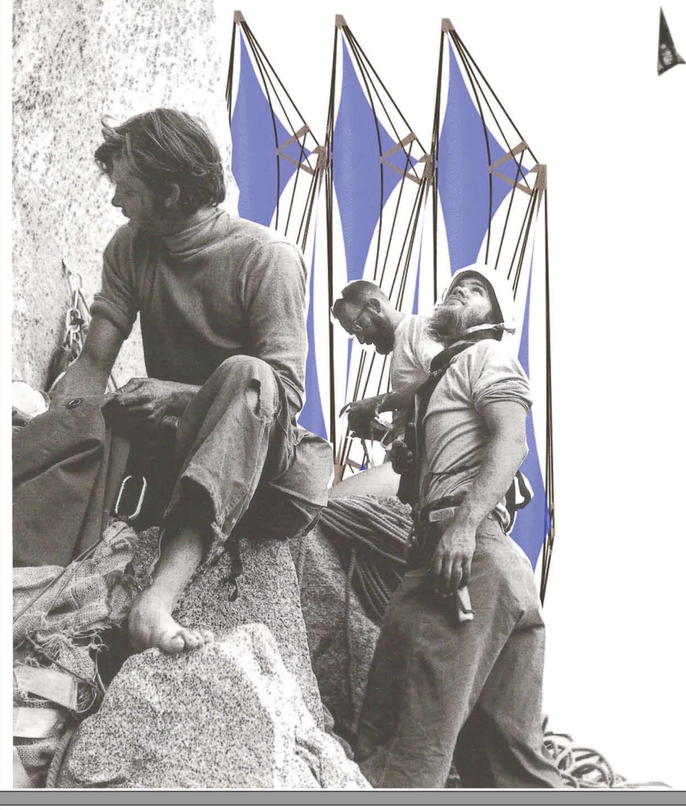


POTENTIAL SITES

EL CAPITAN TOWER
EMERGENCY SHELTER

WIND SHELTER ON THE NOSE

“LOST IN AMERICA” BIVOUAC

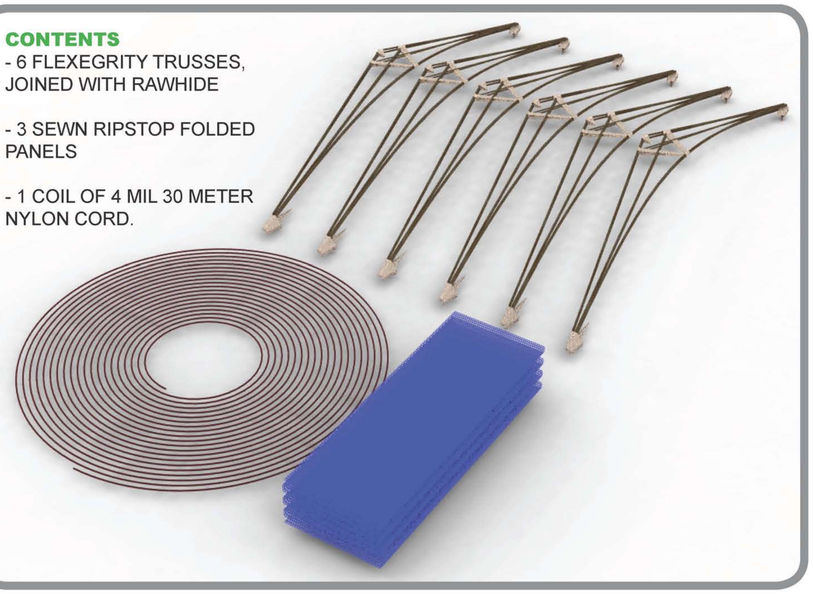


CONTENTS

- 6 FLEXEGRITY TRUSSES, JOINED WITH RAWHIDE

- 3 SEWN RIPSTOP FOLDED PANELS

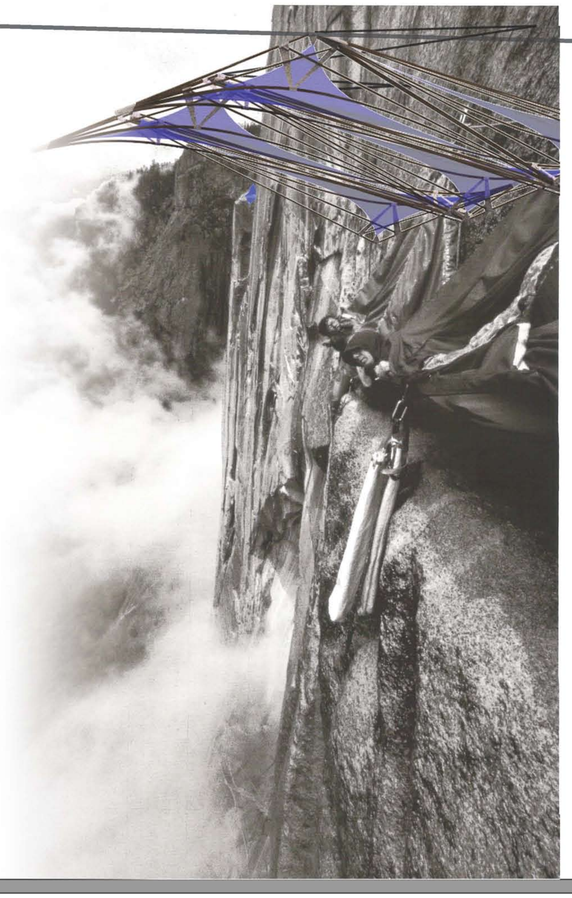
- 1 COIL OF 4 MIL 30 METER NYLON CORD.



JUSTIFICATION

- Elements are low imapct and low visibility. Material is easily erecteted and can be qiuckly replaced and maintained on a low budget. Material is biodegradeable and can be left in place or dicsarded in the natural enviornment.

- Spaces of retreat and refuge are in high demand during rainy and cold season. Frequently people seek refuge at these areas durring times of distress.



POTENTIAL APPLICATION: EL CAPITAN EMERGENCY STATIONS

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MODE_BUNDLING

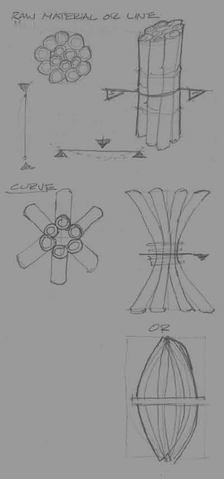
DEFINITION:

A group of things fastened together for convienent handling.

A small band of mostly parallel fibers (as nerve or muscle)

METHOD:

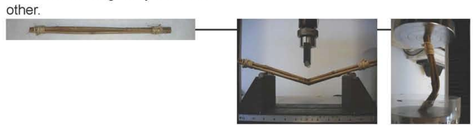
1. **Collect linear elements to achieve desired cross section.**
2. **Arrange to desired length, form, or pattern.**
3. **Bind elements together either by using glue, lashing, or sleeving.**



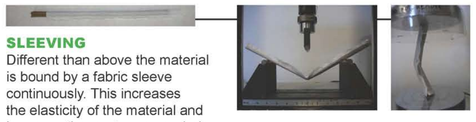
CONNECTION_BUNDLING

CONNECTIONS
Bundling is an important method for building with bamboo; however, it is equally important to examine how to bundle. I have composed 5 types of methods.

NO CONNECTION
By not joining or lashing the material there is simple failure in the system. In Bending the tubular forms simply snap and in an axial condition the culms buckle and splay in multiple directions moving away from each other.



WOVEN STRANDS
As before the material has a loss of elasticity in bending; yet the deflection is better directed in axial compression.

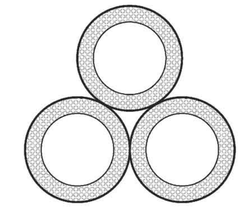


SLEEVING
Different than above the material is bound by a fabric sleeve continuously. This increases the elasticity of the material and improves the system as a whole. Sleeving is the most appropriate way to bundle.

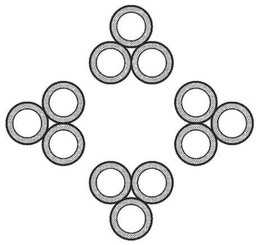
PREVIOUS PROBES
Investigations in play, now under scrutiny based from cataloged knowledge.

SCALE_BUNDLING

MATERIAL SECTION

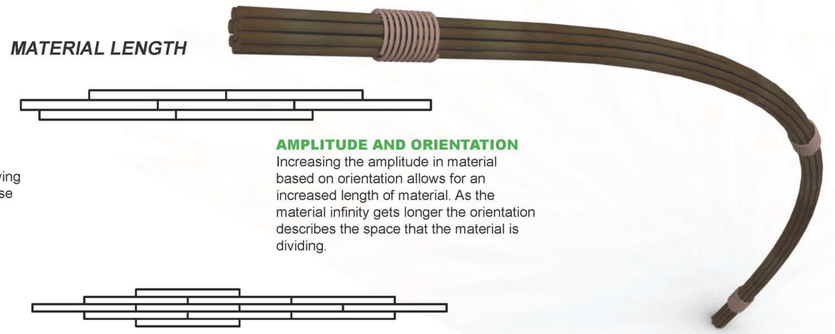


AMPLITUDE AND PROPORTION
Increasing the material section is both a function of amplitude or section of the material. Based on the geometry created and varying sections of material, a sense of proportion becomes evident.



FREQUENCY AND BOUNDARY
Using multiple bundles in a system begins to dictate the frequency and the orientation of the material. Frequency allows for spatial development and reduction of material while still responding to to the scale of force. Boundary sets the parameters for where forces should be concentrated.

MATERIAL LENGTH



AMPLITUDE AND ORIENTATION
Increasing the amplitude in material based on orientation allows for an increased length of material. As the material infinity gets longer the orientation describes the space that the material is dividing.

FREQUENCY AND BALANCE
Changing the frequency where bundling occurs, helps to balance how the force is traveling through the system. Choosing where to increase material section is relevant in the sense of achieving a successful length.

***NOTE**
Scale may also be compensated by use and application of composite materials.

Bundling is an act of containing a volume.

MODE_SPLITING

DEFINITION:

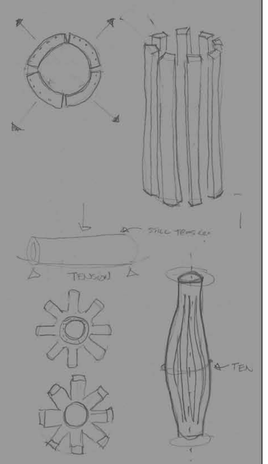
A fracture in a system of linear elements

In mathematics, referring to the creation of a partition.

The bifurcation of 2 lines through space

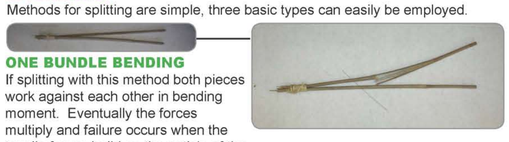
METHOD:

1. **Define a system, usually bundled, of elements running in parallel or a woven manner.**
2. **Systematically choose and break the bonds that confine the system.**
3. **Apply force to separate and splay the system.**

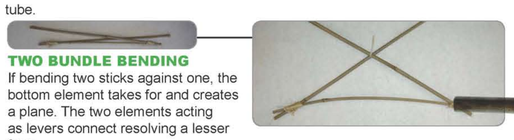


ACTION _SPLITTING

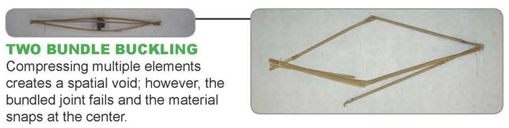
OPERATIONS
Methods for splitting are simple, three basic types can easily be employed.



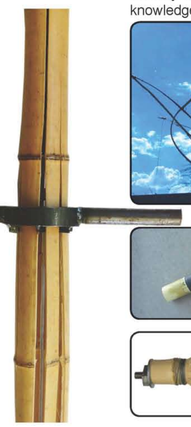
ONE BUNDLE BENDING
If splitting with this method both pieces work against each other in bending moment. Eventually the forces multiply and failure occurs when the tensile forces build on the cuticle of the tube.



TWO BUNDLE BENDING
If bending two sticks against one, the bottom element takes for and creates a plane. The two elements acting as levers connect resolving a lesser force.



TWO BUNDLE BUCKLING
Compressing multiple elements creates a spatial void; however, the bundled joint fails and the material snaps at the center.

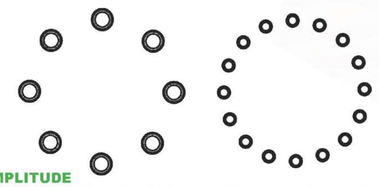


PREVIOUS PROBES
Investigations in play, now under scrutiny based from cataloged knowledge.

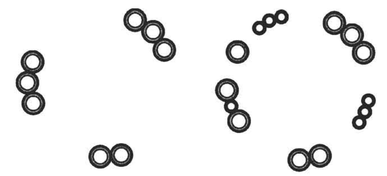
Splitting is an act of releasing a volume.

SCALE_SPLITTING

MATERIAL SECTION

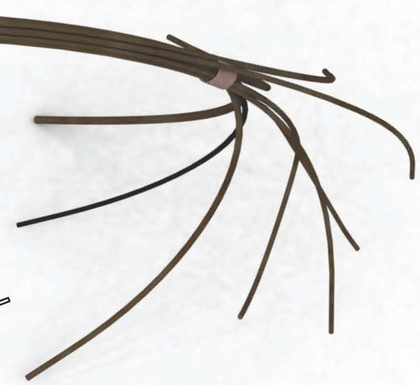


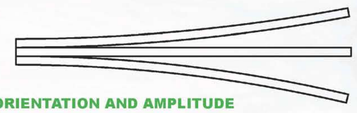
AMPLITUDE
Amplitude in splitting refers to the size of the section that one is splitting. This allows for use of smaller material in conjunction with larger sections. Splitting by amplitude can be viewed as a fractal function.



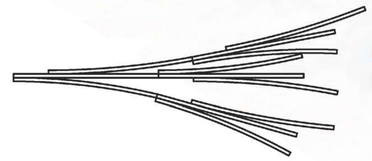
FREQUENCY AND PROPORTION
The frequency in size where the material or system is split allows for more economy in material, and begins to lend towards a proportion of cross section.

MATERIAL LENGTH





ORIENTATION AND AMPLITUDE
The size of the system being split dictated by direction creates a symmetrical system.



ORIENTATION AND FREQUENCY
Changing the frequency of how a system splits and splays into itself can increase the size of the system and propagate with or without boundary.

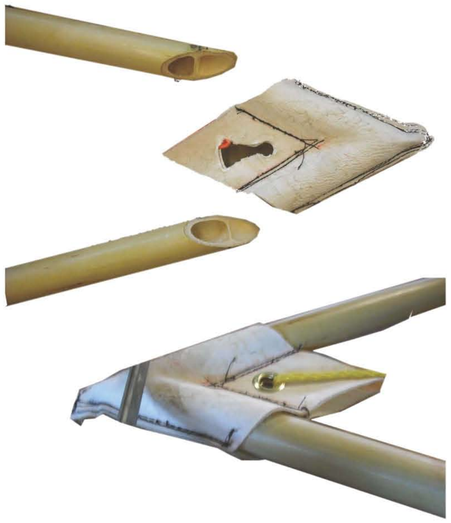
OBSERVATIONS
- Assembly is tedious and time consuming. Geometries are strictly guided by material dimmension
- Increases modulus of elasticity
- Connections work well in conjunction with bundling
- Material failure is extremely high.

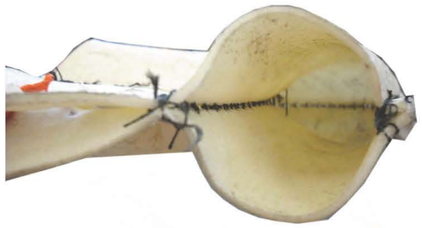
FLEXEGRITY_CONNECTION

Bundling decreases flexure

BUNDLED ELEMENTS:

As the material terminates into a bundling sleeve, the system at that point becomes more rigid. The system described above demonstrates increased strength at points of loading.

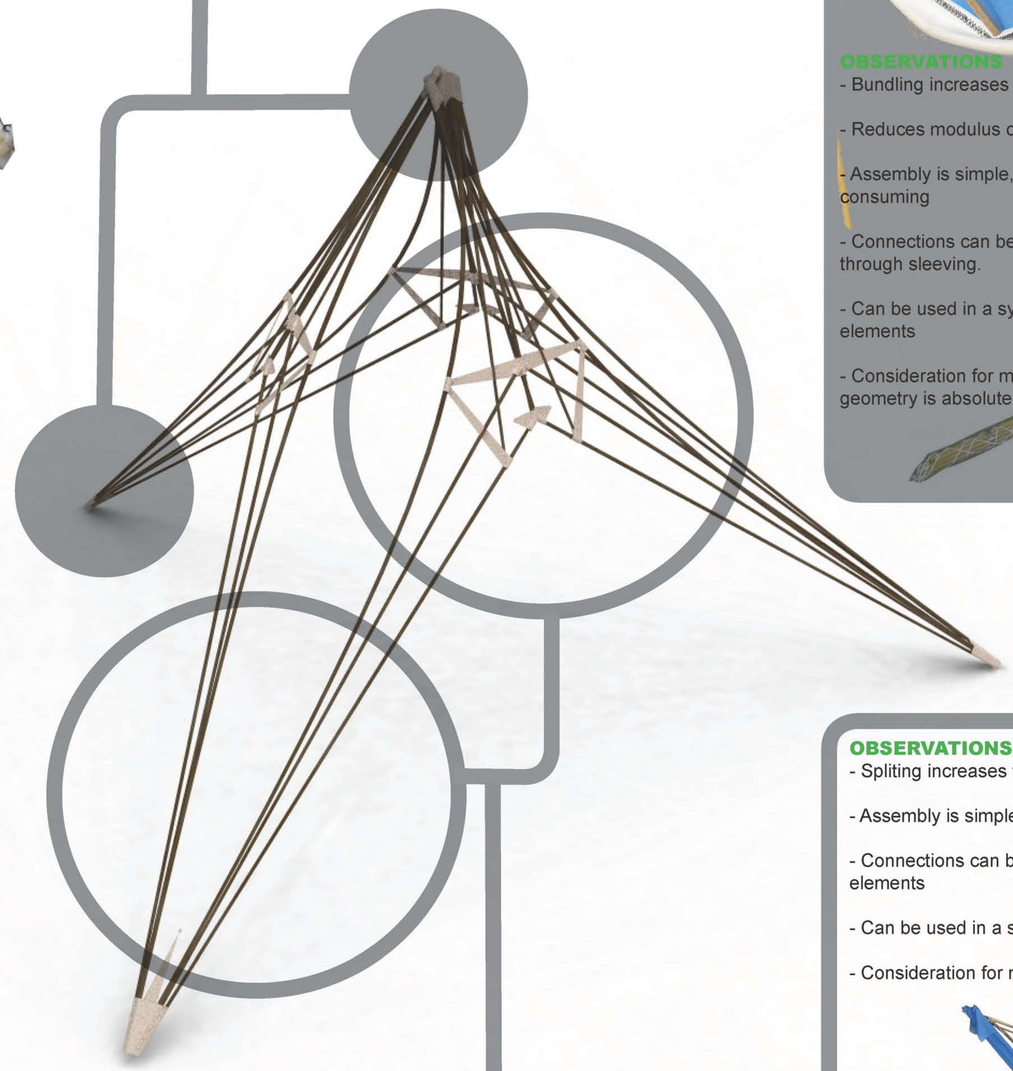


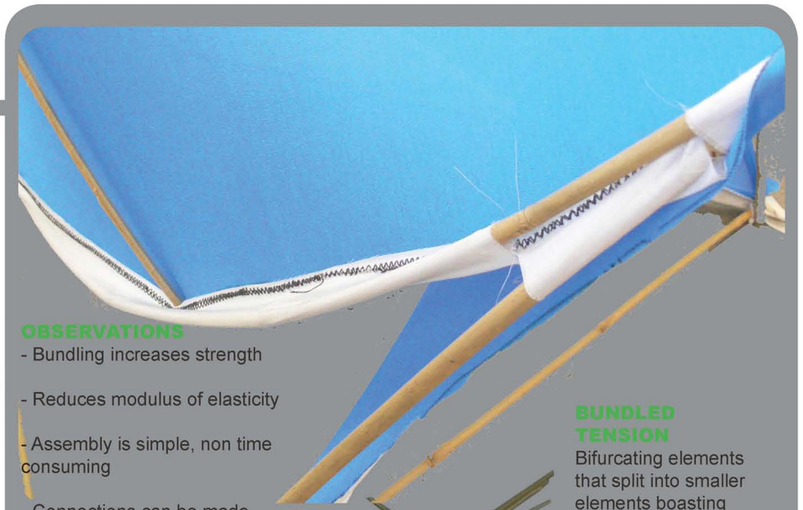


RAWHIDE JOINTS:

Soaked rawhide allows for formed joints that eaqually distribute loads about the cuticle of the material.

GNOMONS





OBSERVATIONS

- Bundling increases strength
- Reduces modulus of elasticity
- Assembly is simple, non time consuming
- Connections can be made through sleeving.
- Can be used in a system of elements
- Consideration for material geometry is absolute.

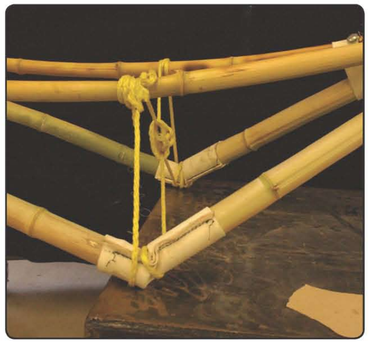
BUNDLED TENSION

Bifurcating elements that split into smaller elements boasting the catenary forms of bamboo.

FLEXEGRITY_CONNECTION

SPLIT ELEMENTS:

In areas where loading is not prevalent, flexure is naturally allowed. This is similar to the composite structure of the material. In a sense one could call the internode a split system.



SPLIT JOINERY:

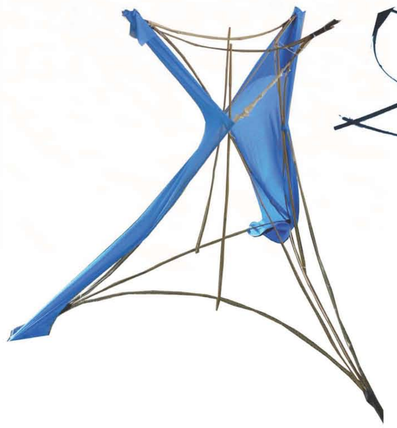
Joinery where bending is to be applied requires a simple sleeve that allows movement about an axis.

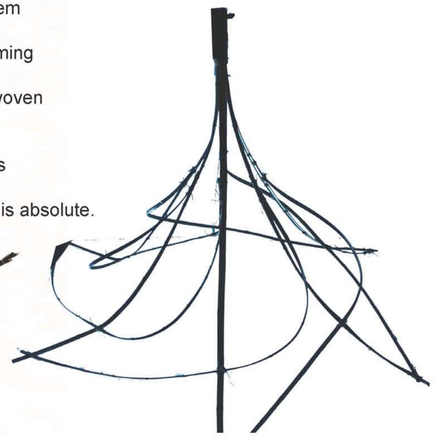
Splitting increases flexure

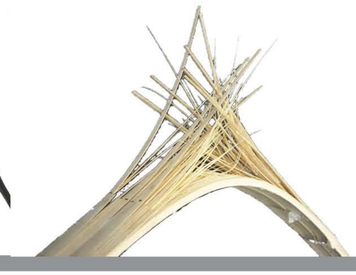
GNOMONS

OBSERVATIONS

- Spliting increases flexibility in a system
- Assembly is simple, non time consuming
- Connections can be made through woven elements
- Can be used in a system of elements
- Consideration for material geometry is absolute.







Structural Flexegrity: Building with Bamboo
Anton Toth Final Capstone Presentation
University of Arizona College of Architecture Landscape Architecture.
May 6th, 2009

Capstone Chairs:
Álvaro Malo
Chris Trumble
Committee Members:
Beth Wienstien
Matt Gindlesparger

MODE_WEAVING

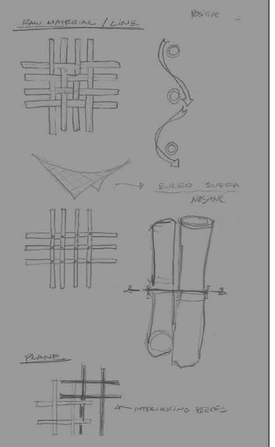
DEFINITION:

A system that produces strength by interlocking weaker elements.

The process of creating a lattice of interlocking fibers to define a volume.

METHOD:

1. **Collect linear elements at desired length to begin constructing a system.**
2. **Layout elements in parallel at desired spacing.**
3. **Stitch in other elements in an angular direction, forming structural system.**



MODE_TENSION

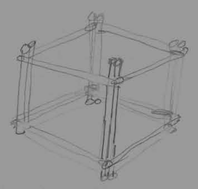
DEFINITION:

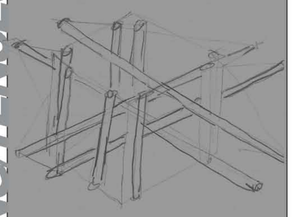
A term describing tensional integrity. Derived from weaving.

A system of elements finding synergy or balance between tension and compression members.

METHOD:

1. **Using members that are suitable for axial loading conditions, choose a number of planes.**
2. **Attach a system of tensile members at opposing ends of compressive pieces.**
3. **Interlock these elements, directing force into the compressive member.**



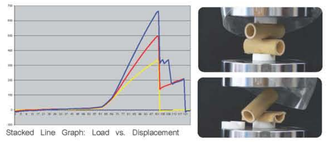


WEAVINGTENSEGRITYWEAVINGTENSEGRITYWEAVINGTENSEGRITY

ASSEMBLY _WEAVING

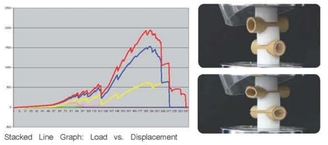
POINT TO POINT

The point to point loading condition: Considering the compressive strength of bamboo parallel to the vascular bundles in the culm it is obvious that its performance would be more than adequate. However, if the material is connected in a lattice condition for construction of a gridshell, the periphery of the stock is compromised and functions poorly. This first test simulates two culms point loading each other.



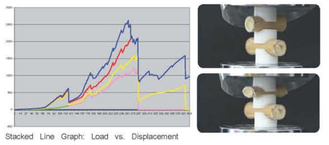
NESTED JOINT

To further the previous test, the condition of bamboo bearing on itself, had to be completely removed. By creating a joint that addresses the shape of the material a larger load and higher displacement was yielded.



NESTED JOINT WITH FOAM

To further increase the potential for loading and manipulating these joints, foam was introduced as a method for allowing even greater displacement in the system.

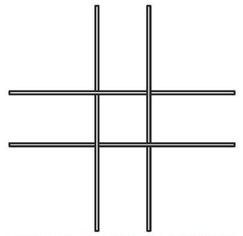


PREVIOUS PROBES

Investigations in play, now under scrutiny based from cataloged knowledge.

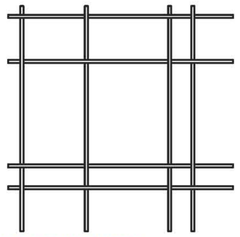
Weaving defines planes through frequency and scale.

SCALE_WEAVING



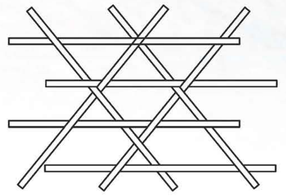
AMPLITUDE AND BOUNDARY

A simple system allows a clear boundary of form, usually resulting in a grid shell. the amplitude is defined by the size of the rods and there spacing there after. The boundary presents itself by the limitation of the material.



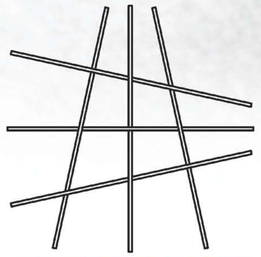
FREQUENCY AND PROPORTION

The spacing and size of the rods can be spaced to increase strength in certain areas where needed. When assembled a proportion of force, is defined.



ORIENTATION AND FREQUENCY

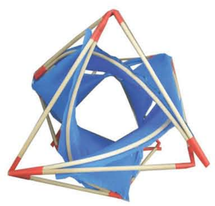
Increasing the frequency with orientation increases strength through patterning.



ORIENTATION AND BALANCE

Ordering the direction of the material allows for a balance of form. Changing the direction and angles in which they weave produces warped planes.

MODE _TENSION

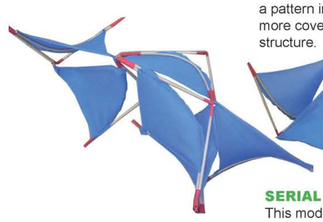


TWO SYSTEMS VERTICAL

Stacking tensegrity elements allows for vertical growth while allowing the elastic qualities of the material to remain.

TWO SYSTEM PROPAGATION

Arraying a these systems through a pattern in the x,y axis allows for more cover of space and a more rigid structure.



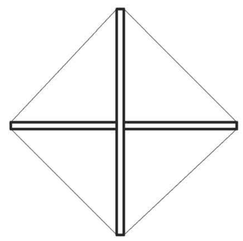
SERIAL DEVELOPMENT

This mode begins to respond to outside forces through repetition of system.

PREVIOUS PROBES

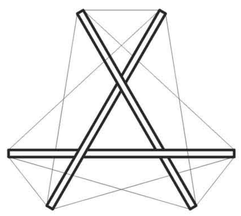
Investigations in play, now under scrutiny based from cataloged knowledge.

SCALE_TENSION



AMPLITUDE AND ORIENTATION

Kenneth Snellson believes that a kite frame is the most basic element of tensegrity. In this case orientation and amplitude are key ingredients to a more rigid form.

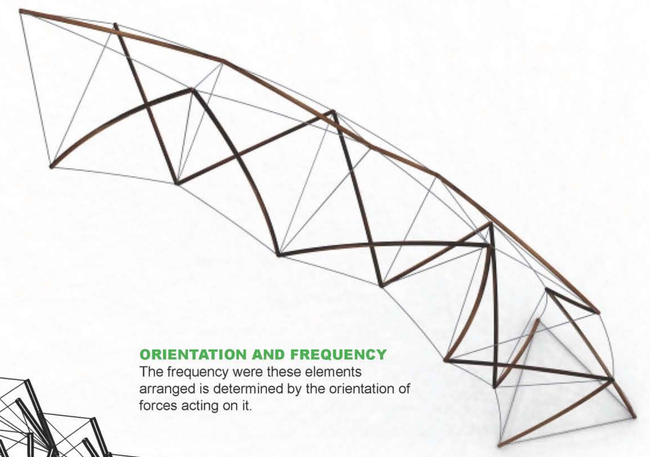


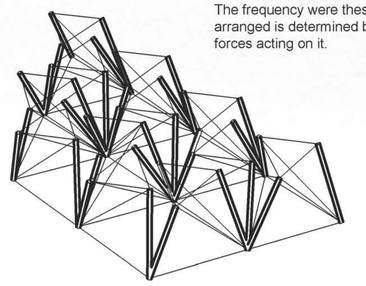
FREQUENCY AND BALANCE

The frequency in which you arrange the members depends on balancing the forces of the system.

AMPLITUDE AND BOUNDARY

How elements begin to grow in size helps define boundary. By changing the amplitude in height of the system other systems must be employed to ensure growth.





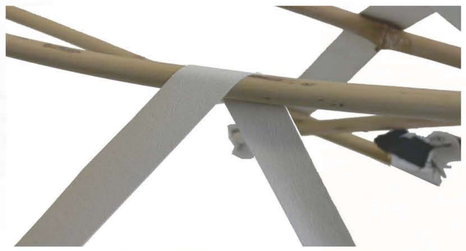
ORIENTATION AND FREQUENCY

The frequency were these elements arranged is determined by the orientation of forces acting on it.

Tensegrity uses frequency and scale to define space.

FLEXEGRITY_CONNECTION

Weaving decreases integrity

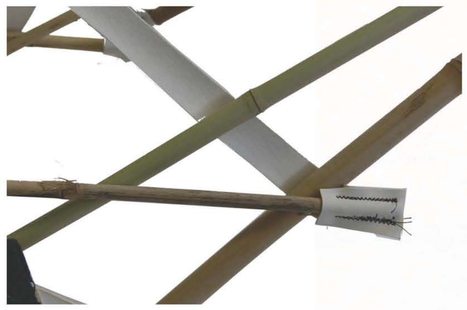


WOVEN ELEMENTS:

Integrity is decreased in this area through a woven connection. Weaving lends itself to split elements, due to its creation of diaphragm like systems.

WOVEN JOINERY:

Where bamboo diverges from the system, the issue of joinery becomes an issue. In order to maintain a flexible system, one needs a flexible joint. Here elements are held into place by a sliding woven rawhide joint.



OBSERVATIONS

-Weaving is a system of warp and weft. Weft being the material that turns a corner and changes direction. most flexibility is found in the weft.

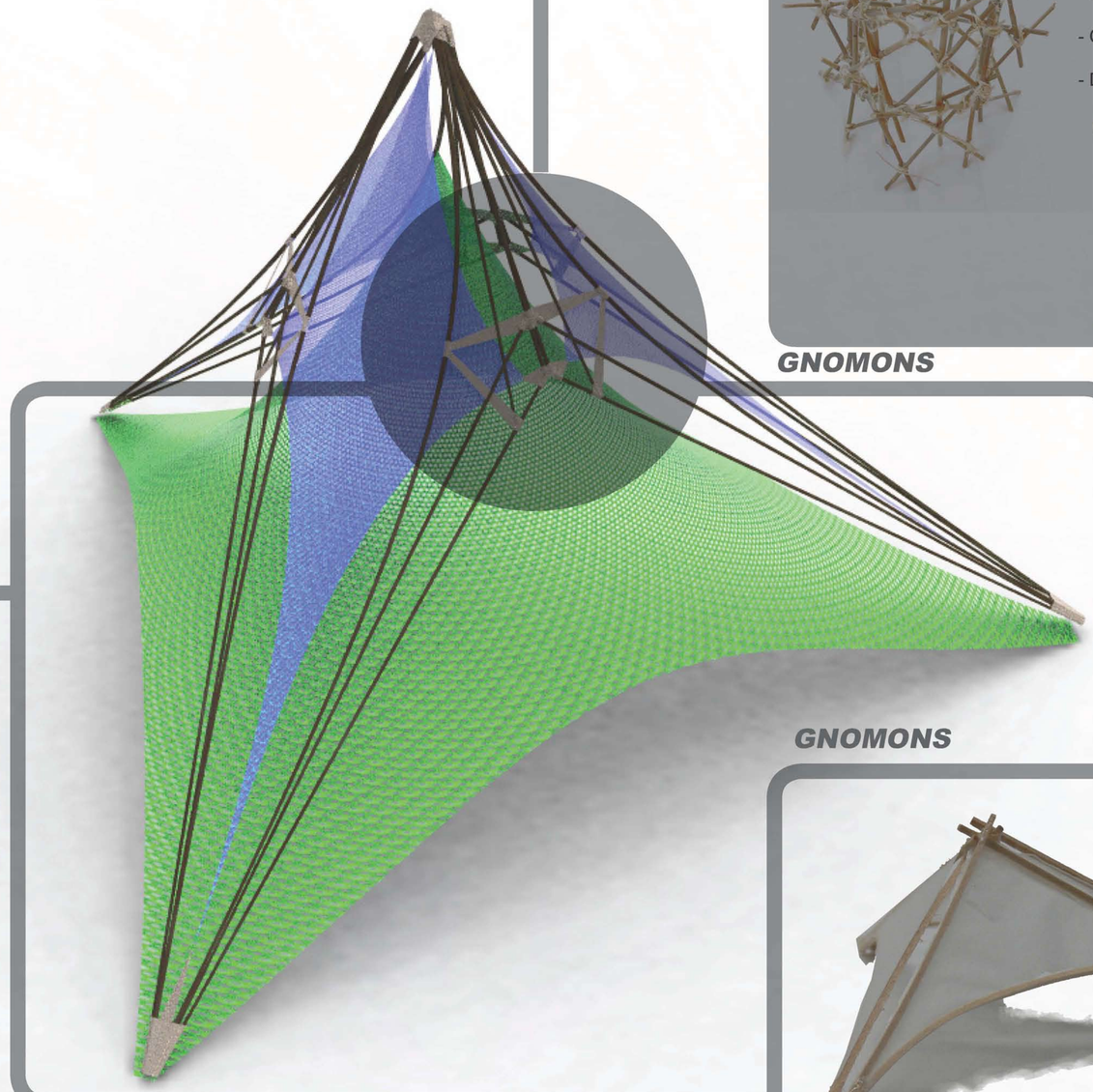
- Assembly is more complex, and hard to tune.

- Connections are woven elements

- Can be used in a system of elements

- Direction of flexibility is important.

GNOMONS

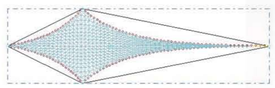


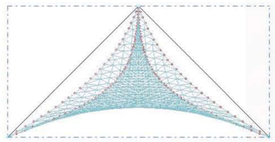
FLEXEGRITY_CONNECTION

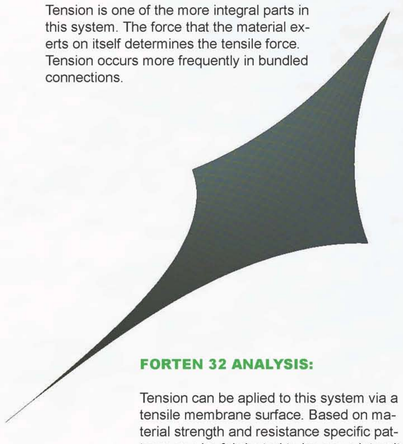
Surface tension increases intergrity

TENSILE ELEMENTS:

Tension is one of the more integral parts in this system. The force that the material exerts on itself determines the tensile force. Tension occurs more frequently in bundled connections.

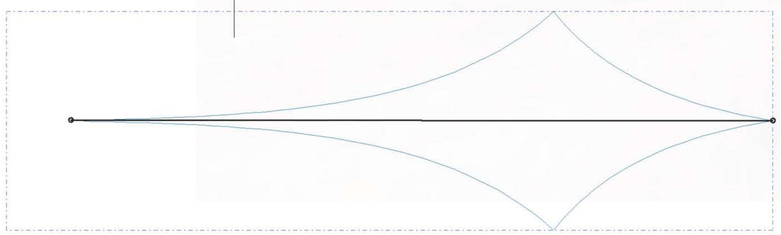






FORTEN 32 ANALYSIS:

Tension can be aplied to this system via a tensile membrane surface. Based on material strength and resistance specific patterns can be fabricated to increase integrity of the system.



GNOMONS

OBSERVATIONS

- Surface tension binds and pulls all the systems together in an integral matter.

- Fabric biases motion while allowing it.

- Material acts as a flexible shear plane.

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