4.1- Frame

4.1.1 Introduction/ Needs:

The frame team was tasked with coming up with the shelter's skeleton that is simple in design, easy to assemble and disassemble, lightweight, and portable. Refugees need to travel or escape danger at a moment's notice, so a simple, robust and collapsible structure is essential. Keeping in mind that the average refugee family unit is a mother and her two children, our frame is spacious enough to allow for sitting and sleeping. Because of the short-term use of the shelter, we narrowed our materials to being completely biodegradable so as to reduce the environmental impact when the shelter is discarded. The following chapters and sections document our journey of coming up with the final design of RiFSK 2020.

4.1.2 Organization

Upon receiving the design project, we began by considering the significant constraints that could limit our tent designs: typical refugee family unit, the maximum weight of the tent, the average height of a refugee, the maximum number of bamboo spars involved in construction, and available materials. Communication with other teams- Kit, Situation and Needs, and Skin- was essential in retrieving this data. Furthermore, the model RiFSK reports from 2017 and 2018 helped us in establishing a core understanding of RiFSK and getting standard values for maximum weight and surface area of the tent. Once we were aware of the properties of an ideal frame design, each member decided to work independently and implement their ideas into mini-prototypes using straws, kebab sticks, and bamboo spars. Because of the covid crisis and inability to meet in person, we collaborated by exchanging drawings and videos as small demonstrations of our prototypes. For each of our design iterations, we emphasized simplicity in joints and construction, minimum use of bamboo, ease of assembly, maximum volume to materials ratio, the ability to be carried in a kit, and low cost.

4.1.3 Design principles

4.1.3.1 Chinese Traditional Bridges

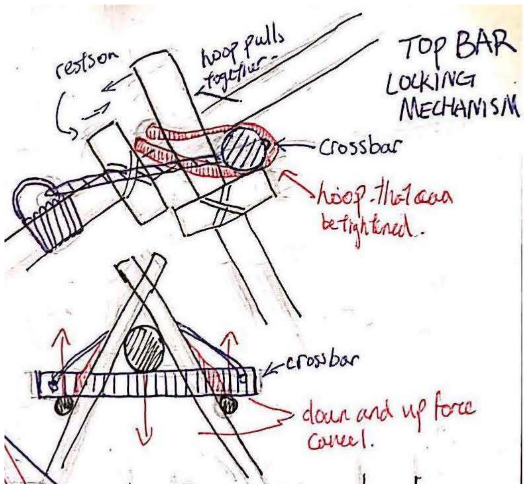


Figure 1: (Drawing made by Ricky)

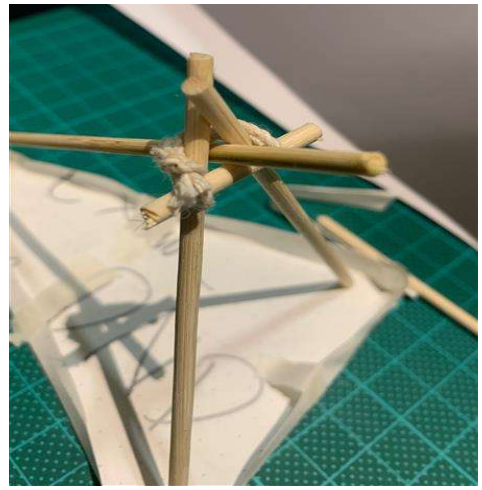
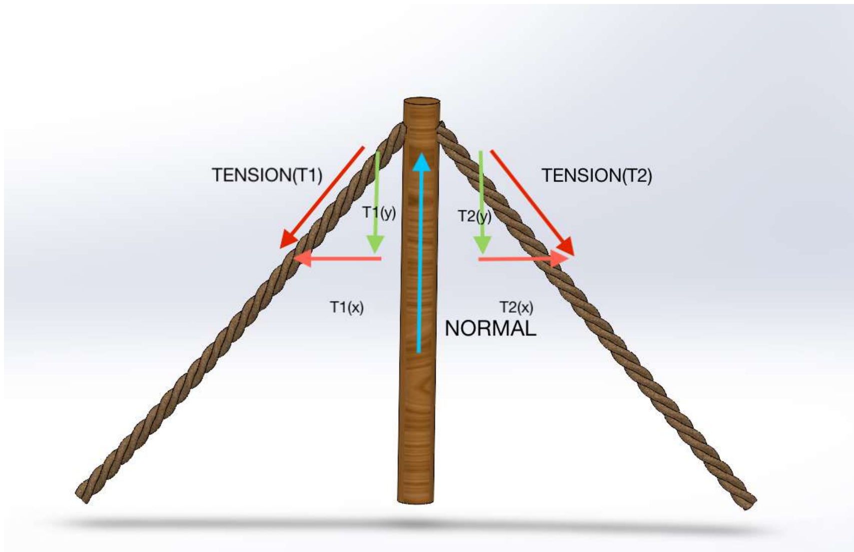


Figure 2: (Model made by Ricky, composed of bamboo sticks)

Traditional Chinese architecture constructs buildings and bridges using interlocking wooden poles to create a stable structure, without the need for any nails or other forms of binding (though they were sometimes used to improve stability). An idea for conjoining 3 perpendicular rods in a tripod structure stemmed from this concept. The locking mechanism comprises a crossbar resting on two fixed stops on the sidebars. The top bar would push down on the crossbar while the stops would provide a reactionary force, resulting in a stable system. This design was further improved by using a hoop to keep the crossbar in place (Figure 1). This hoop can keep the tripod shape intact all on its own using friction (pictured in figure 2), but didn't stop the rods from sliding along its length, thus necessitating the continued presence of stops. The locking mechanism was implemented in the Adidas tent featured below, and the other lean-to or triangle base prism-shaped tent designs.

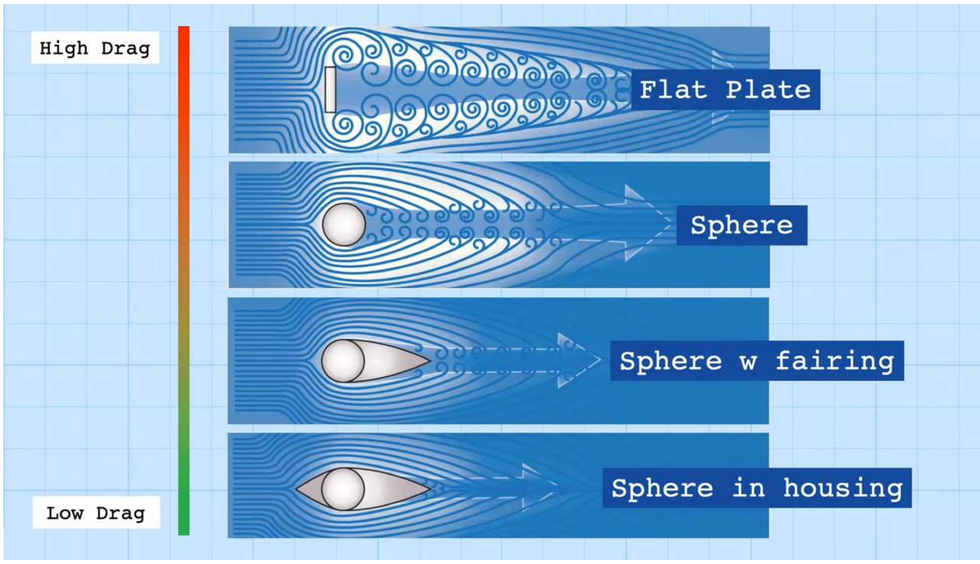
4.1.3.2 Tensegrity



(Solidworks design made by Ricky)

Tensegrity is a structural principle involving isolated components held under compression and tension. The forces, under which the system holds, push, and pull its application simultaneously, making the system rigid. These forces are provided through strings connecting the isolated components of the structure. As seen in the picture, the bamboo in the middle is connected with two strings that pull it in opposing directions. Given that the tension force in the string is equal (T1=T2), the entire system becomes rigid enough to prevent back-and-forth motion. Moreover, since the force of the string is applied at an angle, the component of the force along the bamboo spar increases the downward weight (force) of the bamboo. So in reality, the weight of the bamboo becomes the sum of the weight of the bamboo, the vertical downwards force of the first string [(T1) * (cos of the angle between the string and the bamboo)], and the vertical downwards force of the second string [(T2) * (cos of the angle between the string and the bamboo)]. Because of its ability to cut down the weight requirement of the tent, everyone agreed to use the principle of tensegrity in our design.

4.1.3.3 Aerodynamic structures



(Source: CFD simulation by hackaday)

While figuring out possible geometries of the tent, we came to realize that every shape cannot hold its ground in high-speed winds in Sub-Saharan Africa. In fact, most of the previous designs failed because of their inability to resist wind turbulence. Our team decided to research the fundamentals of making an object/body aerodynamic. Upon our study, we discovered that the drag force caused by the wind depends upon its angle of attack, surface friction, and the cross-sectional area exposed to the wind. A flat surface will be more prone to wind obstruction since it collides with the wind normally. Meaning that the angle of attack is 90 degrees and the surface experiences the full force of the wind. Curved surfaces provide less obstruction to the wind because of their non-uniformity in the wind's angle of attack. Round surfaces are not at 90 degrees collision with the wind because of their curvature. This forces the wind's force to be split up into horizontal and vertical components which depend on the cos of the angle between the wind and the horizontal. Consequently, less force is applied in the horizontal direction. The length of the arrows in the CFD analysis relates to the slice in the wind caused by obstruction. The smaller the arrow, the better it is because it means that the wind is not deviating that much. The contour lines are basically the pathways that wind takes after striking the surface.

4.1.4 Joints:

4.1.4.1 Collar Joint

Figure 1: (Collar joint assembled by Khushant)

Figure 2- (Socket made of PVC pipe by Prof. Cumberbatch)

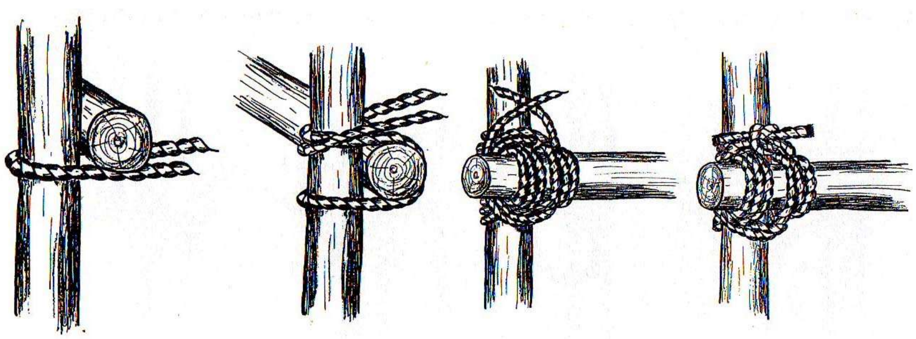
Collar joints, conjoining two overlapping bamboo spars, are the joint structure used in our final prototype. They are simple in design, small, lightweight, and biodegradable. The intersecting rods can easily rest on each other and are stuck together using a socket. For our designs, we used sockets that are made out of bamboo (Figure 1) The overlap between bamboo for each of our designs is 3.81 cm. Moreover, the insertion of bamboo spars into the socket would cause the spars to push against the walls of the collar joints, thereby creating more friction. This, in turn, creates a de facto locking mechanism that keeps two conjoined rods secure. Furthermore, because the collar joints are decently wide in diameter, we can conjoin rods of various diameters, so there is not much of a need to look for bamboo whose diameter fits into the socket with a great degree of accuracy.

4.1.4.2 Pockets inside the skin

(Skin pockets made by Khushant)

While building our prototypes, we kept running into the issue of having the frame and skin different. This not only decreased the ease of assembly/disassembly but also made the structure more complex to manufacture. Therefore, we decided to introduce our bamboo spars inside pockets sewed throughout the skin, integrating the skin and the frame. In doing so, we used the principle of tensegrity by treating the skin as a source of tension. Since the bamboo spars under compression when put into joints, they try to resume back to their linear shape and hence push back. However, when integrated with the skin, the skin pushes inside preventing the bamboo from resuming its original shape. This system of opposite forces allows the entire structure to be rigid. Furthermore, the use of tensegrity in such a fashion also prevents the use of stakes and strings, which is one of a drawback of introducing tension through stakes and strings.

4.1.4.3 Japanese square lashing



(Source: Japanese Mark II Square Lashing | SCOUT PIONEERING)

Japanese Square Lashing is a joint design that conjoins two bamboo rods that are perpendicular to each other. We came up with this particular joint design as an alternative to drilling holes and using pins so two bamboo spars can pivot about each other on an axel. The downside of this particular joint design is that it will need a visual aid to understand how to tie. Additionally, Japanese Square Lashing at multiple joints can be tedious if the person making them is unfamiliar with how to tie them, which we presume are most refugees. As for the material that can be used in this joint, we explored linen and jute string.

4.1.5 Materials

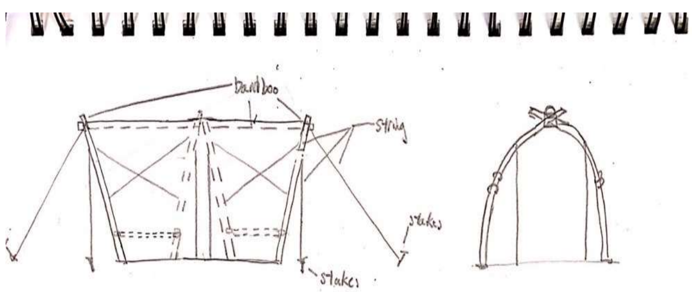
(Our actual materials that we used: Figure 1 and 2- bamboo spars, Figure 3- Linen.)

After researching the plausible geometries and joint designs, we transitioned to the prototyping phase and started finding suitable materials. We wanted to pick materials that would help us construct a frame with our desired properties and. As a class, we decided on using bamboo as the main skeleton of the frame. Along with its extreme flexibility and water-resistant nature, bamboo can be easily found in Sub-Saharan Africa- over 3 million hectares (10,000 square meters). After being cut, bamboo grows back to its regular size in 60 days, which can allow the manufacturers to use a unit of area often. Moreover, the sockets we require for collar joints can be made out from bamboo because it is hollow and has a wide range of diameters. To create the frame, we could use a bamboo splitter to separate the bamboo into spars and connect each spar accordingly. A second material that also plays a big part in the structural integrity of the frame is Linen. Just like bamboo, linen is also biodegradable, lightweight, durable, and available in Sub-Saharan Africa. We used linen strings to tie the Japanese square lashing joint and bending the bamboo, which will be talked about in later sections.

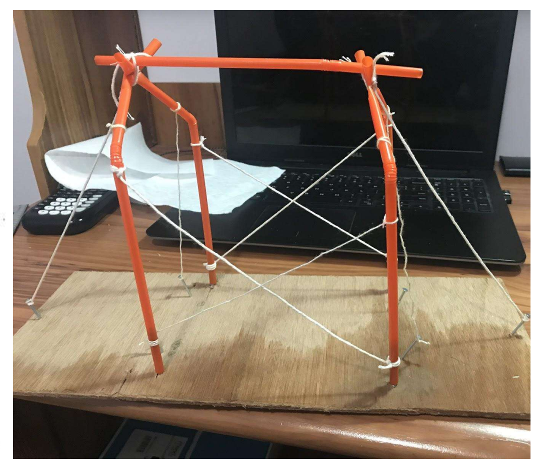
Chapter 5- Designs

5.1 Models

5.1.1 Tensegrity structures



(Ricky's tensegrity drawings)

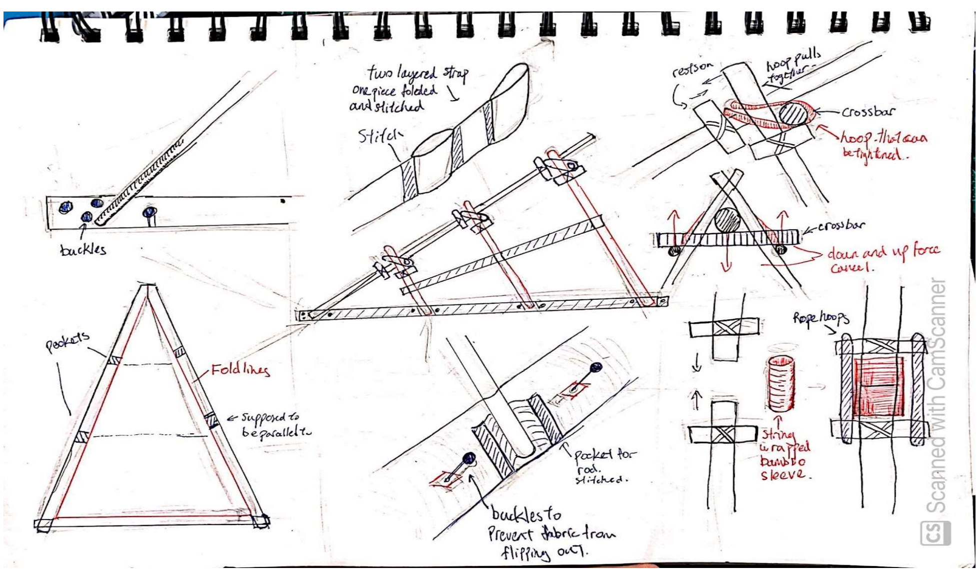


(Khushant's straw tensegrity model)

For our first model, we created a tensegrity structure that relied on the pushing and pulling of ropes connected to poles to keep the system upright. We envisioned the tent to be in a triangular shape with a rod connecting the extremes of the tent, as shown in the picture. The model we initially created was made up of straws, which represented the bamboo spars we would be using. Those straws were held in place by the pulling of the outer and inner strings, which created compression forces along with the inside and tension forces along the outside of the structure. From modeling this type of structure, we realized the strength of tensegrity and how it could be implemented in future designs. The reliance on tension would allow us to create a structure that would have fewer bamboo spars decreasing the overall weight and improving our volume to material ratio.

At the same time, we found there to be three major disadvantages surrounding this type of design. Despite the structure being small, it still needed more rods to become rigid. The addition of more spars and ropes proved to be a drawback since it made the design more difficult to construct. Ultimately, this would decrease the volume to weight ratio, make the tent less portable, and also increase the cost of the tent. The last drawback of this design is its stakes. Having stakes in the frame design would not be ideal since the ground a refugee passes may not necessarily be hard enough to be staked.

5.1.2 Adidas Design



(Ricky's drawings)

The goal of this design was to create a tent structure composed of straight bamboo rods. This goal was set to reduce strain on the bamboo spars by putting them under tension and compression, and therefore reduce wear and ultimately create a longer-lasting tent. The design took the shape of a triangular based prism made out of a series of interlocking rods or spars of bamboo (designed to accommodate both). The triangular prism shape was ideal as the slanted rods would resist the side-load induced by the wind effectively, producing a reaction force from the floor. This is unlike the bent domed structures which relied on the elasticity of the rods to resist side-load. The tent had 3 rods of varying lengths that comprised the walls of the tent, which were kept in place by pockets in the base skin, and a locking mechanism on the top bar. These long rods were made from smaller spars that would join together using a collar joint. The design also used pockets in the skin of the tent to provide extra tension between the rods and mount the skin to the frame.

Potential alterations to the design were removing 2 sets of sidebars to leave only the longest sidebar and the top bar, which would have reduced the number of spars, reduced the complexity of the assembly, and reduced the weight of the tent. However, this would necessitate more rigid and tauter skin to provide resistance against the wind, since the removal of side rods meant fewer contact points between the skin and the frame.

Ultimately this design was not chosen because it was deemed too complicated, and with the limited time and resources and lack of interaction with other group members as a result of the pandemic, prototyping and building this design became impractical.

5.1.3 Yule log shelter

Figure 1- Yule Log Shelter made by Khushant

Figure 2- Shelter turned upside down showing the stings

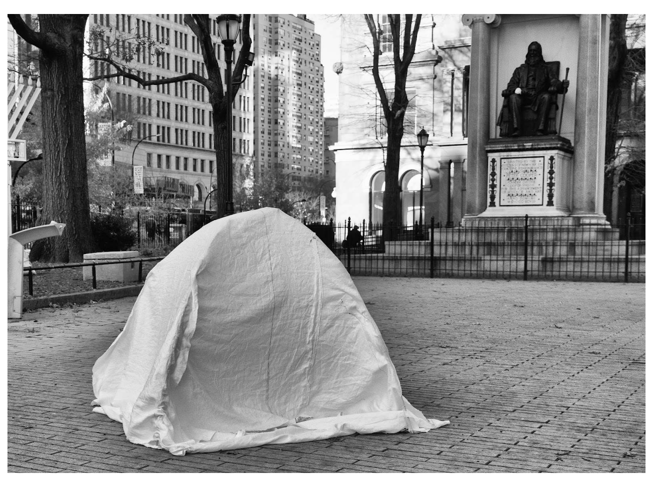
Building tents with linear bamboo spars required complex joint mechanisms. To simplify the frame structure, we leveraged the bamboo’s natural flexibility to create arches, reducing the number of joints, and easing the assembly. This design, deemed the Yule Log, takes inspiration from a bow’s drawstring. The tent forms the shape of a half-cylinder, consisting of three equidistant bamboo arches. The design features collar joints to form the long rods and pockets in the skin to maintain the structure of the frame. Each arch comprises a long bamboo pole made by joining 7 bamboo spars (.46 m each) through collar joints and a linen strap that pulls the ends of the rod together.

We wanted our design to synthesize the frame and skin, which we failed to do in the tensegrity structure. To do so, we sew pockets in the skin and inserted the bamboo rods through those pockets. Using pockets in the skin also allowed us to use skin as a source of tension. After that, we tied each of the rods with a 1.8 m string using a simple shoe-lace knot, while leaving the other eye-splice end to be free. To set up the tent, the refugee can easily hold the end of 1 rod, bend it upwards and insert the eye-splice knot on the other end. After doing this to all the three rods, turn the structure upside down and the frame is ready to use.

The semi-circles in the structure have a diameter of 1.8 m, height of .9 m, and length, along the ground, of 1.2 m. Given that the average height of a man in Sub-Saharan Africa is 1.7 m, the shelter can easily fit over 1 adult and allow the refugees to sit in an upright position. Despite all these traits, the tent has some drawbacks too. Primarily, it uses 21 spars in total and has a high surface area which adds to the weight of the tent and makes it hard to carry. Also, the tent does require tension strings or some support to keep it from falling. The necessity of having stakes and tension strings makes the design only workable in strong ground surfaces, hence limiting its ability.

5.2 Final prototype

(Khushant's frame model)



(At Cooper: Final Product)

After noticing similarities between each design, concepts from every design were implemented in the final prototype. The prototype consisted of two arches formed by two long bent bamboo spars, intersecting perpendicularly to form a half dome. The arches were kept in shape using a bowstring-like attachment that was featured in the yule log shelter design. These spars were threaded through pockets sewn into the skin of the tent, keeping the entire structure in place.

Our final design is simple, easy to assemble and disassemble, and does not require a visual aid for assembly. Our lightweight design is less than 4 kilograms and allows refugees in-flight to disassemble their shelter and carry it over long distances. As for the dimensions, each arch is 7 bamboo spars long, with each bamboo spar being a bit less than half a meter. A total of 6 collar joints conjoin rods on each arch. The height of the frame is right under a meter and can easily accommodate an adult sitting. The diameter of the frame is a bit less than 2 meters and can accommodate a typical adult sleeping.

Our basic dome structure is packable, portable, and easily manufacturable. The downsides of this design include some movement in bamboo spars along the length of the collar joints. Scalability is also limited because as we increase the size of the tent, it becomes structurally weaker in that it cannot withstand wind turbulence effectively. In fact, the lateral force created by strong winds is opposed only by the bamboo arches' elasticity. Additionally, string from one end of an arch to another to maintain its arched formation is prone to slipping off if it is not secured properly.

5.3 Reflection/Final Thoughts

The 2020 RiFSK frame team aimed to create a frame that could withstand the environmental conditions of Sub-Saharan Africa while still being sustainable and easily manufactured locally. Iterations of the design would implement the concepts of tensegrity and take inspiration from a multitude of sources including traditional shelters and architecture, bows, bridges, and more. While we weren't able to prototype and test every design due to constraints imposed by the coronavirus pandemic, a final prototype was settled upon through a process of elimination that satisfied the design criteria and employed the four-step design process.

Further testing on the tent needs to be done before the production of the final product. We would like to perform stress tests on the individual components of the frame: the bamboo spars, the collar joints, and test the structural integrity of the entire assembly. This could be done by placing the completed tent in windy conditions or attempting to collapse the structure to simulate potential stresses the tent may encounter.