Truss Bridge Design Project Technical Report

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Submitted To

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Signatures: By Signing this, we agree we have not received any unauthorized assistance on any aspect of this project. We have each read and edited this report.

Frank B: Was a part of writing sections 2.5, 2.8, 3.4, 4.4, 5, 6

Sabastian S: Was a part of writing sections 2.1, 2.2, 3.1, 4.1, 5, 6

Raafay U: Was a part of writing sections 1, 2.3, 2.6, 3.2, 4.2, 5, 6

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Abstract

Trusses are triangular structures, made of vertical, horizontal, and diagonal members, based on the type of truss. They are highly efficient in resisting heavy loads as all members are equally stressed. They are used for large spans. The top beams are known as top chords and are normally in compression, the bottom beams are known as bottom chords and are normally in tension. (IJCEM 9) This paper represents the analysis and design of 4 different truss styles: Warren, Pratt, Pennsylvania and Parker to determine the best design for a request made by the Department of Transportation. The goal is to provide a truss that is most economical, along with having a high capacity to carry load along with being strong enough to do so. The testing concludes that for a span of 44 meters, the Pratt truss would be the most feasible for the given parameters. If the length was shorter, the Warren truss would have been ideal while the Parker truss would have been more appropriate for distances between 200-300 feet. This is concluded after methodical evaluation of each truss. The Pratt truss had the lowest variance among forces in phase one of testing, proving the ability of equally distribution weight among all members of the truss. Additionally, it also had the most satisfactory safety rating and force:strength ratio.

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1 Introduction

The project aimed to test and design various types of truss bridges capable of spanning 44 meters with low cost, force to strength ratio of 0.5, and a safety factor of 2.0 or greater. Preliminary research was initially done on four different truss styles, giving one insight into determining which truss would best fit the given criteria before testing.

Truss models were built using PASCO structural beams spanning 29 inches and tested using the SparkVue software in the FEP Build Lab. The Bridge Designer 2016 software was then used to test forces and strengths of each truss before concluding the results. This report will start off by giving the reader background information about different truss designs before discussing the methodology, results, discussion, conclusion, and future work of the project.

1.1 Problem Statement

While responding to a request from the Department of Transportation, a new truss bridge to carry a two-lane highway across the river valley was designed. The river valley was 24 meters deep, with an average incline of 63 degrees, resulting in an opening at the top of 44 meters. Overarching problems of the design include the cost of the project, along with the overall strength and safety rating of the structure. The aim was to have the force to strength ratio close to 0.5 and safety rating close to 2.0 while keeping the cost to a minimum. All trusses will be evaluated to make sure they fit the above mentioned criteria.

1.2 Objective

The aim is to research several different truss designs and test them under load to determine which is the most appropriate structure for the given project. Next, the relative cost of each design needs to be compared to their overall structural stability. Findings need to be presented in the following report and presentation delivered to the class, along with the chosen truss design and why it was particularly chosen.

2 Literature Review

2.1 History of Truss Bridges

Beginning in the 16th and 17th centuries, truss bridges emerged from sturdy timber and masonry techniques of the Swiss and Germans; however, the calculations necessary to define forces on the chord and support members of truss structures were not created until 1826 by Claude-Louis Navier (Gasparini and Provost 22). In 1837, a design to outfit Ithiel Town's parallel-chord structure truss with cast iron plates was created by Eaton Hodgkinson and William Fairbairn. This design became popular in the United Kingdom during the 1st industrial revolution as the United Kingdom spanned very few gaps with their railroad lines and did not have lush forests to design trusses from sturdy timber (Gasparini and Provost 25). It was not until the mid to late 1800s that trusses were built in the United States due to the growing railroad transportation needs of the 2nd revolution. The first iterations of truss bridges built in the United States were Warren truss bridges due to their simplistic design. These bridges were made from pine wood soaked in creosote oil and spanned over streams or small lakes. However, as the network of railroad lines expanded, Pratt and Howe's trusses replaced the Warren truss due to their sturdiness and viability over longer distances, replacing pine structural members with steel. Although other truss bridge designs were developed during this period such as the Waddell "A" truss, Fink truss, and many others, these designs did not become widespread. Furthermore, during the early 1900s, other primarily steel and concrete based bridge designs began to take hold in the United States indicating the end of truss bridge design (TN.gov).

2.2 Warren Truss Bridge

The Warren truss (see Fig. 1) was patented in Britain in 1848 by James Warren and Willoughby Monzon. The Warren truss utilizes a series of equilateral or isosceles triangular members along with vertical support beams across longer distances to support the weight of railroad cars (Guise 23). When the Warren truss is not supporting the load of a moving object, the leftmost triangular beam is in compression while the rightmost beam is in tension; however, as a moving load is applied along the truss, the left and right support beams trade forces. For this reason, materials with a relatively high degree of flexibility are required to build such a truss as the designers did not intend for redundant members to be present (Griggs). To accommodate for the varying stresses on the truss, the beams were replaced from solid steel beams to a steel cable jacketed in a steel plate. This steel cable could expand or contract more easily than the steel rods themselves, further preventing buckling (Guise 34). However, as heavier locomotives traversed across these truss bridges, modifications were made to the design of the Warren truss to transition it from cost-effective to viable across large distances by inventors such as Albert Fink and Stephen Long. Albert Fink designed the Fink-Warren truss in 1885 when he built a 512-foot long bridge in Henderson, Kentucky that utilized equilateral triangular support beams, vertical compression members, and mid-height horizontal bracing (Guise 31). Previously, in 1872 Stephen Long created the Long-Warren truss that utilized pinewood equilateral triangular members, iron vertical posts, and horizontal chords connected with iron pins to support tension forces (Gasparini and Provost 29). Ultimately, the Warren truss bridge was removed from industrial use in the early 1900s due to other materials like iron and steel becoming cheaper, undervaluing the cost-effectiveness of the Warren truss.

Fig. 1. Warren Truss (Herbudiman, B., et al. 5)

2.3 Pratt Truss Bridge

The Pratt truss (See Fig. 2) was designed by Thomas Willis Pratt and his father Caleb Pratt (Historic Bridge Patents). Since the early 1840's, this design was used to build numerous bridges up until World War II (Pratt Truss Bridge). The design was primarily used in railroad bridge construction, moving away from wood components to all-steel structures. The Pennsylvania Railroad used the Pratt Truss design to construct bridges with stiffened arches to increase efficiency (Waddell 23). The basic form of the Pratt Truss included a triangular design with diagonal members tilted toward the center of the bridge. When under load, diagonal beams experience tension while vertical beas experienced suspension. This simplified and produced a more efficient design (Pratt Truss Bridge), especially since it used eye bars and field pins to support the structure (Deldot.gov 73).

Fig 2. Pratt Truss (History of Bridges)

2.4 Pennsylvania Truss Bridge

The Pennsylvania truss (See Fig. 3) was developed in 1875 for a bridge on the Pennsylvania railroad. Between its inception and the 1930s, it was very popular; however, better designs caused it to fall out of favor. It is a variation of the pratt truss and was developed to reduce the cost of the material (Bridge Basics). Examples still standing today include the Lower Trenton Bridge, the Schell Bridge, the Inclined Plane Bridge, the Eastern-Phillipsburg Toll Bridge, and the Healdsburg Memorial Bridge (National Register of Historic Places). It is described as “another variant of the Pratt truss with polygonal top chords and panels that are additionally subdivided by ties and struts” by the NC Department of Transportation (NCDOT).

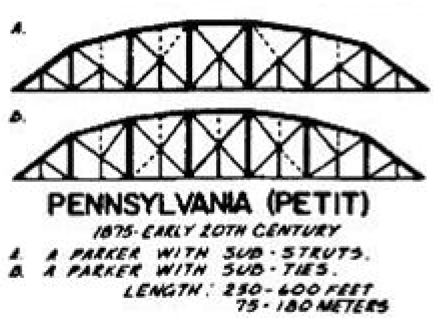


Fig. 3 (Source: HAER)

2.5 Parker Truss Bridge

The Parker truss (See Fig. 4), also referred to as a camelback truss, is a very simple design using vertical and inclined beams to create right triangles. The center of the truss is usually in an ‘X’ pattern. This truss design was designed by C.H. Parker. The Parker truss is another form of a Pratt truss. Parker trusses are typically used for longer spans. The preferred span for a Parker truss is between 200 and 300 feet. (Adeli 14) The difference between a Parker truss and Pratt truss is that the top chords are inclined on the Parker truss rather than being flat, like on the Pratt truss.

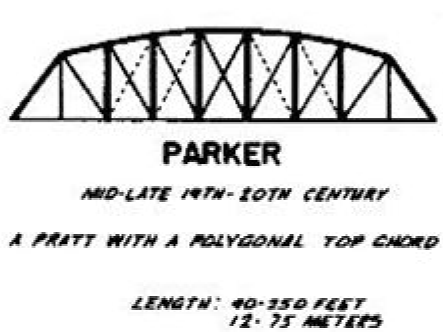


Fig 4 Parker Truss (NCDOT)

2.6 Structural Analysis

The Pratt truss reduced the cost of building bridges since it utilized more efficient and lighter steel members. It proved to be highly productive for its ability to span great distances up to 250 feet (Waddell 468) where a vertical force was applied, evenly spreading out all forces. However, this structure could be dis-advantageous if the load is not vertical (Boon). While Truss bridges normally have a symmetrical design, the Pennsylvania Truss is unique enough to have an asymmetrical design (Truss Bridge Plan). The top and the bottom chord are not parallel. The Parker truss is generally used for spans of 200 feet or more. It was designed to withstand heavier loads and longer spans. Instead of the smooth arch of the Pratt truss, the Parker Truss has rigged arches that directly connect the edges of the truss. The Warren Truss is ideal for shorter spans around 50 feet (Abbett 23). It evenly distributes forces throughout the construction. The structure, however, is inefficient for heavier and concentrated loads.

2.7 Pier / Bridge Abundant Designs

An abutment are found at the end of a bridge, where they connect to land. They experience intense lateral pressures. A pier (also known as a pile, beam, or footing) is a concrete post driven into the ground to support the bridge usually from the center. Typically, single-span bridges--bridges that only contain one “copy” of a bridge’s design--require only an abutment on either side. Multi-span bridges on the other hand require the use of piers to support the area between two different spans. There are many different kinds of abutments. They Include but are not limited to: U, Gravity, Cantilever, Full height, and Stub. Furthermore, there are multiple different uses for an abutment aside from supporting bridges. These include:

“To transfer loads from the superstructure to its foundation elements

To resist and/or transfer self weight, lateral loads (such as the earth pressure) and wind loads

To support one end of an approach slab

To maintain a balance in between the vertical and horizontal force components of an arch bridge” (Christine 449).

2.8 Other Applications for Trusses

Throughout history, the truss has proven to be a very effective tool in any engineer’s toolbox. Although they were originally designed for bridges, there are many other uses for trusses. One of the most used alternative designs trusses are used for are space grid structures. With a need to fill large enclosed spaces effectively, space grid structures are a valuable tool to implement. Space grids are extremely useful for this problem due to their flexibility and diversity. (Chilton 1) Alexander Graham Bell was an avid believer in space grids and made one of the first structures comprised of space grids way before they became popular in the 1940s. The reason why he was so fond of space grids was due to their great strength and lightweight properties. (Chilton 2) In the entertainment industry, truss structures are used for lighting systems, cameras, displays, speakers, and more all mounted to the truss structure. This design is used in many concert venues and even play stages. (Christie 5) This along with other robots and programs can be extremely automated to the point where everything can be controlled from the push of a button. Today, as technology continues to advance, these truss systems are getting more and more sophisticated to increase reliability and efficiency. (Cadena 4)

3 Methods and Materials

For all Truss designs, sketches were initially made in logbooks as a reference figure. Next, a time slot in the FEP Build Lab was reserved to conduct phase one of the testing. Moreover, the SPARKVue app was installed and the PASCO student manual was studied prior to visiting the lab. In the lab, PASCO structural beams were provided for construction. 3D models were built so numerous different points could be tested. Once built, all bridges were placed between a 29 inch gap. Next, a sensor was inserted in place of a beam and connected to the sparkvue app via Bluetooth. A Weight of 1kg was added to three different parts of the bridge with tension and compression forces recorded on the SparkVue app. The sensor was placed in the middle while the weight was shifted from the right, to the left, and then the middle. Once all forces were recorded, the models were disassembled.

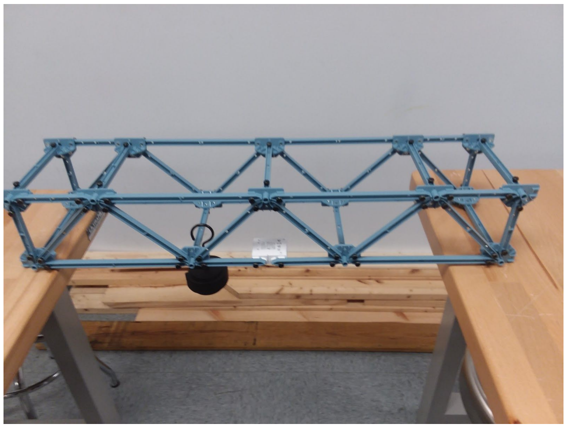
After successful completion of phase one of testing, the bridge designer 2016 software was installed on every members respective laptop for phase two. The sample Pratt Deck Truss design was used a basis for the bridges to be built onto as it satisfied the constraints of the project. After a bridge was built that passed the built-in test, the data was exported to an Excel spreadsheet. The Force:Strength ratio for compression and tension forces was calculated by dividing the force values by the strength values and storing that value in columns H and L respectively. The Safety Factor was determined by taking the Force:Strength ratio that was the most dangerous (furthest away from the 0.5 target), taking its reciprocal, and placing that in column N. The formula used to calculate the safety factor was:

=IF(H5=0,IF(M5=0,0,1/M5),IF(M5=0,1/H5,IF(ABS(0.5-H5)>ABS(0.5-M5),1/H5,1/M5))).

3.1 Warren Truss Bridge

3.1.1 Lab Testing

After analyzing relevant data on Warren Trusses, lab testing to determine scale-model forces was to be conducted. The design draft, utilizing isosceles triangles, can be seen in Figure ii. Upon entering the lab, a bridge was built using 2, 3, and 4 length beams. The structure began by connecting a 4 length beam to a left connector piece at 90 degrees. Then, a 3 length beam was connected to the connector piece at an angle less than 45 degrees. Next, a connector piece was attached to the right of the 4 length beam at another 90 degree angle. After that, a 3 length beam was attached into the diagonal formed between the uppermost connector piece and the right most connector piece. This process was repeated until 6 isosceles triangles were made where 2 sets of 3 from the 6 isosceles triangles have a similar connector piece. Using 4 length beams, the 2 uppermost positions between the uppermost connector pieces were connected in each set of 2. Then, the 2 warren truss frames were connected together by means of 4 4 length beams set perpendicular to the frames near the base. Finally, 2 length beams were used to create 4 right triangles that were connected to the ends of the 2 warren truss frames as a means of vertical support members. This process resulted in a warren truss as referenced in Figure i. Later, using sparkvue force sensors, the forces present on the bridge were measured when a weight was applied. This process was repeated 3 times and a graph similar to the one in Figure iii was produced. Overall, the bridge withstood the applied 1.5kg weight effectively.



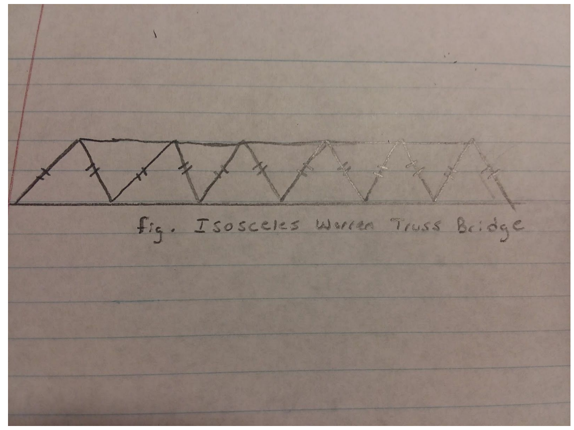


Figure i (Warren Truss Final) Figure ii (Warren truss sketch)

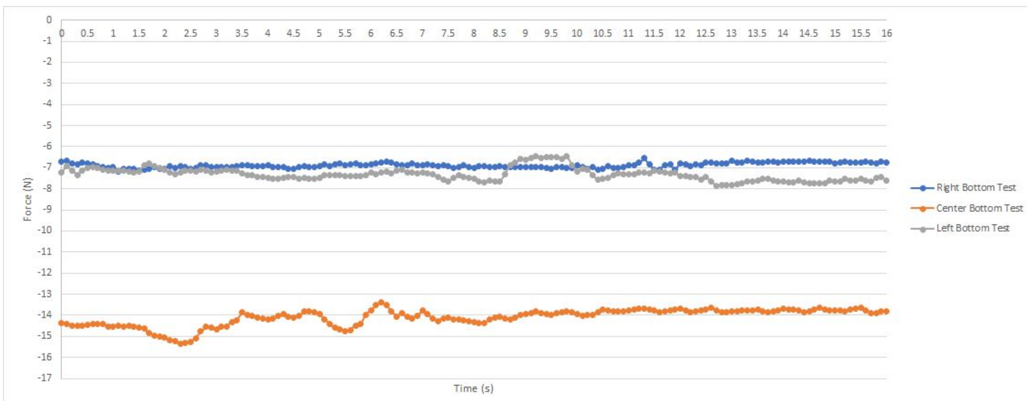


Figure iii (Warren truss forces)

3.1.2 Software Testing

Using the Warren Truss template in Bridge Designer 2016, the bridge shown in Figure iv was constructed. The bridge primarily used solid, carbon steel members of varying diameters to resist the forces present when a moving truck load was applied. After 44 iterations, a satisfactory Warren Truss capable of supporting the load applied was created and the data stored in an excel file shown in table i.

Sabastian Stetten - Warren Truss		Average Safety Factor:	2.533119552				
Dennis H. Mahan Memorial Bridge	F/S AVG:	0.470078754	F/S AVG:	0.319461557		Cost:	
Project ID: 00001A-	F/S MIN:	0.132210415	F/S MIN:	0.042816327		$422,947.21	
Designed By: Sabastian Stetten	F/S MAX:	0.577700726	F/S MAX:	0.580819523			

#	Material Type	Cross Section	Size (mm)	Length (m)	Compression Force	Compression Strength	Compression Status	Tension Force	Tension Strength	Tension Status	Compression F/S	Tension F/S
1	CS	Solid Bar	170x170	5.39	1819.39	3450.41	OK	0	6863.75	OK	0.527296756	0
2	CS	Solid Bar	160x160	5.39	1516.2	2816.68	OK	0	6080	OK	0.53829331	0
3	CS	Solid Bar	150x150	5.39	1207.13	2243.23	OK	0	5343.75	OK	0.53812137	0
4	CS	Solid Bar	150x150	5.39	893.95	2243.23	OK	0	5343.75	OK	0.398510184	0
5	CS	Solid Bar	140x140	5.39	578.43	1732.39	OK	0	4655	OK	0.333891329	0
6	CS	Solid Bar	140x140	5.39	262.16	1732.39	OK	199.31	4655	OK	0.151328511	0.042816327
7	CS	Solid Bar	150x150	5.39	0	2243.23	OK	516.45	5343.75	OK	0	0.096645614
8	CS	Solid Bar	150x150	5.39	0	2243.23	OK	833.72	5343.75	OK	0	0.156017778
9	CS	Solid Bar	140x140	5.39	863.45	1732.39	OK	0	4655	OK	0.498415484	0
10	CS	Solid Bar	140x140	5.39	0	1732.39	OK	1148.51	4655	OK	0	0.246726101
11	CS	Solid Bar	150x150	5.39	1175.75	2243.23	OK	0	5343.75	OK	0.524132612	0
12	CS	Solid Bar	140x140	5.39	0	1732.39	OK	1460.34	4655	OK	0	0.313714286
13	CS	Solid Bar	160x160	5.39	1484.82	2816.68	OK	0	6080	OK	0.527152534	0
14	CS	Solid Bar	150x150	5.39	0	2243.23	OK	1769.88	5343.75	OK	0	0.331205614
15	CS	Solid Bar	170x170	5.39	1789.76	3450.41	OK	0	6863.75	OK	0.518709371	0
16	CS	Solid Bar	140x140	4	0	2633.62	OK	664.7	4655	OK	0	0.142792696
17	CS	Solid Bar	140x140	4	0	2633.62	OK	1851.55	4655	OK	0	0.397755102
18	CS	Solid Bar	160x160	4	0	3881.59	OK	2792.48	6080	OK	0	0.459289474
19	CS	Solid Bar	160x160	4	0	3881.59	OK	3463.53	6080	OK	0	0.569659539
20	CS	Solid Bar	170x170	4	0	4583.96	OK	3862.08	6863.75	OK	0	0.562677836
21	CS	Solid Bar	170x170	4	0	4583.96	OK	3986.6	6863.75	OK	0	0.580819523
22	CS	Solid Bar	170x170	4	0	4583.96	OK	3837.79	6863.75	OK	0	0.559138955
23	CS	Solid Bar	160x160	4	0	3881.59	OK	3451.47	6080	OK	0	0.567675987
24	CS	Solid Bar	160x160	4	0	3881.59	OK	2795.52	6080	OK	0	0.459789474
25	CS	Solid Bar	140x140	4	0	2633.62	OK	1869.37	4655	OK	0	0.401583244
26	CS	Solid Bar	140x140	4	0	2633.62	OK	675.71	4655	OK	0	0.145157895
27	CS	Solid Bar	140x140	4	1344.35	2633.62	OK	0	4655	OK	0.510457089	0

Table i

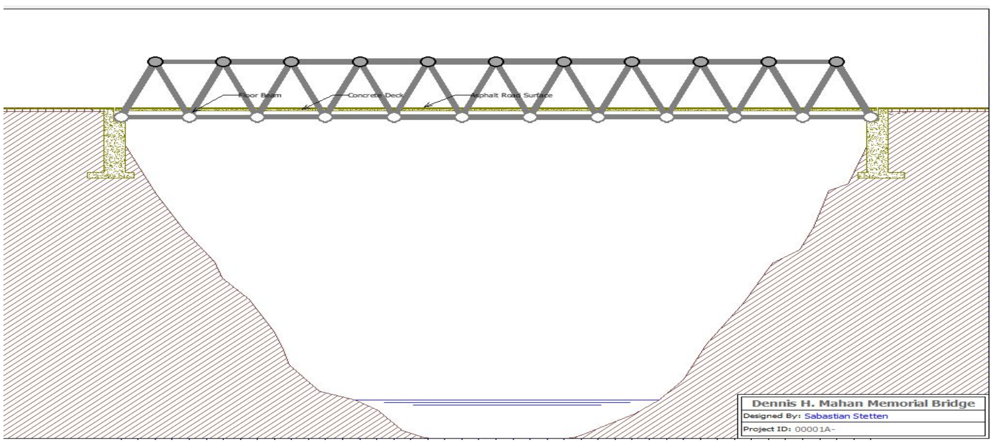
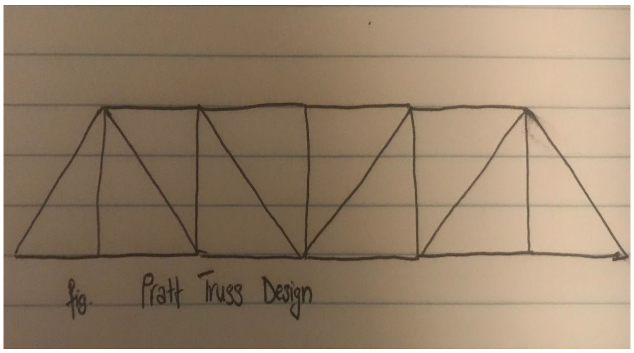


Figure iv

3.2 Pratt Truss:

3.2.1 Lab Testing

After initial research on the Pratt truss, a design was sketched using online sources as shown in Figure v. Using primarily beam sizes 3 and 4, the Pratt truss bridge was then constructed as seen in Figure vi and Figure vii. Both sides were made separately before joining them from the center, continuously using Figure v as a reference. Numerous triangles were made at 45 degree angles until the span of 29 inches was satisfied. The graph of forces present was recorded for the bridge as seen in Figure viii.



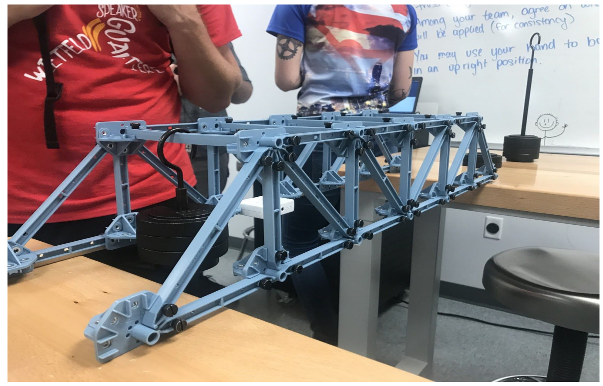


Figure v (Pratt truss sketch) Figure vi (Pratt truss final)

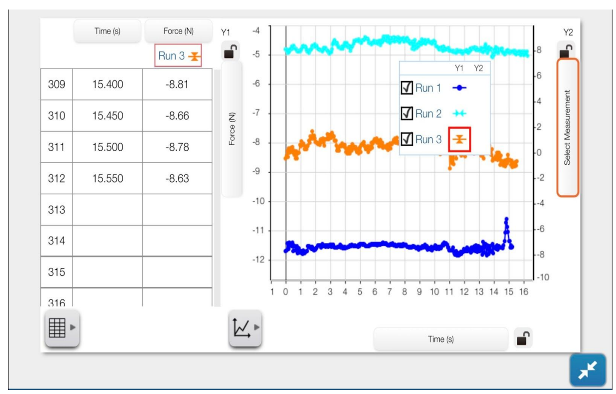


Figure vii (Pratt truss final) Figure viii (Pratt truss forces)

3.2.2 Software Testing

The Pratt truss template was used in order to design this bridge. Solid carbon steel members were used for the most part with some hollow tubes were used to offset the cost. After around 52 iterations to increase strength while minimizing cost, the bridge was successful with data shown in Table ii. .

Raafy Uqaily - Pratt Truss	Average Safety Factor:	1.906974732		
Dennis H. Mahan Memorial Bridge	F/S AVG: 0.678168828	F/S AVG: 0.370612766	Cost:	
Project ID: 00001C-	F/S MIN: 0.059382195	F/S MIN: 0.064894302	$314,947.28	
Designed By: H08 - Group 7	F/S MAX: 0.884786613	F/S MAX: 0.681935553		

#	Material Type	Cross Section	Size (mm)	Length (m)	Compression Force	Compression Strength	Compression Status	Tension Force	Tension Strength	Tension Status	Compression F/S	Tension F/S
1	CS	Solid Bar	110x110	6.4	0	465.22	OK	1421.05	2873.75	OK	0	0.49449326
2	CS	Solid Bar	110x110	6.4	0	465.22	OK	1137.17	2873.75	OK	0	0.39570944
3	CS	Solid Bar	90x90	6.4	0	208.48	OK	853.86	1923.75	OK	0	0.44385185
4	CS	Solid Bar	90x90	6.4	0	208.48	OK	573.97	1923.75	OK	0	0.29835997
5	CS	Solid Bar	90x90	6.4	12.38	208.48	OK	536.33	1923.75	OK	0.059382195	0.27879402
6	CS	Solid Bar	90x90	6.4	0	208.48	OK	816.22	1923.75	OK	0	0.4242859
7	CS	Solid Bar	110x110	6.4	0	465.22	OK	1099.53	2873.75	OK	0	0.38261157
8	CS	Solid Bar	110x110	6.4	0	465.22	OK	1383.41	2873.75	OK	0	0.48139539
9	CS	Hollow Tube	260x260x13	4	1914.86	2660.84	OK	0	3050.45	OK	0.719644924	0
10	CS	Hollow Tube	280x280x14	4	2549.06	3121.25	OK	0	3537.8	OK	0.816679215	0
11	CS	Hollow Tube	300x300x15	4	2968.21	3616.1	OK	0	4061.25	OK	0.820831835	0
12	CS	Hollow Tube	320x320x16	4	3174.41	4145.34	OK	0	4620.8	OK	0.765777958	0
13	CS	Hollow Tube	320x320x16	4	3165.36	4145.34	OK	0	4620.8	OK	0.763594784	0
14	CS	Hollow Tube	320x320x16	4	3165.36	4145.34	OK	0	4620.8	OK	0.763594784	0
15	CS	Hollow Tube	300x300x15	4	2944.58	3616.1	OK	0	4061.25	OK	0.814297171	0
16	CS	Hollow Tube	280x280x14	4	2510.86	3121.25	OK	0	3537.8	OK	0.804440529	0
17	CS	Hollow Tube	260x260x13	4	1867.83	2660.84	OK	0	3050.45	OK	0.701970055	0
18	CS	Solid Bar	160x160	6.4	1667.55	2082.43	OK	0	6080	OK	0.800771214	0
19	CS	Solid Bar	110x110	5	0	762.96	OK	577.19	2873.75	OK	0	0.20084906
20	CS	Solid Bar	120x120	5	872.12	1080.58	OK	0	3420	OK	0.807085084	0
21	CS	Solid Bar	120x120	5	650.45	1080.58	OK	0	3420	OK	0.601945252	0
22	CS	Solid Bar	100x100	5	431.69	521.12	OK	0	2375	OK	0.828388855	0
23	CS	Solid Bar	60x60	5	9.02	67.54	OK	0	855	OK	0.133550489	0
24	CS	Solid Bar	110x110	5	241.98	762.96	OK	186.49	2873.75	OK	0.317159484	0.0648943
25	CS	Solid Bar	100x100	5	461.08	521.12	OK	0	2375	OK	0.884786613	0

Table ii

3.3 Pennsylvania Truss Bridge

3.3.1 Lab Testing

After concluding the background research, an initial design was sketched as shown in figure ix. Using primarily sizes 1, 2, and 3 pieces, a full pennsylvania truss bridge was built as shown in figure x. One side of the bridge was built first, using figure ix as a reference. The other side was then made exactly the same as the first side. The two sides were connected on the bottom with number 4 pieces and on the top was made using octagon connectors and bendable number 4 pieces as shown in figure xi. The graph of forces present on the bridge was recorded and shown in figure xii. The bridge was extremely sturdy and stable.

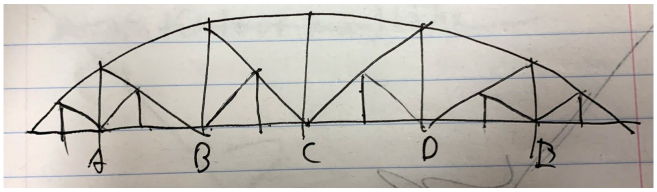


Figure ix

Figure x

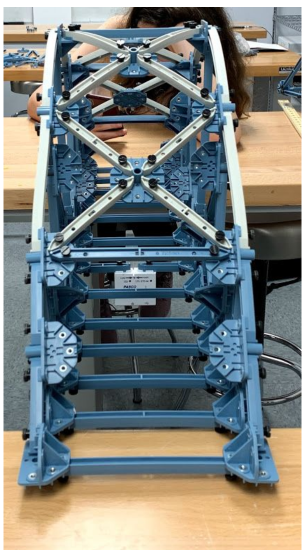


Figure xi

Figure xii

3.3.2 Software Testing

The Pratt Deck Truss template was used as a basis for the pennsylvania truss as seen in figure xiii. The bridge was made primarily of 140x140x7 hollow carbon steel, except for the bottom and the top arch which used 140x140x7 solid bar carbon steel. The design was followed as close as possible to the drawing, except where extra diagonal members were added in order to make the bridge stable enough to carry the truck across. Finally the test data was copied to an excel spreadsheet where the Force:Strength ratios and safety factor were calculated as seen in table iii.

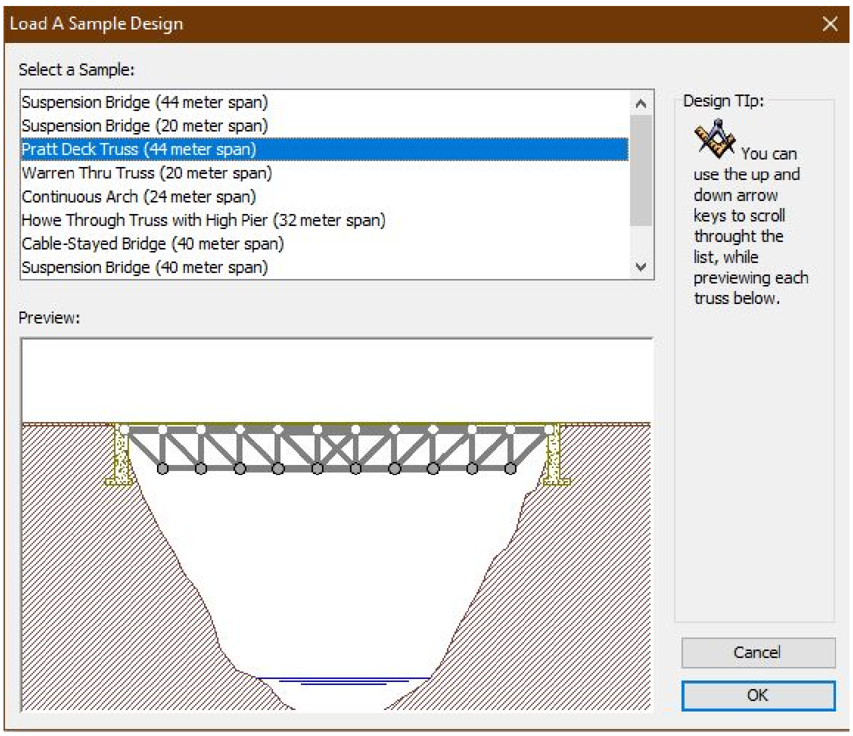


Figure xiii

#	Material Type	Cross Section	Size (mm)	Length (m)	Compression Force	Compression Strength	Force:Compression	Compression Status	Tension Force	Tension Strength	Force:Compression	Tension Status	Safety Factor
1	CS	Hollow Tube	140x140x7	6	0	441.45	0	OK	234.01	884.45	0.264582509	OK	3.779539336
2	CS	Solid Bar	140x140	2.83	2150.78	3407.97	0.631102973	OK	0	4655	0	OK	1.584527474
3	CS	Solid Bar	140x140	2.83	2234.58	3407.97	0.655692392	OK	0	4655	0	OK	1.525105389
4	CS	Hollow Tube	140x140x7	2.83	0	726.68	0	OK	173.55	884.45	0.196223642	OK	5.096225872
5	CS	Solid Bar	140x140	2.83	2275.7	3407.97	0.667758226	OK	0	4655	0	OK	1.497548007
6	CS	Solid Bar	140x140	2.83	2160.42	3407.97	0.633931637	OK	0	4655	0	OK	1.577457161
7	CS	Hollow Tube	140x140x7	2.83	0	726.68	0	OK	184.56	884.45	0.208672056	OK	4.792208496
8	CS	Hollow Tube	140x140x7	2.83	0	726.68	0	OK	471.3	884.45	0.532873537	OK	1.876617865
9	CS	Hollow Tube	140x140x7	2.83	0	726.68	0	OK	385.9	884.45	0.436316355	OK	2.291915004
10	CS	Hollow Tube	140x140x7	2.83	0	726.68	0	OK	334.28	884.45	0.3779524	OK	2.645835826

Table iii

3.4 Parker Truss Bridge

3.4.1 Lab Testing

After conducting background research on the Parker truss, a sketch was drawn out of the basic shape of a Parker truss as shown in figure xiv. Size 4 and 5 beams were most used throughout the entire design process as seen in figure xv and xvi. Figure xiv was continuously looked back on for reference when building the truss bridge one side at a time. Each side was then connected on the bottom and top using size 4 beam pieces. A graph of the forces present on the bridge were recorded using the SparkVue app and can be seen in figure xvii.

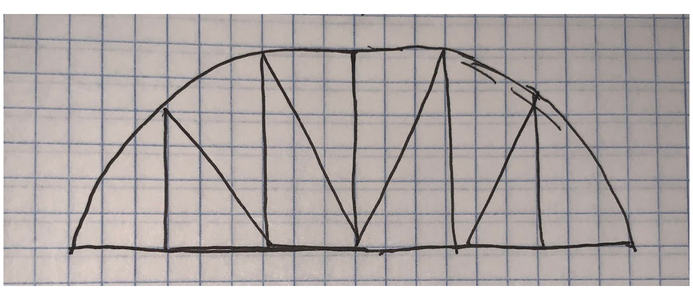


Fig. xiv

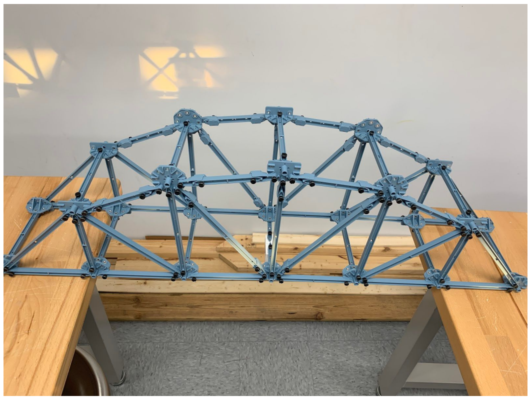


Fig. xvi

Fig. xv

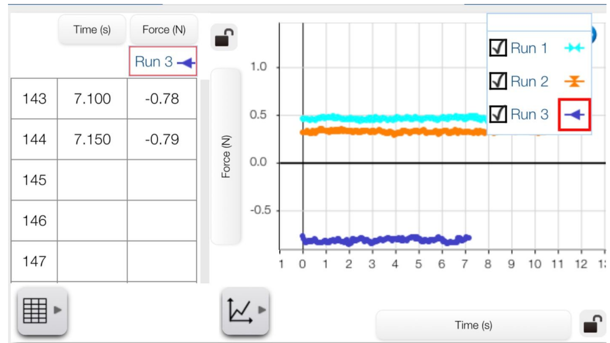


Fig. xvii

3.4.2 Software Testing

The Pratt truss template was used as a starting point for the Parker truss. The bridge was made using a combination of solid bars and hollow tubes made of carbon steel. The top and bottom chords are made entirely of solid carbon steel bars with the top chord having a thickness of 160x160 and the bottom chord having a thickness of 140x140. All of the inner support members were made of hollow carbon steel tubes with a thickness of 160x160x8. The design followed the original sketch in figure xiv as similar as possible with the only addition being more members to compensate for the longer length and odd number of bottom members. To finish the testing, data was copied to an excel spreadsheet where the Force:Strength ratios and safety factor were calculated as seen in table iv.

Frank Bonanno - Parker Truss		Average Safety Factor:	2.27877205		
Dennis H. Mahan Memorial Bridge	F/S AVG: 0.518167327		F/S AVG: 0.359498344		Cost:
Project ID: 00001A-	F/S MIN: 0.000163474		F/S MIN: 0.040061754		$305,615.70
Designed By: Frank Bonanno	F/S MAX: 0.916620469		F/S MAX: 0.541585873		

#	Material Type	Cross Section	Size (mm)	Length (m)	Compression Force	Compression Strength	Compression Status	Tension Force	Tension Strength	Tension Status	Compression F/S	Tension F/S
1	CS	Solid Bar	160x160	5	2649.42	3108.78	OK	0	6080	OK	0.852237855	0
2	CS	Hollow Tube	160x160x8	3	0	968.07	OK	625.64	1155.2	OK	0	0.54158587
3	CS	Hollow Tube	160x160x8	5	110.38	778.4	OK	295.03	1155.2	OK	0.1418037	0.25539301
4	CS	Hollow Tube	160x160x8	5	0	778.4	OK	450.39	1155.2	OK	0	0.38988054
5	CS	Solid Bar	160x160	4.47	2562.62	3516.87	OK	0	6080	OK	0.728664978	0
6	CS	Solid Bar	160x160	4.27	2513.7	3672.02	OK	0	6080	OK	0.684555095	0
7	CS	Solid Bar	160x160	4.12	2455.98	3787.01	OK	0	6080	OK	0.648527466	0
8	CS	Solid Bar	160x160	4.03	2411.07	3857.73	OK	0	6080	OK	0.624997084	0
9	CS	Solid Bar	140x140	4	2414.03	2633.62	OK	0	4655	OK	0.916620469	0
10	CS	Solid Bar	160x160	4.03	2406.38	3857.73	OK	0	6080	OK	0.623781343	0
11	CS	Solid Bar	160x160	4.12	2440.62	3787.01	OK	0	6080	OK	0.644471496	0
12	CS	Solid Bar	160x160	4.27	2483.11	3672.02	OK	0	6080	OK	0.67622453	0
13	CS	Solid Bar	160x160	4.47	2510.77	3516.87	OK	0	6080	OK	0.713921754	0
14	CS	Solid Bar	160x160	5	2601.1	3108.78	OK	0	6080	OK	0.836694781	0
15	CS	Solid Bar	140x140	4	0	2633.62	OK	2080.88	4655	OK	0	0.44702041
16	CS	Solid Bar	140x140	4	0	2633.62	OK	2080.88	4655	OK	0	0.44702041
17	CS	Solid Bar	140x140	4	0	2633.62	OK	2245.7	4655	OK	0	0.4824275
18	CS	Solid Bar	140x140	4	0	2633.62	OK	2325.01	4655	OK	0	0.49946509
19	CS	Solid Bar	140x140	4	0	2633.62	OK	2367.75	4655	OK	0	0.50864662
20	CS	Solid Bar	140x140	4	0	2633.62	OK	2298.41	4655	OK	0	0.49375081
21	CS	Solid Bar	140x140	4	0	2633.62	OK	2382.65	4655	OK	0	0.51184748
22	CS	Solid Bar	140x140	4	0	2633.62	OK	2353.66	4655	OK	0	0.50561976
23	CS	Solid Bar	140x140	4	0	2633.62	OK	2292.08	4655	OK	0	0.49239098
24	CS	Solid Bar	140x140	4	0	2633.62	OK	2119.53	4655	OK	0	0.45532331
25	CS	Solid Bar	140x140	4	0	2633.62	OK	2119.53	4655	OK	0	0.45532331

Table iv

4 Results

All truss designs were successful in both withstanding the total 1.5kg weight in the lab as part of phase one and holding the weight of the truck in the bridge designer 2016 software.

4.1 Warren Truss Results

The Warren Truss designed in the lab held a total of 1.5 kg without breaking. The average force in Newtons experienced during Run 1 was -6.88209N. The average force in Newtons experienced during Run 2 was -14.0085N. The average force experienced during Run 3 was -7.31982N. The max force experienced for Run 1 was -7.16N. The max force experienced for Run 2 was -15.37N. The max force experienced for Run 3 was -7.88N. The min force experienced for Run 1 was -6.55N. The min force experienced for Run 2 was -13.38N. The min force experienced for Run 3 was -6.44N.

The Warren Truss designed in Bridge Designer 2016 came out to a total cost of $422,947.21 with an average safety factor of 2.533. The max safety factor was 23.3557 while the minimum safety factor was 1.7218, resulting in a range of (+20.8227/-0.8112) excluding 0s. The average Force:Strength ratio of compressive forces was 0.4701. The max Force:Strength ratio of compressive forces was 0.5777 while the minimum Force:Strength ratio of compressive forces was 0.1322, resulting in a range of (+0.1076/-0.3379) excluding 0s. The average Force:Strength ratio of tensile forces was 0.3195. The max Force:Strength ratio of tensile forces was 0.5808 while the minimum Force:Strength ratio of tensile forces was 0.0428, resulting in a range of (+0.2613/-0.2767) excluding 0s.

4.2 Pratt Truss Results

The Pratt Truss designed in the lab held a total of 1.5 kg without breaking. The average force in Newtons experienced during Run 1 was -1.08N. The average force in Newtons experienced during Run 2 was -3.39N. The average force experienced during Run 3 was -2.6N. The max force experienced for Run 1 was -0.08N. The max force experienced for Run 2 was -0.2N. The max force experienced for Run 3 was -2.51N. The min force experienced for Run 1 was -0.16N. The min force experienced for Run 2 was -0.2N. The min force experienced for Run 3 was -2.7N.

The Pratt Truss designed in Bridge Designer 2016 came out to a total cost of $314,947.21 with an average safety factor of 1.91, excluding 0s. The average Force:Strength ratio of compressive forces was 0.678. The max Force:Strength ratio of compressive forces was 0.884 while the minimum Force:Strength ratio of compressive forces was 0.594, excluding 0s. The average Force:Strength ratio of tensile forces was 0.371. The max Force:Strength ratio of tensile forces was 0.682 while the minimum Force:Strength ratio of tensile forces was 0.0648, excluding 0s.

4.3 Pennsylvania Truss Results

The Pennsylvania Truss designed in the lab successfully held a total of 1.5kg. The average force in Newtons experienced during Run 1 was -0.06348N. The average force in Newtons experienced during Run 2 was 0.017598N. The average force experienced during Run 3 was -1.99044N. The max force experienced for Run 1 was -0.01N. The max force experienced for Run 2 was 0.06N. The max force experienced for Run 3 was -1.95N. The min force experienced for Run 1 was -0.1N. The min force experienced for Run 2 was -0.03N. The min force experienced for Run 3 was -2.03N.

The Pennsylvania Truss designed in Bridge Designer 2016 came out to a total cost of $382,193.42 with an average safety factor of 5.203418235. The max safety factor was 23.38357806 while the minimum safety factor was 1.497548007, resulting in a range of +18.180159825/-3.705870228. The average Force:Strength ratio of compressive forces was 0.145212759. The max Force:Strength ratio of compressive forces was 0.667758226 while the minimum Force:Strength ratio of compressive forces was 0, resulting in a range of +0.522545467/-0.145212759. The average Force:Strength ratio of tensile forces was 0.163782827. The max Force:Strength ratio of tensile forces was 0.536683136 while the minimum Force:Strength ratio of tensile forces was 0, resulting in a range of +0.372900309/-0.163782827.

4.4 Parker Truss Results

The Parker Truss designed in the lab held a total of 1.5kg without breaking. The average force in Newtons experienced during Run 1 was 0.46435N. The average force in Newtons experienced during Run 2 was 0.32676N. The average force experienced during Run 3 was -0.81236N. The max force experienced for Run 1 was 0.5N. The max force experienced for Run 2 was 0.36N. The max force experienced for Run 3 was -0.77N. The min force experienced for Run 1 was 0.43N. The min force experienced for Run 2 was 0.29N. The min force experienced for Run 3 was -0.86N.

The Parker Truss designed in Bridge Designer 2016 came out to a total cost of $305,615.70 with an average safety factor of 3.68. The max safety factor was 24.96146 while the minimum safety factor was 1.09096, resulting in a range of +21.28146/-2.76904. The average Force:Strength ratio of compressive forces was 0.246746. The max Force:Strength ratio of compressive forces was 0.91662 while the minimum Force:Strength ratio of compressive forces was 0, resulting in a range of +0.669874/-0.246746. The average Force:Strength ratio of tensile forces was 0.26534. The max Force:Strength ratio of tensile forces was 0.54148 while the minimum Force:Strength ratio of tensile forces was 0, resulting in a range of +0.27614/-0.26534.

5 Discussion

Forces measured in phase one varied among all of the bridge designs. The average forces for the Warren truss ranged from -6.88N to -14N. The average forces for the Pennsylvania truss ranged from 0.01N to -1.99N while the Parker truss had an average range of 0.46N to - 0.81N.

The Pratt truss, however, had an average value of all 3 runs between -1.08N and -3.39. This proved that the Pratt truss had the lowest variance among all truss designs, highlighting its ability to equally distribute weight among all members of the structure. After further inspection of the data, however, the Pennsylvania Truss could have also been considered as the best choice with a relatively low force value after Run 1 of -0.06348N. This low force value indicated that each beam of the truss better distributed weight during testing. However, this phase testing was only on a scale model.

Once the respective bridges were built in Bridge Designer 2016, more quantitative data was available and more customizability was added to our designs. Additionally, in phase two of testing, each truss design had a different force to strength ratio, resulting in different safety ratings. This could be attributed to the variety of different materials and slenderness used for each member of the beam. The Warren, Parker, and Pennsylvania Trusse's all held average safety factor values above 2.0, but when compared to the Pratt Truss, these higher safety values were not worth the additional cost.While more optimization could have potentially occurred in the Bridge Designer 2016 software, time constraints prevented further testing to be done.

6 Conclusion

In conclusion the pratt truss was best suited for the job as it offered an average safety factor of 1.91 at a low cost of $314,947.28. An average Force:Strength ratio for tensile forces of around 0.371 ensured that the bridge will not try and rip itself apart, while an average Force:Strength ratio for compression forces of around 0.678 ensures the bridge's beams will not not collapse under the weight of itself and vehicles. Additionally, the Pratt truss had one of the lowest variance between the forces in each run, which proved to evenly distribute weight evenly across the entire truss.

A cost of $314,000 ensured that the bridge is cost effective and light on material. The low amount of material supplemented by the use of hollow members also ensured that maintenance costs and initial construction costs are kept low, resulting in a lower long-term cost as compared to other truss designs.

6.1 Future work

Besides building bridges, truss designs can also be used for constructing industrial and residential complexes to name a few applications.

Different weights should be tested in the lab component to study if increased forces are negatively managed by each of the respective truss designs. Also, more iterations could be done to find a more optimal force:strength ratio and safety rating which are extremely close to 0.5 and 2.0 respectively.

Future designs could be tested using piers and abutments to focus on their impact on the strength and safety on bridges using truss designs made impractical due to excessive tensile or compressive forces. Additionally, the use of other materials like timber and aluminum alloy should also be used to understand their shortcomings in maintaining a stable bridge.

Moreover, different software could also be used to test the reliability and accuracy of each software's algorithms. Different software have their own unique features which can be used to observe any differences in the final design. Also, environmental concerns should also be taken into consideration while constructing these colossal structures in the future.

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