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Constructing Tensegrity Structures

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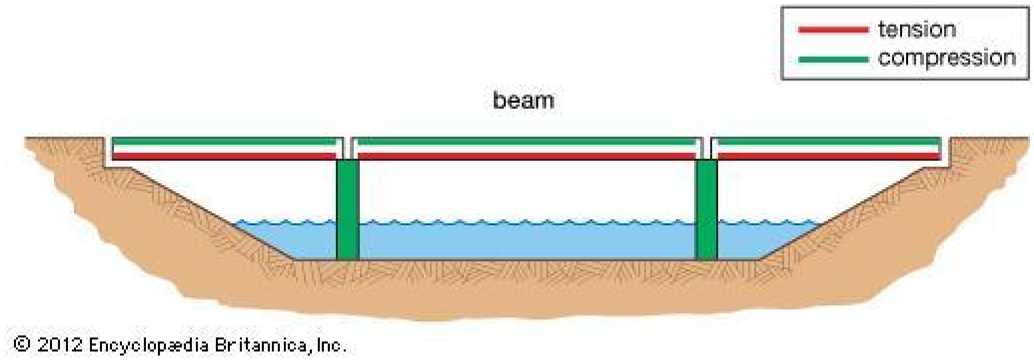
Project Overview

The aim of the project is to design and construct a number of successively complex tensegrity structures using simple building materials and understand their properties. This would culminate in the design of the largest tensegrity structure in India.

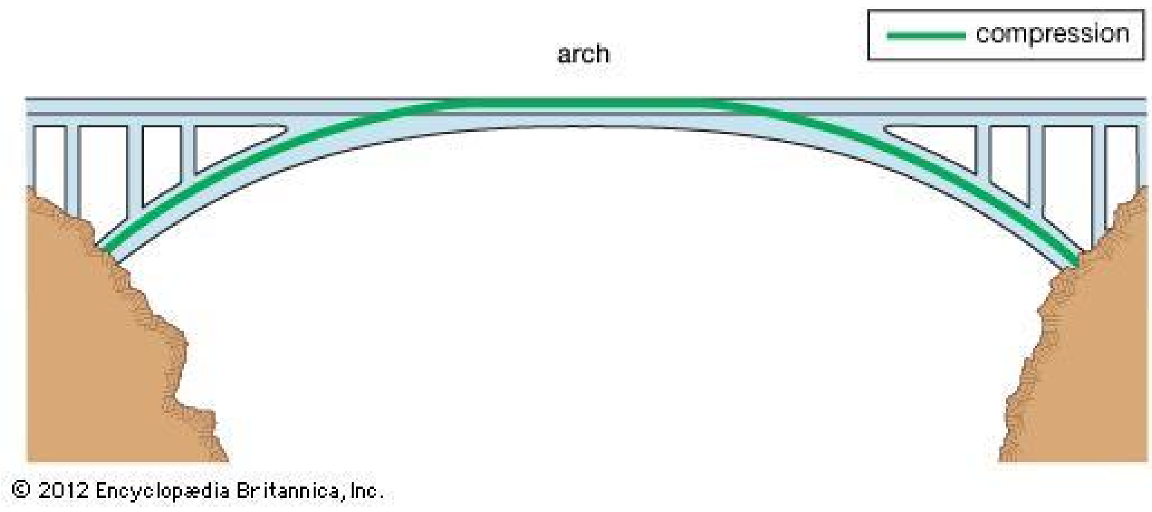
Ⅰ. Overview of tensegrity

Tensegrity or tensional integrity is a property of a structure which allows for objects to be in pure tension and pure compression remaining in stability .This concept was first popularized by Buckminster Fuller in the 1950’s. The difference between tensegrity and conventional structures can be best explained using examples and figures given below.

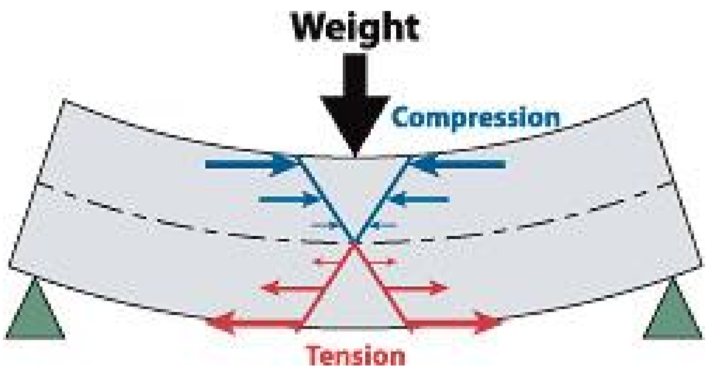
The most common bridge type, a beam bridge is an example of a structure where tension and compression are present together and unevenly distributed.In the picture below the beam carries the vertical load because of this the beam bends causing horizontal compression and tension. This load is in turn carried by the horizontal supports to the foundation of the structure.



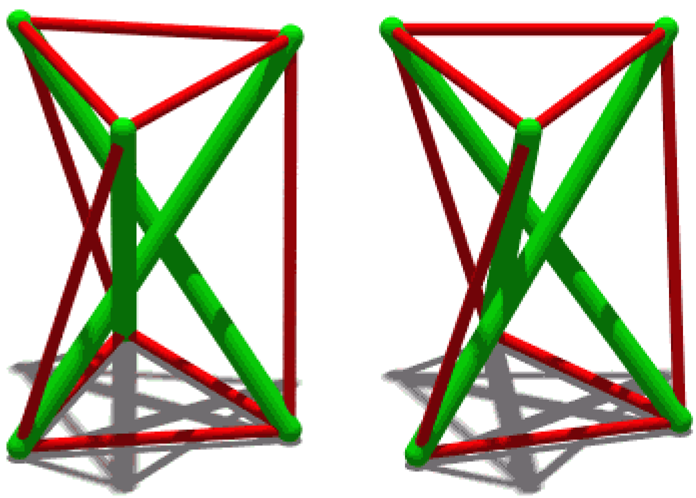
Another example is the arch bridge. This bridge is almost purely comprised of compression elements.



A concrete structure is a non-tensegrity structure, since when a load is applied both tension and compression is experienced asymmetrically through the concrete body.



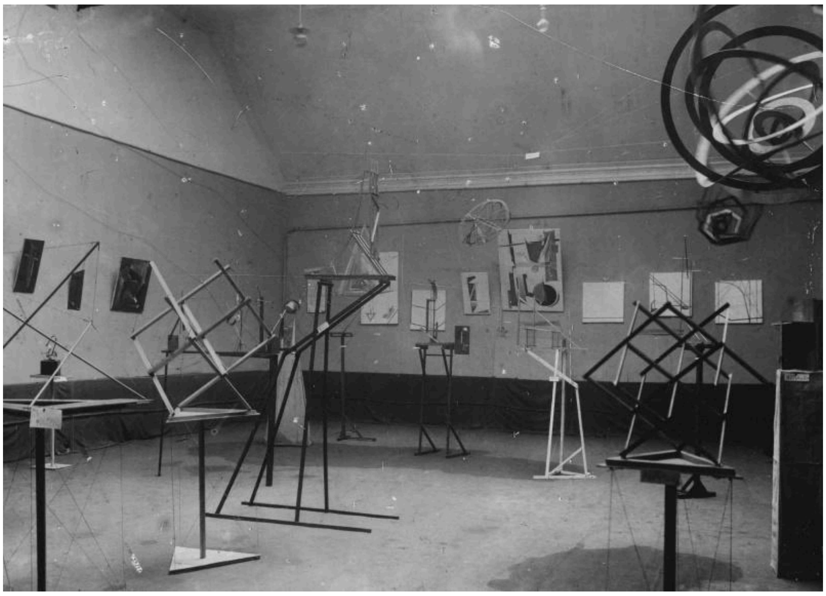
While tensegrity structures contain both compression and tension elements, the tension and compression elements are in their pure form. Some structural elements (known as struts) experience only compressive stress, while other structural elements (knows as cables) experience only tension. Another characteristic feature of tensegrity structures is that the compression members do not touch each other, they provide local support unlike the ones in bridges.



Hence, tensegrity can be defined as "Tensegrity describes a closed structural system composed of a set of three or more elongate compression struts within a network of tension tendons, the combined parts mutually supportive in such a way that the struts do not touch one another, but press outwardly against nodal points in the tension network to form a firm, triangulated, prestressed, tension and compression unit.” Tensegrity structures possess high resilience, high strength to weight ratios and high compressibility. Tensegrity structures are commonly found in the fields of architecture,robotics and are also important in the understanding of cellular biology.

Ⅱ. The History of Tensegrity

The idea behind tensegrity was prevalent much before the term was introduced. The first exploration into “tensional tensegrity” was shown in Karl Ioganson work - ‘Gleichgewichtkonstruktion’ in the early 1920’s.



It took almost two decades for works to express tensegrity in the way it is defined today. This concept was seen more and more often beginning with David Georges Emmerich .He was inspired by Ioganson and did intensive studies of tensile prisms and other more complex tensile systems.With this research he defined and patented ‘Construction de reseaux autotendants’.

Buckminster Fuller and Kenneth Snelson were key to furthering the concepts of tensegrity. In 1927, Fuller proposed the building of a suspension bridge using the arrangement of discontinuous compression and continuous tension. In 1948 he was invited to teach at Black Mountain College as it specialized in experimental arts. During that summer one of his students, Kenneth Snelson realised the peculiar properties of a swinging pendulum structure once its mobility was removed; he realised the outcome led to a free standing structure with elements of pure compression and tension.By the end of 1948 Snelson had revealed his now renowned work the ‘X Module’.Snelson went on to design and build many more.

Tensegrity X Module

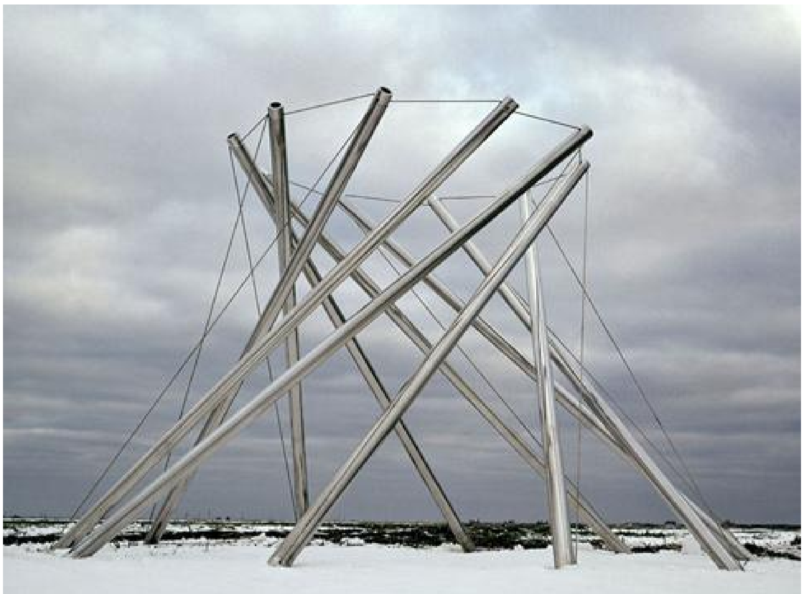
In the beginning of the 1950’s ; in 1951, today’s largest tensile sculpture was built - the Skylon.Throughout the following years Fuller acquired many patents for the work in this field and during this time dubbed this structural feature as tensegrity.Tensegrity structures were first revealed more publicly during these years, including one collection displayed at the Museum of Modern Arts in New York.

Skylon

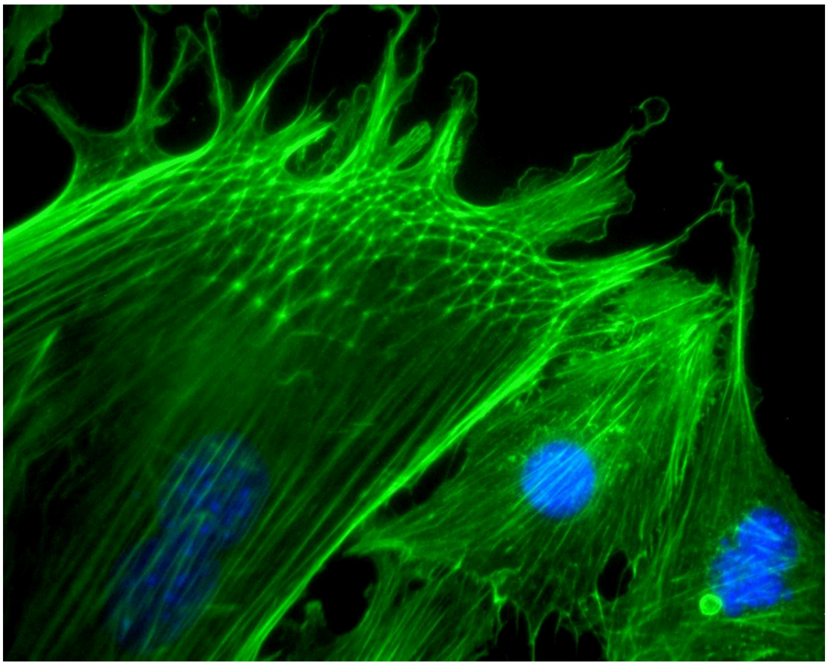
In 1960's structures started to become more varied and complicated :from Fuller's geodesic dome to moon and satellite structures.From then on, more and more people started to see it's utilitarian properties in the real world as well as its stylistic appeal. During these years tensegrity was expanded into the art science interface.With the help of artist John McHale and scientists Aaron Klug and Donald Caspar a Nobel prize winning biological discovery was made.It discussed how virsuses establish shape stability using geodesic architecture.This was done, by examing Fuller's work on tensegrity spheres.

Basket Weave Tensegrity by Fuller

By the 1970's both Fuller and Snelson were popular names with the common people.Fuller's geodesic domes made appearances in military camps and industrial parks and Snelson Aluminium-Cable sculptures popped up in numerous public spaces.Their works influenced many civil engineers to build pavilions domes and space frames.



In the latter part of the 1970's more advances in Biology were made using tensegrity, beginning with Donald Ingber. Ingber realised the similarities in properties between simple tensegrity structures and cultured cells.He thought that maybe cells were tensegrity structures! He created a model which mimicked a cell and its nucleus and observed its movement.He further experimented and confirmed that living cells show the exact same behaviour as tensegrities. Ingber and his team were also able to prove that all cell parts are intraconnected.



In recent years more and more research is being done in this novel field.Tensegrity has found a place nanotechnology,architecture,space exploration and tissue engineering.This makes tensegrity a very interdisciplinary idea and hopefully has scope to become even bigger in the future.

Ⅲ. Building Tensegrity Structures

The goal of the project was build a number of successively more complex tensegrity structures using simple building materials and understand their properties. This would culminate in the design of the largest tensegrity structure in India.

Structure 1

The first tensegrity structure attempted was a simple one containing only 3 compression elements (struts) and nine tension elements (cables). The tensegrity structures isolate compression elements form tension elements. In this structure, the compression elements used are aluminium rods of inner and outer diameter of 1 cm and 1.2 cm respectively. The tension element used is a nylon string consisting of 3 tightly wound nylon fibres. Holes were drilled at a certain distance (varies with the length of the rod and design of the structure) from both the ends of the rod. Four holes were drilled on each end as given in the figure below.

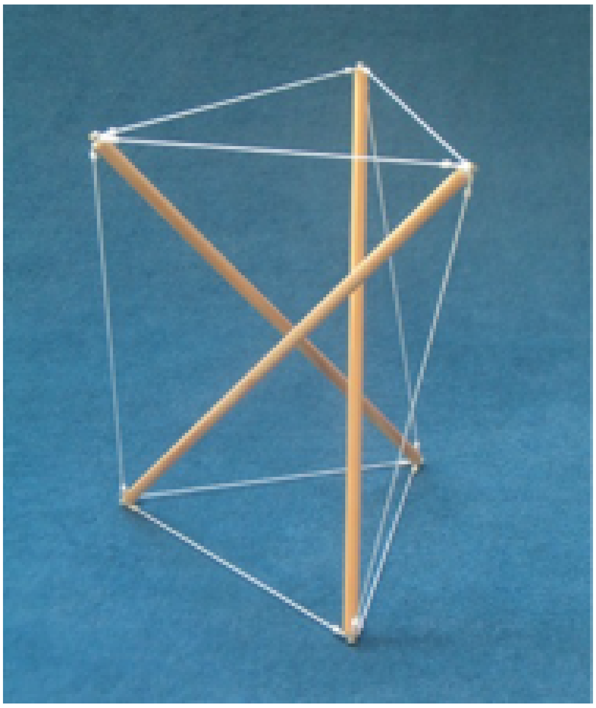


Fig. 1.2 The image on the left resembles structure 1

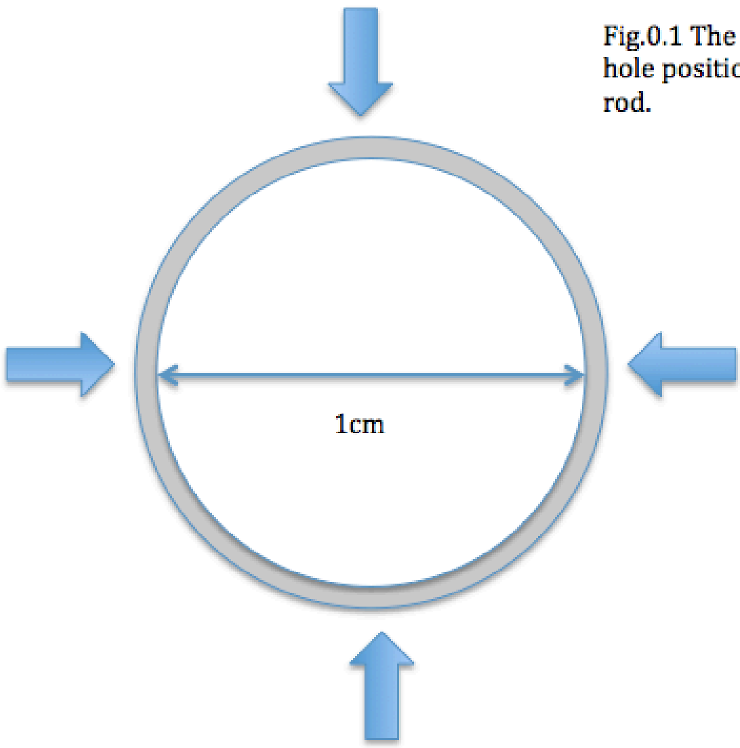


Fig.0.1 The arrows indicate the 4 hole positions on the aluminum rod.

The 4mm holes are drilled at 0°, 90°, 180° and 270° as shown in fig 0.1. This is done to increase the options of places to attach the nylon to the aluminium rod. This positioning of the holes is to also make sure that no string will wind around the rod in the final structure. If this happens, the rod is forced to rotate as shown in fig 0.2. The rotation might cause the structure to be unstable. A measuring tape was used to ensure all aluminium rods where the correct length.It was aslo used ensure holes were drilled at right angles. A lighter was used to cut the nylon string.

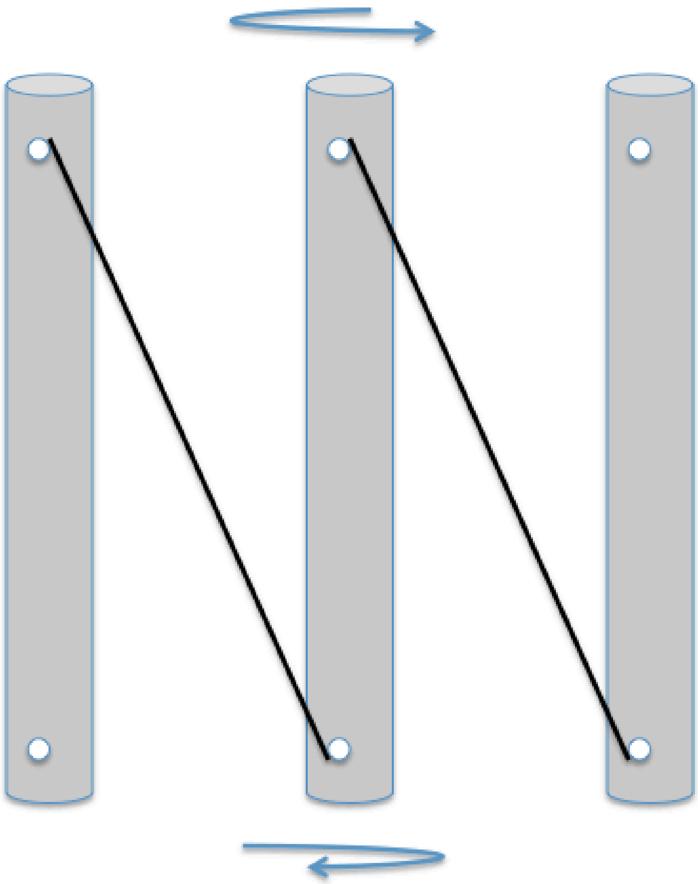


Fig 0.2 Both ends of the rod are forced to rotate in opposite directions, hereby causing an angular strain and harming the integrity of the structure.

Calculations:

By applying the three equations of tensegrity design documented in the book *Geodesic Math, and How to Use It* by Hugh Kenner, appropriate measurements for the strut length, side and end tendons were derived. The equations are as follows:

$$Eq.\ 1.1\ strut(s) = \sqrt{r1^2 + r2^2 + 2r1r2sin(180/n) + h^2}$$

$$Eq.\ 1.2\ side\ tendon(t) = \sqrt{r1^2 + r2^2 - 2r1r2sin(180/n) + h^2}$$

$$Eq\ 1.3\ end\ tendon(e) = dsin(180/n)$$

(where r1 = radius of effective bottom circle, r2 = radius of effective top circle, n = number

of

struts/rods, h = effective height of the structure, d = diameter of particular circle)

The formulas can be used to calculate the radius of the circles on upper (r2) and lower surfaces (r1), which makes up the vertices of the equilateral triangle formed by the base and top of the tensegrity structure.This formula can also be used to understand how tall the tensegrity structure will be (h).

The process was initialized by establishing a constant value for the radii of both the bottom and top of the structure. n = 3 as there a 3 compression elements in this tensegrity.

Taking r1 = 20 cm, r2 = 20 cm and effective strut length = 80 cm

By rearranging Eq. 1.1 and solving for height, h = 70.05126464 cm

From Eq. 1.2, t = 70.81214129 cm

From Eq. 1.3, e = 34.64101615 cm

Procedure:

1. Each rod measured 85cm. Four holes were drilled 2.5 cm from the edge on both sides, making the effective length 80cm. Four holes were required in order to minimize angular strain (caused by forced rotation by nylon strings as explained in Fig 0.2)
2. By drawing an opened re-imagination of the structure (as shown in Fig.1.1) the points of connection for each string and rod were established. The open structure is given below. Fig.1.2 is an example of a closed structure.

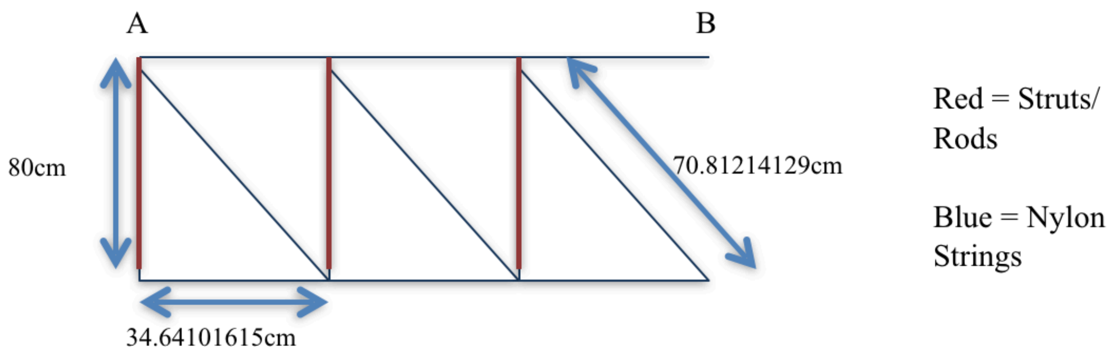


Fig. 1.1

3. Using a buffer length of 10cm on both ends of each string, constrictor knots were tied at the appropriate holes following the open structure given above. Constrictor knots were chosen as they are one of the most effective binding knots due to their strength and self-tightening properties.
4. In reference to Fig. 1.1 when point B of the string is tied at point A of the rod, the entire structure is seen to twist and take the shape of a tensegrity structure in which none of the rods are in contact with another.

Mass of the Structure:

Each rod weighs 117g while the weight of the nylon string is so less, it's can be considered negligible. Hence, since 3 rods were used, the total weight of the structure is 351g.

Experiments:

1. The structure was tested by placing a 10 kg weight on top of it. It withstood the weight without any problems

Fig. 1.3 The initial construction process of structure 1

The Second Structure

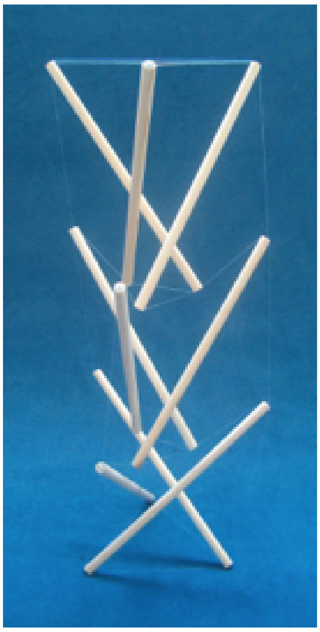


Fig.2.2 A 3 layered structure similar to the second structure

The second structure involved layering tensegrity structures similar to the first structure. Though the number of compress This was an important milestone in the quest to build the tallest tensegrity structure in India. This structure contained 3 layers and required 9 aluminium rods. However, it is still considered a 3 strut tensegrity structure since only 3 compression elements are required in a single layer.

Calculations:

Number of layers proposed = 3 (including structure 1 on the bottom). The top radii for each layer was kept the same, i.e, 20 cm.

For further reference, the number right after the alphabet refers to the layer and the number to its right refers to either the bottom (1) or top (2) of that layer. For example, e21 refers to the bottom end tendons of layer 2. The bottom radii for the layers other than the bottom to be 1/3rd of the top radii (20cm). This is taken arbitrarily for symmetric purposes.

Therefore,

$$r11 = r12 = r22 = r32 = 20\ cm$$

$$r21 = r31 = 1/3(20) = 6.67\ cm$$

$$s = 80\ cm$$

Using Eq. 1.1, h2 = h3 = 75.66013166 cm

Using Eq. 1.2, t2 = t3 = 77.05769816 cm

Using Eq. 1.3, e21 = e31 = 11.55277889 cm

In order to calculate the strings required to attach layer 2 to layer 1 (j12) and layer 2 to layer 3 (j23) equations were derived by constructing a cross-section of the plane joining the two layers.

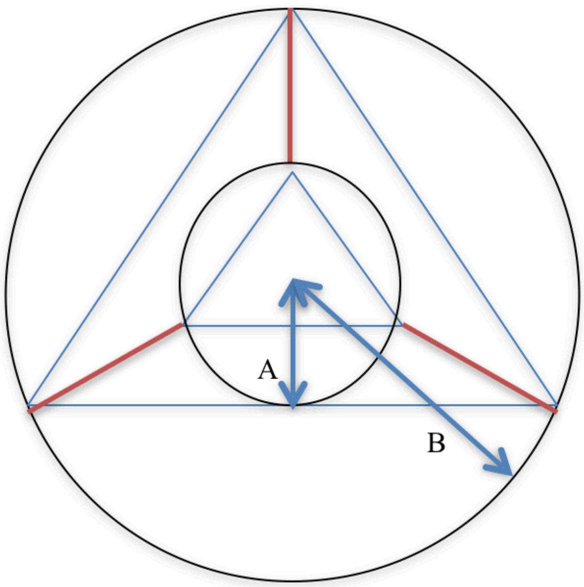


Fig. 2.1. Bigger triangle is the top of layer 1 or 2 and smaller triangle is the bottom layer 2 or 3. Red = Joining tendons, Blue = Nylon Strings, Black = Imaginary (for calculation purpose only)

In Fig.2.1 A = r21 = r31 = 6.67cm and B = r12 = r22 = r32 = 20cm

Therefore, the Joining tendons j1 = j2 = j3 = A – B = 20 – 6.67 = 13.33cm

Procedure:

1. Layers 2 and 3 were constructed using the same procedure laid out for structure 1.

2. The next step was to join layer 2 to layer 1. For this, three joining tendons were attached from each vertex on the top of layer 1 to the closest vertex on the bottom of layer 2 as shown in Fig.2.1.
3. Step 2 was repeated for layer 2 and 3.
4. By attaching strings of length equal to the height of layer 2 and 3,i.e, 75.66013166cm from the vertex on top of layer 3 / 2 to the closest vertex on the top of layer 2 / 1 our structure was complete.

Problems:

1. Slacking strings – It was observed that a few strings in structure 2 underwent slack while others were taught or extremely taught. This resulted in an overall imbalance structure. In order to reduce the slacking, equal pretension was added to each wire, per layer. Pretension was applied by winding the strings around a screw only once, hereby using the revolution around the screw as a measurement of distance and therefore, tension. Since extra tension (equal to the maximum weight to be added) was added to the structure, all the strings remained taught under it's original condition as well as under pressure due to weight placed on top of it.
2. Rods touching each other- The moment even one rod touched another in the structure compromised the tensegrity element of the project, This was eradicated by the use of pretension as given above.
3. Angular Tension- Since we had used a set of four holes on each end of the rods as the connection point, the twist of the final product resulted in an angular twist and therefore, angular tension in a few strings. Although the 4 hole design was used to minimize angular tension, it did not eradicate it completely. This problem could not

be addressed without rebuilding the entire structure with a one-point connection (loops).

The Third Structure

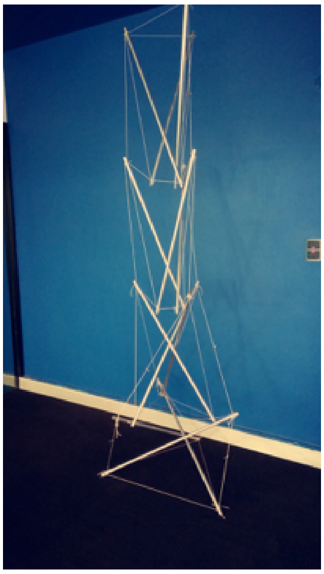


Fig.3.1. 4 layer tensegrity structure including a foundation.

The third structure build was a modified version of the second structure. The third structure used a wider base, a creation a stronger foundation. The structural layout of the foundation layer was similar to that of the other layers except that its bottom radius was larger than the top radius.

[rf1 = Base radius of foundation, rf2 = Top radius of foundation]

Taking strut(s) = 80 cm, rf1 = 35 cm, rf2 = 30 cm

From E.q.1.1 hf = 49.56154408 cm

From E.q.1.2 tf = 52.132898 cm

From E.q.1.3 ef1 = 60.62177826 cm and ef2 = 51.96152423 cm

The joining tendons were calculated by using the same method that was used for structure 2. Therefore, jf = rf2 – r11 = 30 – 20 = 10 cm.

Procedure:

1. The layer was assembled by following the same procedure to build structure 1.
2. Next, the foundation was attached to layer 1 by following steps 2,3 and 4 in the procedure for structure 2.
3. Since the structure was stable,the end tendons on the top of the foundation layer were cut off since they started slacking due to the weight of the other layers.
4. Pretension was applied using screws, similar to the procedure for structure 2.

Problem:

1. The structure seemed to become unstable due to the lack of end tendons on the top of the foundation layer. This caused the structure to sway in a particular direction when it came into contact with an external force such as wind or human touch. It was observed that the direction of swaying/vibration was perpendicular to the direction of tension displacement. Since the end tendons were cut off on the top of the foundation layer, the tension on the vertex of the top was distributed only upwards and downwards, i.e., along one plane. The absence of the end tendons did not allow the dissipation of tension into other planes and hence made the structure unstable.

2. Another method to increase the overall stability of the structure was to connect unstable or weak points/vertices in the structure to the most stable point, i.e., any vertex on the bottom of the foundation layer (Since it was in contact with the ground and hence their movement was restricted).

The Fourth Structure

Following the first three structures, it was decided build tensegrity structure with more than 3 struts. The task was to build 3m x 3m tensegrity cube, required by Team Indus, for it's "Billion to Moon" campaign.

The fourth structure was a prototype for the 3m x 3m cube that we were required to build. 2.5mm diameter steel wire was used in the construction of this structure.

Calculations:

Using Angelo Agostini's 8-strut structure - made up of 2 concentric cubes - as a reference, a tesseract structure was calculated and designed as shown below..

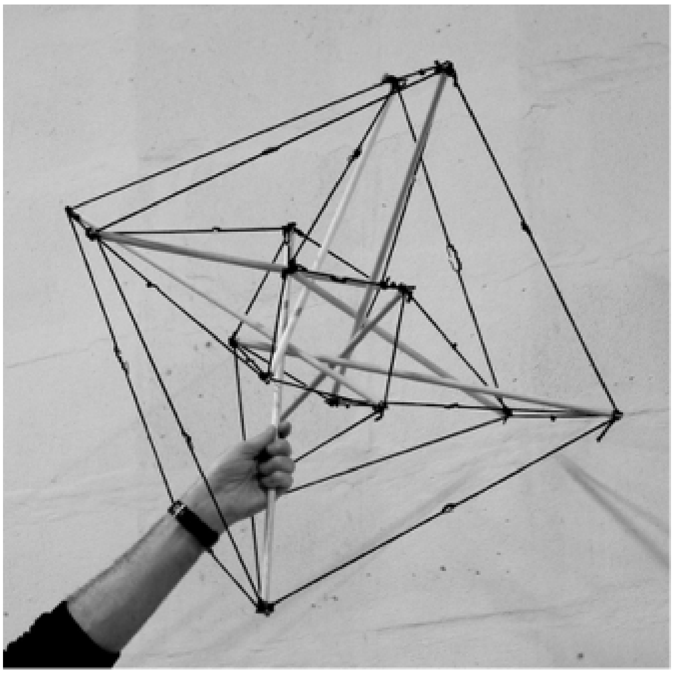


Fig.4.1. Angelo Agostini's 8-strut structure consisting of 2 concentric cubes.

To initialize the process, a constant value was required. From Fig.4.1, the assumption that the strut length was 2/3rd of the diagonal of the bigger cube could be derived.

Since the inventory included rods with effective length = 80cm, the diagonal length was taken to be 80x(3/2) = 120cm.

The side length (a) and diagonal length (dl) of a cube are related by the equation

$$d = \sqrt{3} \times a$$

Using E.q.4.1, a = 69.2820323028 cm

*'a' is also the string length required to construct the side of the cu*be.

New Method for Adding Pretension:

Using a 2.5mm steel wire as a tightening agent, hybrid cable made up of nylon string and steel wire was constructed (Refer to Fig.4.2)

For a cable length of 69.2820323028 cm, a buffer (extra length required to tie the element to another element - rod/nut/string/wire) string and buffer wire was required to join both the elements.

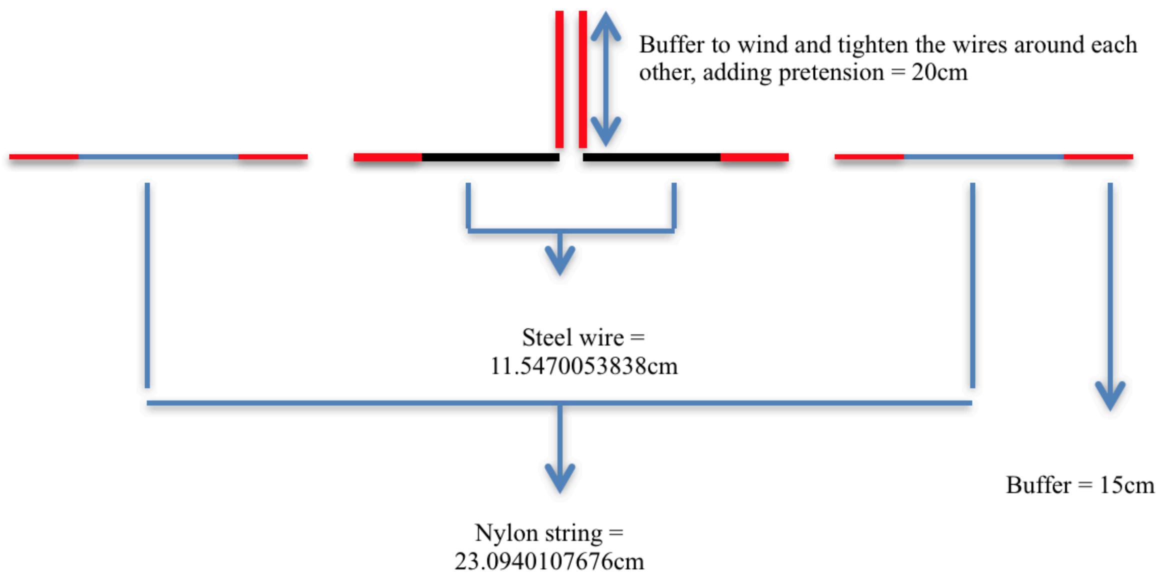


Fig.4.2. Hybrid Cable for applying pretension beforehand. Black = steel wire, Blue = nylon string, Red = buffer length.

Total length = 69.2820323028cm (without buffers)

Procedure:

1. The struts were placed in a position similar to Fig.4.1.
2. First the bottom square was constructed following which the top and side squares were made..
3. The smaller cube was constructed by attaching the nylon string to its opposite vertex on the small cube (as given in Fig.4.1)
4. After the structure was constructed, the observation was that a few cables were slacking and some rods were in contact with others. To rectify this problem, the buffer length of steel wire on the hybrid cables were forced to wind around each other and twisted using a set of pliers in order to apply pretension to the structure (Refer to Fig.4.2). Once equal pretension was added throughout, the structure was complete.

Problem:

1. While applying pretension the structure, due to the thin gauge of the steel wire, it broke at the point of twisting. Since one cable broke entirely, the whole structure eventually collapsed.

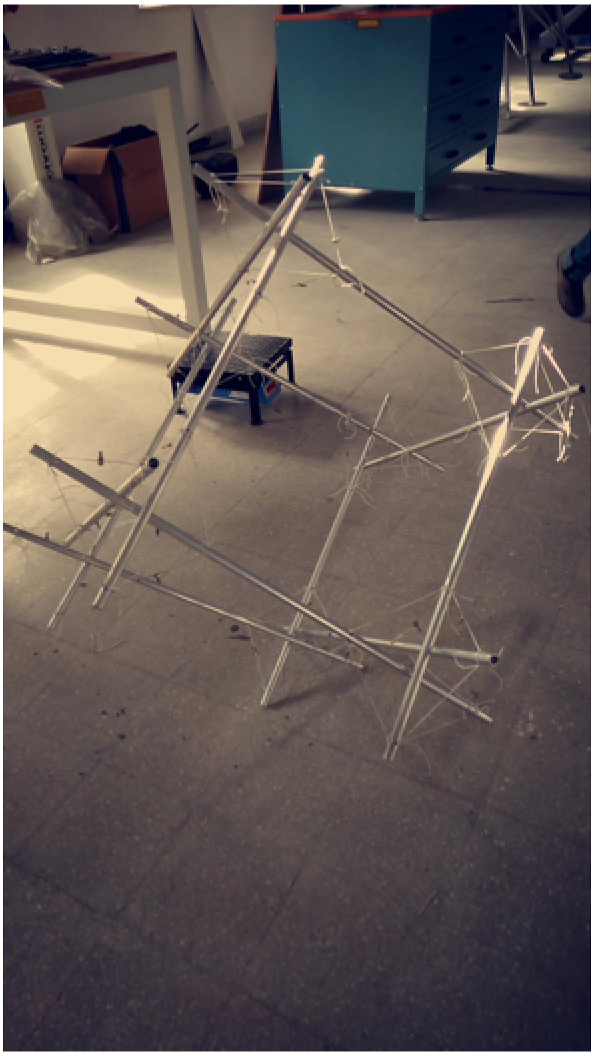


Fig.4.3. Tesseract tensegrity structure built

The Fifth Structure

Since adding pretension resulted in the collapse of structure 4, the design of the 3m x 3m structure was changed to a design similar to Fig.5.1.

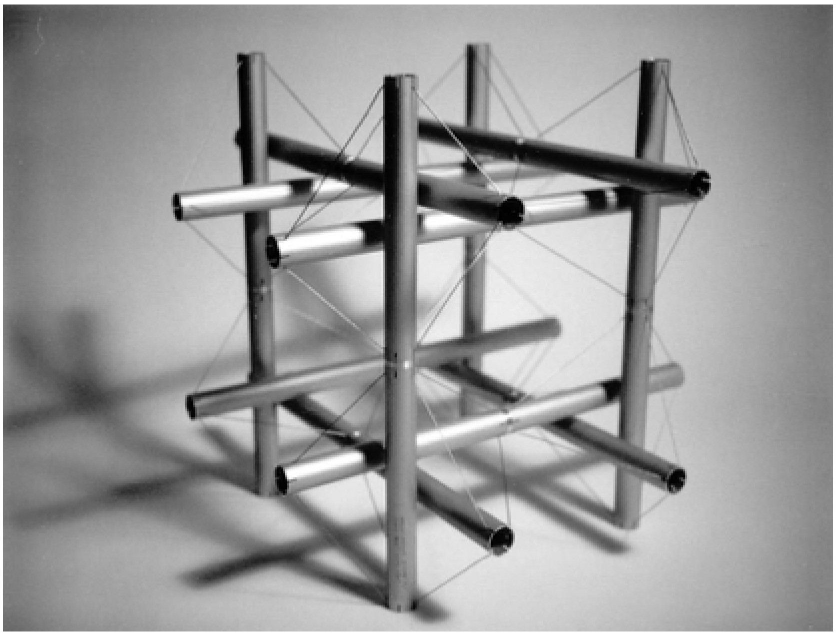


Fig 5.1 Kenneth Snelson's cube

Calculations:

From Fig.5.1, it can be observed that each corner of the cube can be visualized as extended version of the 3 strut tensegrity in structure 1. This observation simplified the calculations considerably.

Rod length given = 3.8 m

Effective rod length required = 3 m

4 holes were drilled 2.5 cm and 42.5 cm from the edge of each rod. Thus, effectively dividing the rod into 5 parts – 2.5 cm + 40 cm + 3 m + 40 cm + 2.5cm (ignoring the 20 cm on each end). Refer to figure 5.2.

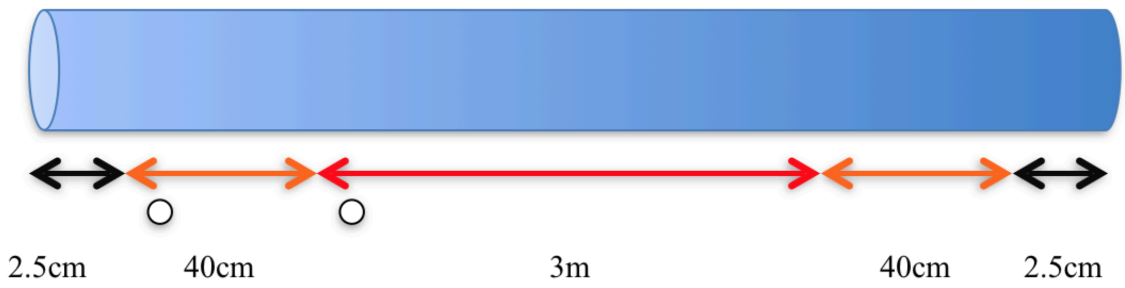


Fig.5.2 Division of the rod and placement of the holes.

Taking bottom radius (rb) and top radius (rt) of any corner as 18cm.

rb = rt = 18 cm

Effective strut length then becomes between the 2.5 cm and 42.5 cm holes. Therefore,

s = 40 cm

Using E.q.1.1.Height of each corner as (h) = 19.76905507 cm

Using E.q.1.2. Side tendon as (t) = 21.8547724 cm

Using E.q.1.3. End tendon as (e) = 31.17691454 cm

Due to the efficiency of the hybrid cable used in structure 4, a hybrid nylon-steel cable (used in structure 4) was used with the exception of a thicker gauge wire = 3.0 mm.

12 aluminum rods of length 3.85 m were used to make this structure.

Procedure:

1. By Implementing all the steps to make structure 1, each corner for the cube was constructed. The only difference was tying the cables to nuts which prevented the attachment from loosening or moving away from it's position in the structure.

2. After assembling each corner using the 3 strut procedure, a final cube shape along with a few slacking cables and rods in contact were observed. To rectify the problem, we added pretension by winding and tightening the steel wires in the hybrid cable. Then our structure was complete.

Problem:

1. While constructing the corners, one step involved flipping the structure completely. This process put extra tension on a few strings that had to take the weight of the entire structure while moving. Some cables broke under extra tension. This problem could not be rectified at that point, hence, the process had to be initiated again.

Fig.5.3 Above is a picture of the corner of the cube (similar to that of a 3-strut structure) using hybrid cables.

Fig.5.3 Above is a picture of the complete 3m x 3m tensegrity cube

The Final Structure

The sixth structure is the design for the 15m tall tensegrity structure, which was the ultimate goal of our tensegrity study.

Calculations:

The structure consists of 2 foundation layers + 6 x (20 strut) layers all arranged in the shape of a tower with a 5cm radius needle (10m) pointing upwards from the 4^{th}-5^{th} layer junction. The foundation and 6 upper layers are designed to be in the shape of a whirlpool. Refer to Fig.6.1.

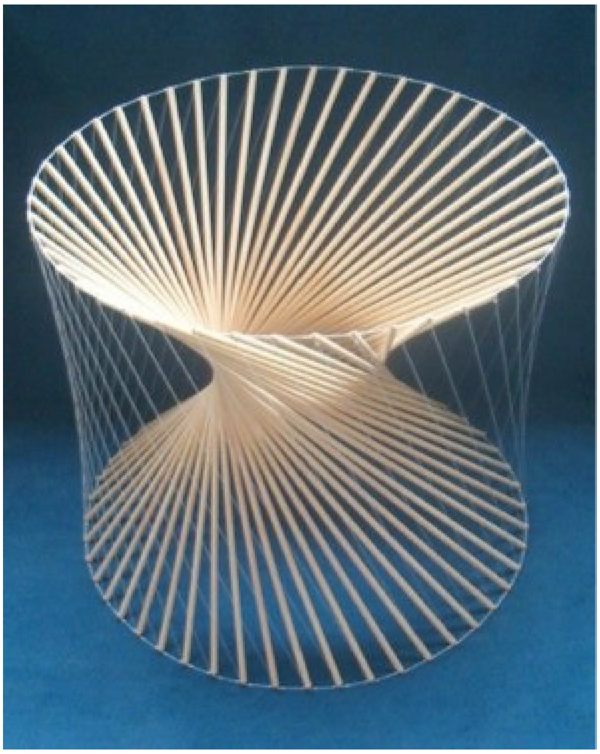


Fig.6.2. Above is a whirlpool structure, which are the reference and inspiration for the foundation layers and 6 upper layers as well.

The equations used for the foundation and upper layers are the same as the one's used for structure 1. The only difference is that the number of struts used is 20.

Using E.q.1.1, E.q.1.2 and E.q.1.3, the following is gotten.

Key: e1 = Bottom end tendon, e2 = Top end tendon, t = Side tendon, h = height, r1 = Bottom radius, r2 = Top radius, s = Length of struts.

First Layer (Foundation 1):

e1 = 0.4693033951 m

e2 = 0.6257378602 m

h = 2.25 m

t = 3.221 m

r1 = 1.5 m

r2 = 2 m

s= 3.5 m

number of struts = 20

Second Layer (Foundation 2):

r1 = 1 r2 = 1.25 m

h = 2.082405781 m

s = = = 2.7 m

t = 2.551044428 m

e1 = 0.3128689301 m

e2 = 0.3910861626 m

3^{rd} + 4^{th} + 5^{th} + 6^{th} + 7^{th} + 8^{th} Layers:

r1 = 0.75 m

r2 = 1 m

h = 1.04539385 m

s= = 1.7 m

e1 = 0.2346516976 m

e2 = 0.3128689301 m

t = 1.555859 m

Height without the needle = 10.60476888 m

Height of needle = 10 m

Needle starting height = 6.423193481 m

Height of needle jutting out of the structure = 4.181575399 m

Therefore, **total height of structure (without sagging) = 14.78634428 m**

Materials Required:

Strut Lengths:

S for layer 1 = 3.5m x 20

S for layer 2 = 2.7m x 20

S for layer 3, 4, 5, 6, 7, 8 = 1.7m x 20 x 6

Side Tendons:

t for layer 1 = 3.0793m x 20

t for layer 2 = 2.551m x 20

t for layer 3, 4, 5, 6, 7, 8 = 1.5559m x 20 x 6

End Tendons:

e11 = 0.4693m, e12 = 0.62574m x 6

e21 = 0.312869, e22 = 0.39109m x 60

e31 = 0.23465m, e32 = 0.31287m x 6 (same for layers 4,5,6,7,8)

Joining Tendons:

Top of Layer 1 to Bottom of Layer 2: J1 = 50cm x 20

Top of Layer 2 to Bottom of Layer 3: J2 = 50cm x 20

Top of Layer 3 (plus) to Bottom of Layer 4: JT3 = 25cm x 20 x 6

Absolute Side Tendons:

AST1 = 2.097353037m (without drop due to weight) x 20

AST2 = 1.0748713m (without drop due to weight) x 20

AST3 (plus) = 1.04539m (without drop due to weight) x 20 x 6

Space per Strut (S/S):

Layer 1 : S/S1 = 0.47124m, S/S2 = 0.6283m

Layer 2 : S/S1 = 0.314m, S/S2 = 0.3927m

Layer 3,4,5,6,7,8 : S/S1 = 0.2357m, S/S2 = 0.314m

NEEDLE COMES IN ON THE 4th/5th junction, Needle length = 10 m

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