Chinese Timber Woven Arch Bridges

A Senior Project By:
Owen Anderson
Kaleigh Kant

Project Advisor:
Professor John Lawson

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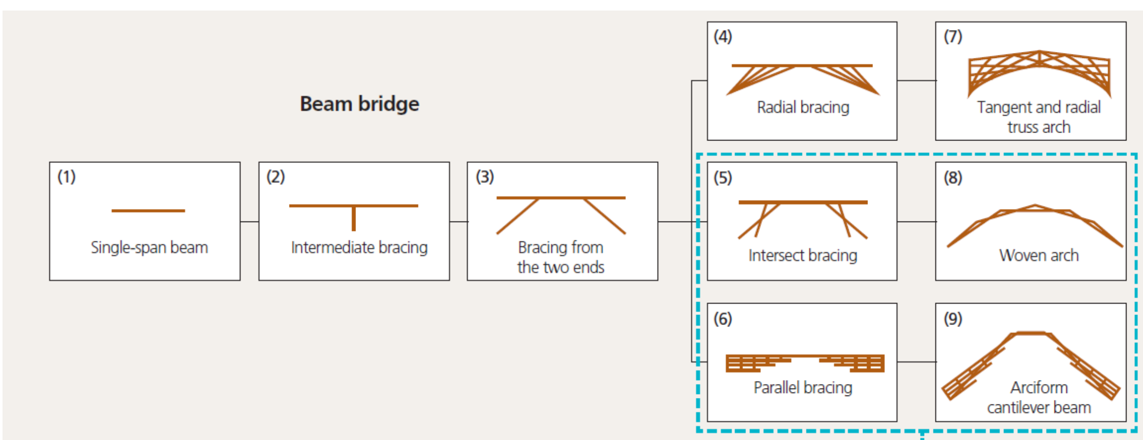
I. INTRODUCTION

We are Owen Anderson and Kaleigh Kant, Architectural Engineering students at California Polytechnic State University, San Luis Obispo. For our senior project, we decided to study and explore the idea of China's timber woven bridges under the advisory of Professor John Lawson. Throughout the academic quarter, we dove into historical and analytical research of these bridges, and herein is our final report on those studies.

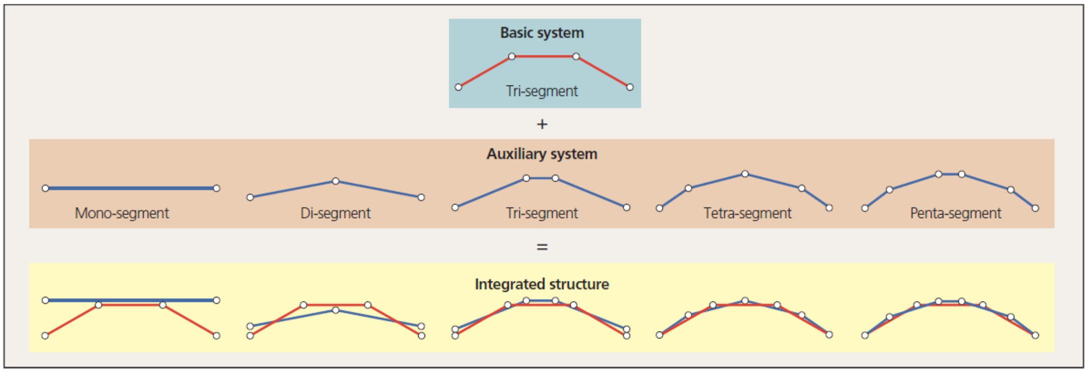
II. BACKGROUND & HISTORY

Timber woven bridges were first designed around 1000 years ago, in China, during the reign of the Song Dynasty. It is speculated that a prison guard was trying to solve the problem of pillars of traditional bridges being washed away in rising flood waters. The design was rediscovered in 1954 by Tang Huan Cheng, a modern bridge engineer, when a famous Chinese painting of the Rainbow Bridge was publicly displayed. This Rainbow Bridge had a 20m span, but the design techniques were still not understood until the 1980s when more bridges with similar designs were being discovered. Over 100 of these bridges still exist in China today.

Typically, these woven arch bridges can span over 40m with a span-to-height ratio that ranges from 2 to 7. The design evolved from bracing members in the center of the span from each end. With this came three types of bracing: radial, intersect, and parallel. We primarily focused on the intersect bracing as the woven timber bridge was descended from this idea (see *Fig. 1*). Each of these bridges has a basic tri-segment system that intersects with a secondary, auxiliary system that would range from one to five segments (see *Fig. 2*). The Rainbow Bridge itself had a tetra-segment auxiliary system.

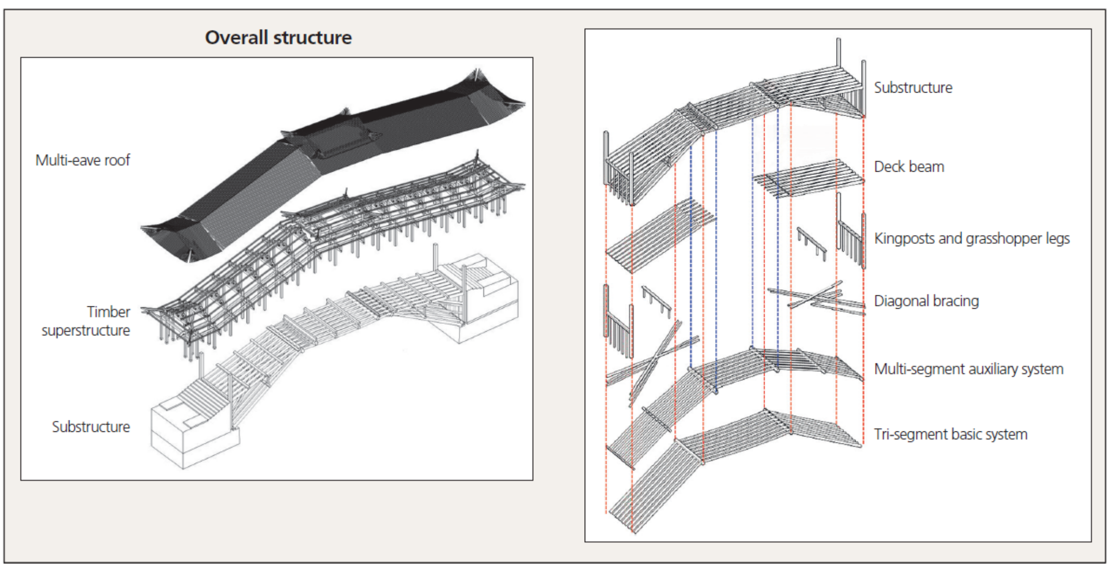


(Figure 1)



(Figure 2)

These bridges were constructed with cross beams (also called "bull-heads") which included mortise and tenon joints to hold the structure together, as well as a ground beam that was used similarly at the abutment. The traditional Chinese coverings we would recognize today also bore on these bull-heads. Symmetric, diagonal bracing is then installed on either side of the arch for lateral stability plus columns at each end to support an upper deck (see *Fig. 3*).



(Figure 3)

III. SCOPE OF PROJECT

In the Western world, a similar concept of a woven timber bridge had been designed and drawn by Leonardo Da Vinci in the 1400s. Starting off the project, we wanted to decide which of two concepts we were going to dive deeper into. Because the Chinese bridge design was richer in historical and cultural background, and still has many surviving examples today, it was decided that we were interested in exploring and analyzing that design. In the beginning, we

were interested in finding out how exactly these bridges behaved structurally, with a goal of finding a way to simplify or optimize the design with some set of equations. As we continued into the quarter, we also began to explore load prediction and how it affected the design using funiculars. Additionally, as we looked into how members were connected, we were able to use 2D and 3D modeling to design scaled bullheads.

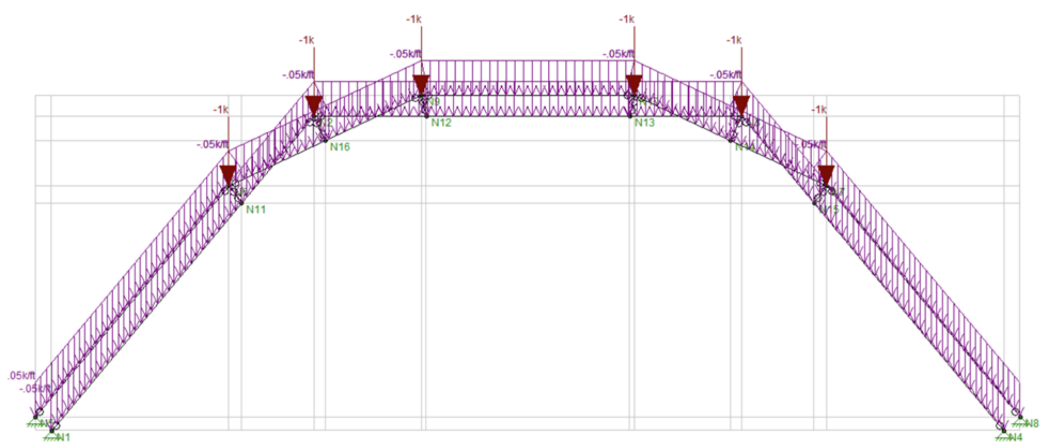
IV. ANALYSIS

A. Preliminary

The first challenge for our structural analyses was to determine how we could model the bridge's structure digitally. We were concerned that with the way the separate elements in this bridge interact, it could be challenging for the design to be represented accurately in a two-dimensional structural analysis program. The way in which pieces of the bridge are interwoven, the way they stand side-by-side and yet are independent of one another, was not something we knew could be interpreted correctly by our software.

Fortunately, it was found that RISA-2D would allow structural members to occupy the same point in 2-D space, and yet pass by one another, as well as allow them to behave dependently at their intersection when needed.

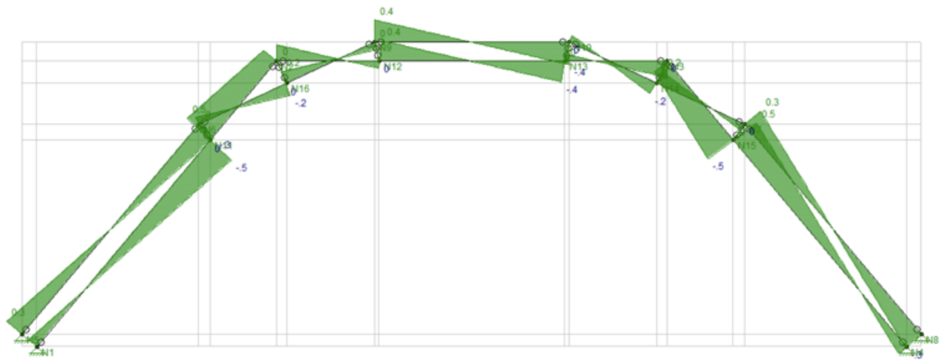
To prove that RISA could perform analyses on this structure, a model was made with arbitrary dimensions and loading (see *Fig. 4*). This includes point loads on the nodes where the bridge deck would be supported, as well as distributed loads for the members' self-weight.



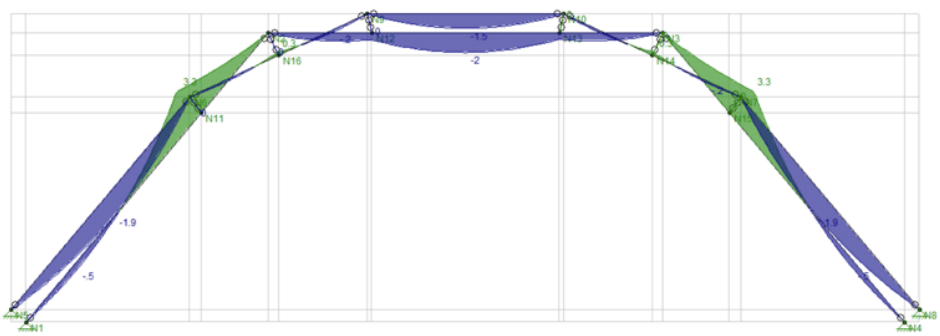
(Figure 4)

This resulted in high shears and moments (see *Fig*. 5), but our mission up until this point had been a success; our model worked and we could now focus on pushing it further to understand its inner workings.

Resulting shear member forces in *kips*:

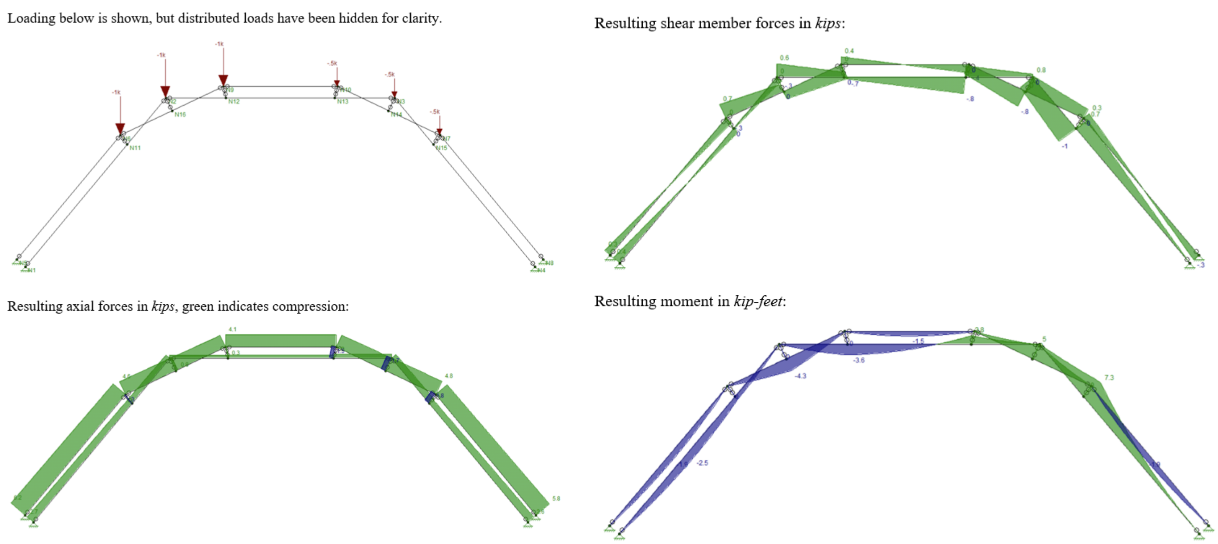


Resulting moment in *kip-feet*:



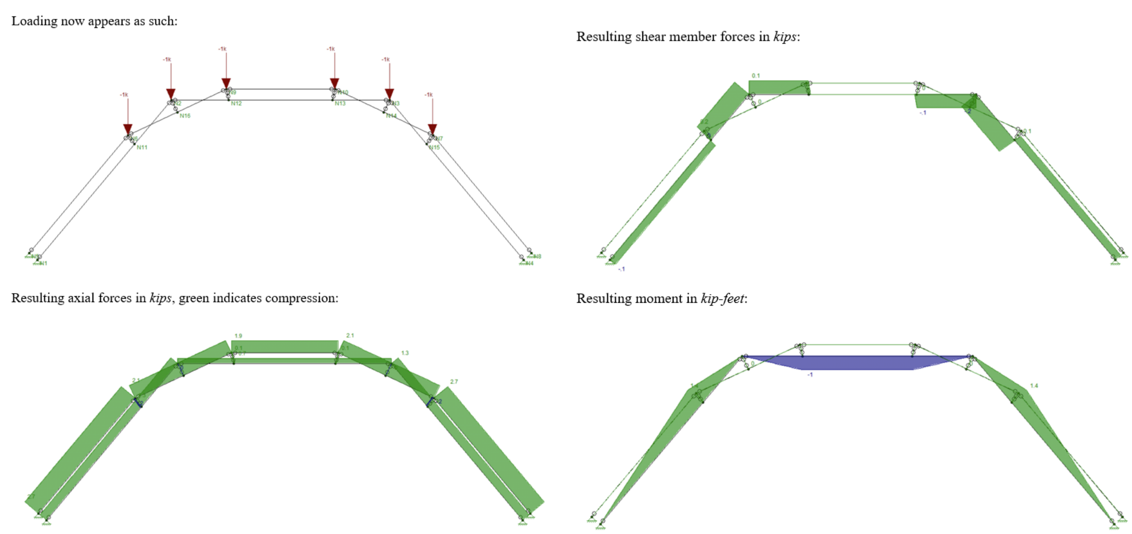
(Figure 5)

One important feature of this structure became apparent when we applied an unbalanced load (see *Fig. 6*). In this case, one side of the bridge was loaded twice as much as the other on the deck, and what we found was that the two interwoven frames of the bridge restrained one another. This revealed one function of the cross beams: <u>to make the two independent frames of the bridge act together.</u>



(Figure 6)

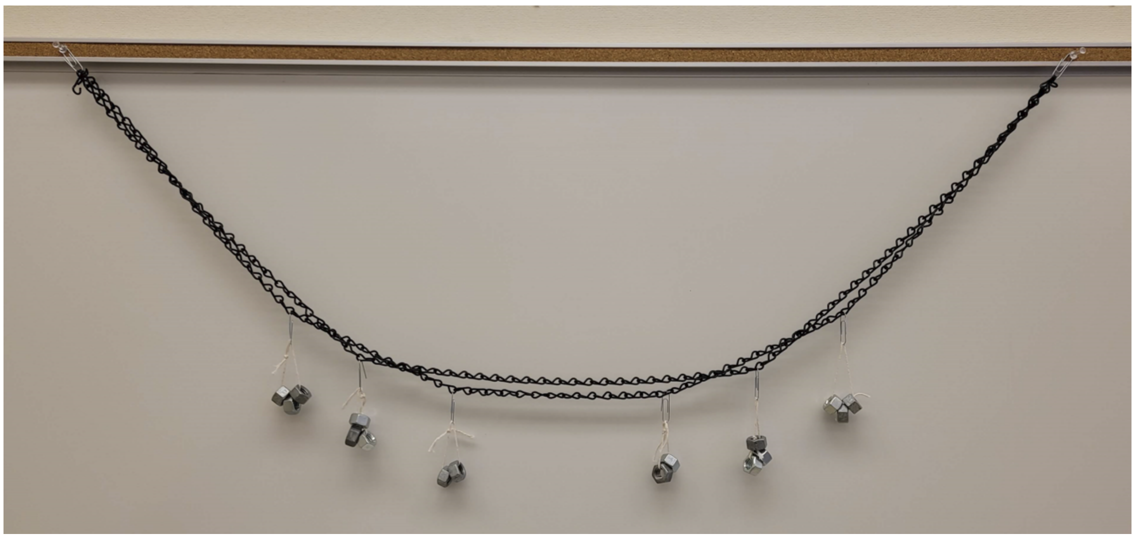
The next thing we tried was to try to simulate a "perfect world." In this case, the distributed load which stood for the structural element's self-weight was eliminated. The Young's Modulus of the structure's material was also adjusted to a very large number (1,000,000 ksi) to negate any second-order effects. The results showed comparatively little bending being induced in the bridge (see *Fig. 7*). With this, we began to think this structure could really behave as an arch in near-pure bending.



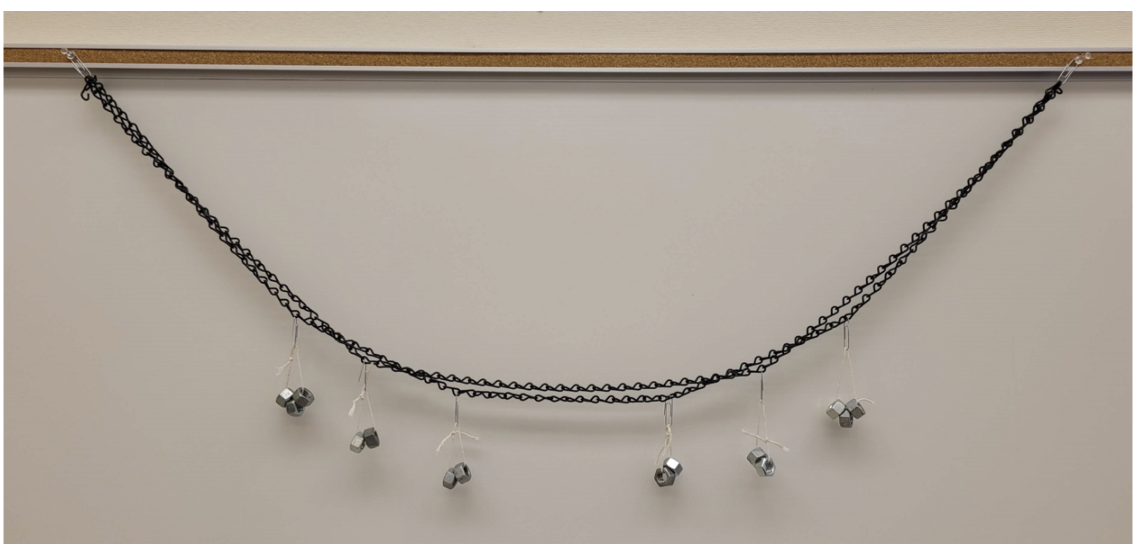
(Figure 7)

B. Funicular Study

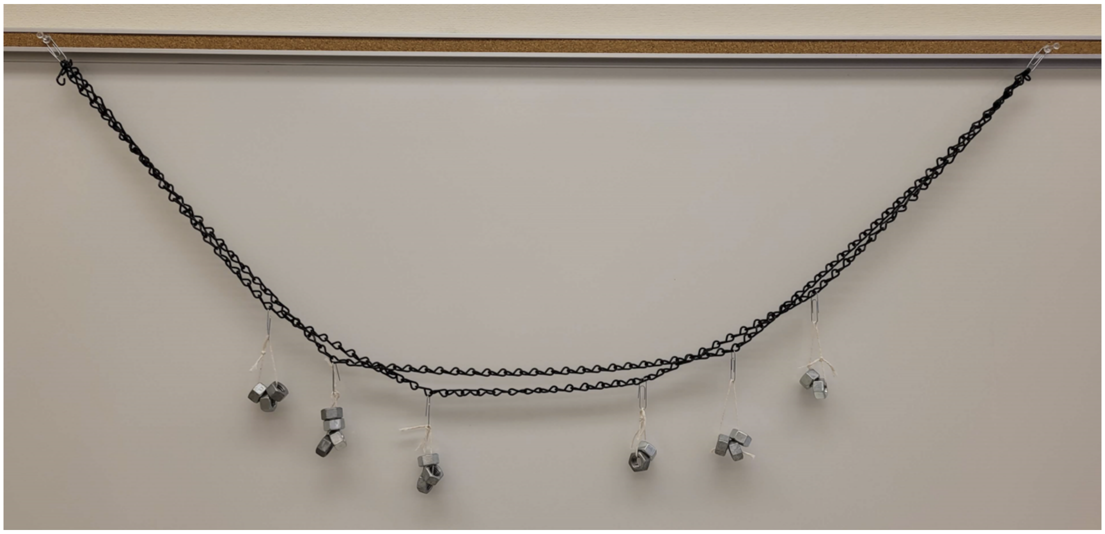
To refine this, we embarked on a funicular study to find the shape of bridge which would best support a given load. To do this we hung chains with weights in the node locations. The magnitude of these loads were assumed, but stood in for the coverings that we found from our historical research. The aim of this study is to identify a shape which will yield pure compression in the structure for a given loading. Since chains possess only tension, if the shape is inverted it will theoretically contain pure compression and no bending. We photographed several different load cases, including some unbalanced loadings (see *Figs. 8, 9, and 10*).



(Figure 8)

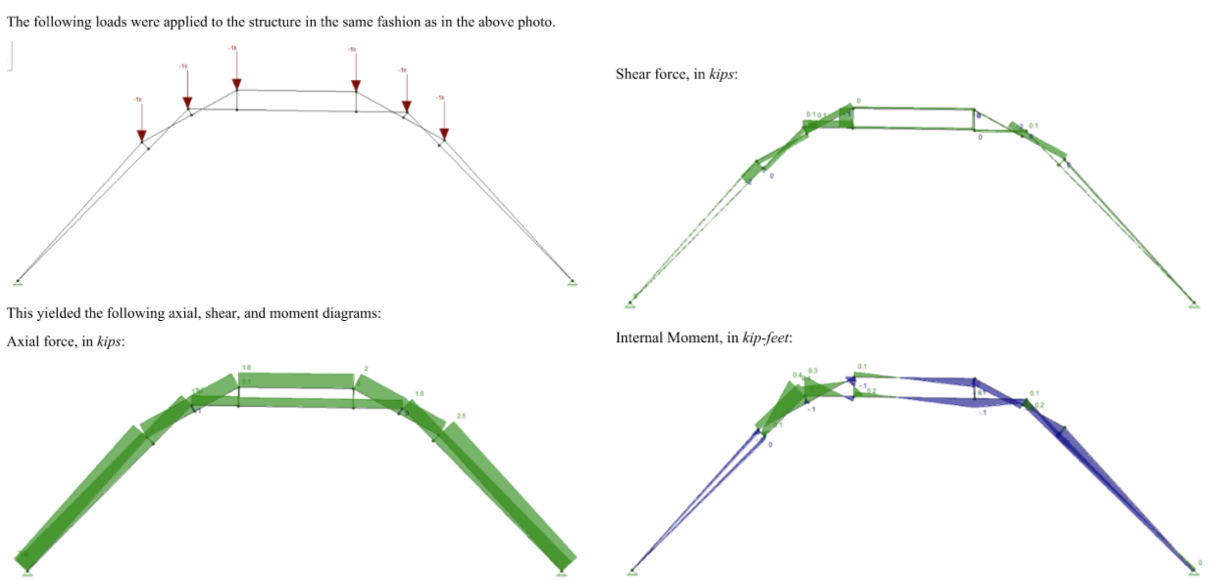


(Figure 9)



(Figure 10)

These pictures were imported into AutoCAD where they were scaled to match the previous model, and the coordinates of each node recorded. These were used to recreate our funiculars in RISA to match our funicular study, and what we found was that our model had worked quite well. The results from RISA showed very little moment in the bridge members (see *Fig.* 11).



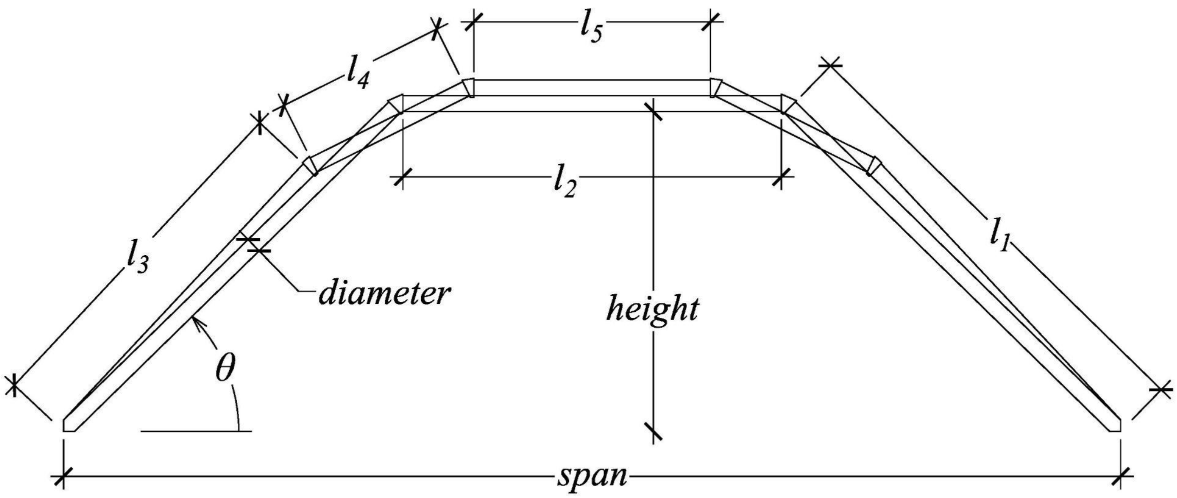
(Figure 11)

This analysis demonstrated that the bridge can behave as an arch. Whereas before we had viewed the bridge as a frame system, we had now deduced that this bridge was in fact <u>an arch masquerading as a frame</u>.

C. Application

One of the important questions we wanted to answer was what degree of flexibility a bridge designer would have in the shape of the bridge and the lengths of the poles.

To design the bridge, we derived several equations. These equations were determined geometrically on several inputs (listed below the diagram in *Fig. 12*), and there are also two intermediate values used for calculation.



height   *θ*   *span*   *diameter* l_5

(Figure 12)

Equations :

$$l_1 = \frac{height}{\sin\theta} \ or \ \frac{span - l_2}{2\cos\theta}$$

$$l_2 = span - 2l_1\cos\theta$$

$$\beta = 2\tan^{-1}\left(\frac{2\,diameter}{l_2 - l_5}\right)$$

$$\delta = \frac{diameter}{\tan\left(\frac{1}{2}(\theta - \beta)\right)}\cos\left(\frac{1}{2}(\theta + \beta)\right)$$

$$l_4 = \frac{1}{2}(l_2 - l_5) + \frac{\delta}{\cos\beta}$$

$$l_3 = \sqrt{\left(\frac{1}{2}span - \frac{1}{2}l_2 - \delta\right)^2 + (height + diameter - l_4\sin\beta)^2}$$

These equations were entered into a Microsoft Excel workbook to expedite design (see *Fig. 13*). It was found that the design of this structure can be made fairly simple, requiring only a

handful of inputs to produce the preliminary dimensions of the whole bridge. These equations were confirmed to work based on measurements taken from the models in AutoCAD.

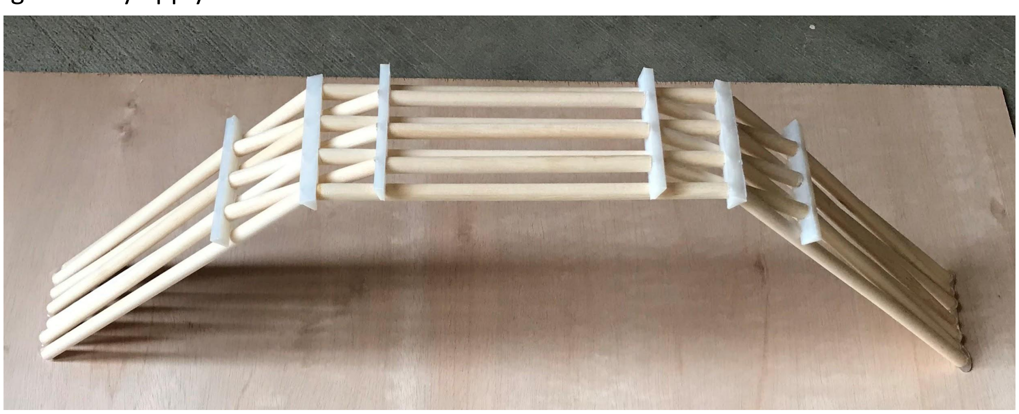
Input :			Output :	
HEIGHT	8.00 ft		l_1	10.56 ft
SPAN	29.04 ft			
DIAMETER	0.50 ft		l_2	15.24 ft
θ	49.237°	= 0.859 rad		
l_5	6.79 ft		β	0.235 rad
			δ	1.32 ft
			l_4	5.59 ft
			l_3	9.10 ft

(Figure 13)

This shows that these structures do not possess too much complexity to design from scratch with span, height, or pole diameter requirements in mind. It could easily be designed and redesigned as conditions require and this concept could apply further to bridges of greater complexity. The addition of other pole sizes or more nodes in the auxiliary system could be accomplished by any well-equipped designer.

D. Model

Using these equations we were able to design and build a scaled model (see *Fig. 14*) out of wood dowels. This is also when we looked deeper into how the Chinese were able to make the connections between members, and thus model and 3D print our own bullheads. We used 4 basic tri-segments woven with 3 of the auxiliary systems in order to build out the third dimension. Since up to this point in time our research had only existed two-dimensionally, it was exciting to finally apply it in 3D. The scale used was about ⅜" = 1'-0".



(Figure 14)

V. REAL WORLD IMPACT

A. Economic

Since the rediscovery of the woven bridge design, many Chinese builders have come forward to pass on the techniques they had been taught from generation to generation. It might be safe to say they have the construction process down to a science, and because of this the erection of such a bridge can be done quickly and efficiently. While money may be saved in this regard, materials are another problem. Despite using materials that do not require much processing, timber is still an increasingly expensive material to use.

B. Environmental

The construction of new timber woven bridges could have a large effect on the environment. Traditionally, these bridges have been built from full logs, meaning that each member used is equivalent to almost a whole tree being cut down. Because of this, it could become unsustainable on a larger scale, or in the case that this design becomes more widely used. Additionally, the construction of these bridges are also limited by the availability of trees large enough for the project. The Chinese have also considered the environmental effects and choose their logging days accordingly and to show respect to nature. However, they are also limited by cultural ties to use a particular species of fir trees.

C. Global

During a time when China was more isolated from the rest of the world, few ideas and innovations were exchanged or shared between China and the Western world. This may have been one of the leading factors as to why woven timber bridges have only just come into reach of Western scholars, even though the design has been around for a thousand years already. As a result, the idea of woven members has not yet been explored or expanded much into modern architecture. Now, with recent discovery and analysis, the bridge design can continue to be used around the globe, in addition to concepts it employs such as reciprocal frames.

D. Social

The design of timber woven bridges appears to be much more complicated than it is. Since the design, construction, and purpose can be quite simplified, it is an idea that can be used worldwide in underserved communities. Small scale, pedestrian bridges can provide safer and shorter routes to basic necessities such as food, water, shelter, and education where these resources would otherwise be scarce.

E. Cultural

The study into this type of bridge construction was able to give insight into and a greater appreciation for Eastern structural thinking and construction traditions. The ornamentation and shape of these structures shows the influence of architecture in Chinese buildings being borrowed for this application. In addition, these structures show an impressive degree of economy of materials, and beauty in structures which can be appreciated by anyone.

VI. CONCLUSION

A. Project Summary

Using Chinese historical and cultural influence as a precedent, we were able to model and analyze a timber woven bridge to find its structural behavior. After the initial analysis, we found a funicular shape that would optimize the bridge as a pure compression based arch. Finding the funicular shape helped us to find a series of equations that, with some given input, would output values for member sizes and geometrical values needed to build a bridge. To wrap it all up, we used output from our equations to build a model timber woven bridge .

B. Team Work

Splitting up the work, Owen tackled our initial RISA modeling and analysis as well as developing our key equations; meanwhile, Kaleigh focused on our historical research and physical modeling. Our collaboration significantly steered the direction of the project throughout the quarter in terms of balancing traditional techniques of the bridge design with new ideas and understandings as they came, and physical trial and error from our models.

Rating our teamwork on a scale of 0-5: **5**

VII. RESOURCES

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