PENNSTATE

School of Engineering Design, Technology and Professional Programs
213 Hammond Building
University Park, PA 16802-2701

March 30, 2016

Kevin R. Kline, PE, District Executive
PennDOT Engineering District 2-0
1924 Daisy Street - P.O. Box 342
Clearfield County, PA 16830

Dear Mr. Kline:

Reference. PennDOT Engineering District 2-0, Statement of Work, subj: Concept Design for Vehicle Bridge over Spring Creek along Puddintown Road in College Township, Centre County, PA, dated September 11, 2015.

Statement of Problem. The bridge over Spring Creek along Puddintown Road has collapsed as a result of flooding and it needs to be replaced a quickly as possible to allow traffic to traverse across Spring Creek as the road is a major route to Mount Nittany Medical Center.

Objective. A new bridge needs to be designed and implemented that continuously spans the bridge so that future flooding will not destroy the bridge again.

Design Criteria. The bridge will be a continuous span of 40 meters with no piers and the deck will be made of medium strength concrete (0.23 m thick). The deck shall have an elevation of 20 meters and shall be wide enough for two lanes of traffic.

Technical Approach.

Phase 1: Economic Efficiency. The economic efficiency of the bridge was determined by the EEBD software.

Phase 2: Structural Efficiency The structural efficiency of the prototype bridge was determined by dividing the load the bridge supports at catastrophic failure by the weight of the prototype bridge.

Results.

Phase 1: Economic Efficiency. In Attachment 1, it was determined that the Howe bridge costs significantly less than its counterpart. This is due to the smaller sized steel beams that were used and the lower quality steel. As a result it is more economically efficient to go with the Howe bridge based on this value only.

Phase 2: Structural Efficiency. As shown in Attachment 2, upon testing the prototype bridges to failure, it was determined that the Howe bridge is the weaker of the two bridges in terms of structural efficiency. The results show that the Warren bridge is the better design because it had, on average, a better structural efficiency across all groups.

Best Solution. The best solution to the objective is based on the economic, structural, and design efficiencies of the Howe and Warren truss bridges, in addition to their constructability. As seen in Tables 1 and 4, the Howe truss bridge was constructed in the EEBD software for a total cost of $186,996.14 while the Warren truss bridge was constructed for $210,478.29, respectively. Therefore the Howe truss bridge was the more economically efficient bridge.

As displayed in Table 7, the range of structural efficiency values for the Howe truss bridge was 354, while the average value for all design teams was 334 and the geomean was 318. The lowest and highest structural efficiency values were 201 and 555 respectively. Referring to Table 8, the Warren truss bridge had a structural efficiency range of 925. It had a mean value of 475 and geometric mean of 418. The lowest and highest structural efficiency values were 237 and 1152 respectively. The Warren truss possessed higher structural efficiency values than those of the Howe truss bridge.

The Howe truss bridge had a design efficiency of 842, that is the cost of the bridge divided by its structural efficiency. The design efficiency of the Warren truss bridge was 704. Therefore, the Warren truss bridge was the most design efficient bridge.

Finally, the constructability of the Howe and Warren truss bridges was determined based upon the material, connection, and product costs from the EEBD software. The Howe truss bridge had a material cost of $84,596.14, a connection cost of $16,000 and a product cost of $9,000 as seen in Table 1. The result was a $109,596.14constructability cost for the Howe truss bridge. Likewise, the Warren truss bridge had a material cost of $71,632.49, a connection cost of $16,800 and a product cost of $12,000 as seen in Table 4. The result was a $133,078.29 constructability cost for the Warren truss bridge.

After analysis of the economic, structural, and design efficiencies of the Howe and Warren truss bridges, in addition to their constructability, the best solution was determined to be the Warren truss bridge. It costs approximately $25,000 more than the Howe bridge based on the economic efficiencies from the EEBD software; however, through load testing, the Warren truss bridge was found to have over a 1.4x better average structural efficiency than the Howe truss bridge. In addition, the design efficiency of the Warren truss bridge was determined to be nearly 1.2x better than that of the Howe bridge when cost and structural efficiency were factored in. As a result, the Warren truss bridge is the best solution.

Conclusions and Recommendations. Through careful research, designing and testing, the Warren bridge is the better through truss bridge to span Spring Creek in place of the bridge that has just collapsed. This design has the overall better design efficiency at price per structural efficiency unit. This makes it a reliable candidate because it will be able to withstand the traffic going across it and it will be the cheapest alternative. In order to move this process forward, a full, descriptive design will have to be constructed upon approval of PennDOT.

Respectfully,

Adam Bahl
Engineering Student
EDSGN100 Section 2
Design Team 3
Design Team Good Enough
College of Engineering
Penn State University

Nur Adilah Aljunid
Engineering Student
EDSGN100 Section 2
Design Team 3
Design Team Good Enough
College of Engineering
Penn State University

John Spagnola
Engineering Student
EDSGN100 Section 2
Design Team 3
Design Team Good Enough
College of Engineering
Penn State University

Logan Fries
Engineering Student
EDSGN100 Section 2
Design Team 3
Design Team Good Enough
College of Engineering
Penn State University

ATTACHMENT 1

Phase 1: Economic Efficiency

Howe Truss. The economic efficiency of the Howe truss bridge was determined by the EEBD 2015 software. The software accounted for all costs of the bridge, including material cost, connection cost, product cost, and site cost. As seen in Table 1, carbon steel hollow tube, quenched and tempered steel solid bar, and quenched and tempered steel hollow tube were the materials used in the construction of the trusses. These were counted as material cost (M). The carbon steel tube cost $6.30 per kilogram. 1601.8 kilograms were used which resulted in a cost of $16,390.81. The quenched and tempered steel bar cost $6.00 per kilogram. 3077.2 kilograms were used which resulted in a cost of $18,463.20. The quenched and tempered steel tube cost $7.70 per kilogram. 6460 kilograms were used which resulted in a cost of $49,742.13. The final material cost was $84,596.14. Between the three different material types used on the trusses, there were nine differently dimensioned tubes and bars that were used. The product cost for each differently dimensioned piece was $1000. As a result the product cost (P) was 9,000 dollars.

There were 40 total connections between the two trusses with each connection costing $400. The resulting connection cost (C) was $16,000. The site cost for the bridge included the deck cost, the excavation cost, and the abutment cost. The deck consisted of 10 4-meter panels that cost $4,700. The deck cost was $47,000 as a result. Every cubic meter that was excavated cost one dollar. The 19,400 cubic meters that were excavated resulted in an excavation cost of $19,400. Each abutment on either side of the bridge cost $5,500 therefore the total abutment cost was $11,000. The total site cost (S) was $77,400. The sum of the material, product, connection, and site costs resulted in a total cost of $186,996.14 for the Howe truss bridge.

Warren Truss. Based on the Engineering Encounter Bridge Counter 2015(EEBD 2015), the total cost (T) of building the warren truss bridge is $210,478.29. T is calculated from the addition of material cost (M), connection cost(C), product cost(P), and site cost(S). Contributions of each costs to T are as follows, 50% of M, 8% of C, 5% of P, and 37% of S.

Since the materials used for the warren truss are Carbon Steel Solid Bar (CSB), Carbon Steel Hollow Tube (CST), and Quenched & Tempered Steel Hollow Tube(QTS), therefore M is calculated from the addition of these three materials. The material that contributes the highest cost is QTS where the cost is $7.70 per kg and since ~57% of the weight of the bridge comes from QTS thus causes ~69% of M is the cost of QTS.

C is calculated through the product of the number of joints, cost per joints and the number of trusses. For warren truss particularly, there are 20 joints in each truss which make the total of 40 joints since the bridge consists of two trusses.

P is calculated from the production cost of materials used. Each of the materials has different dimension. QTS has 7 different dimensions (100x100x5mm, 120x120x6 mm, 140x140x7 mm, 160x160x8 mm, 180x180x9 mm, 200x200x10 mm, 240x240x12 mm) CSB has 2 different dimensions (120x120 mm, 130x130 mm) and CST has 3 different dimensions (100x100x5 mm, 120x120x6 mm, 130x130x6mm). However, the cost of every different dimensions are still the same which $1000.00.

S is calculated by the addition of Deck Cost, Excavation Cost and Abutment Cost. Deck cost has the highest contributions to S by ~61%.

ATTACHMENT 2

Phase 2: Structural Efficiency

Howe Truss.

Prototype Bridge. Popsicle sticks, Elmer's glue, hot glue, and binder clips were the materials used in the construction of the Howe Truss Bridge prototype. The process began with a rough sketch of the bridge, accompanied by a temporary placement of Popsicle sticks to get a 3D viewpoint of the desired bridge design. Following a final mock bridge design, it was concluded that the bridge would require 48 Popsicle sticks and would be 8 inches long by 4 inches high. Construction of the prototype bridge began with the outer edges of the bridge to assure proper dimensions and the simplified future additions of the trusses. Each Popsicle stick was attached using Elmer's glue and a binder clip was placed over the glued joint to maximize the molding. The edges of the Popsicle sticks were sanded extensively to increase the surface area for glue to attach the sticks to one another. The addition of each member was measured and marked to assure symmetry in order to stabilize the weight of the bridge. As seen in Figure 3, 20 Popsicle sticks were used on one side of the bridge. After the first side's completion, an exact replica of process, dimensions, and joints was created to form the second side of the bridge. This also required 20 Popsicle sticks. After the two sides were completed, hot glue and 8 Popsicle sticks were used to connect the two trusses together and finalize the prototype. 4 Popsicle sticks were used on the top of the bridge, and the popsicles were arranged horizontally such that the load test could fit comfortably and evenly on top of the bridge during testing. On the bottom, 4 Popsicle sticks were aligned with the top 4 using hot glue at the joints. This concluded construction of the prototype bridge, which can be seen in Figure 3.

Load Testing. As seen from Table 7, the load testing results for EDSGN100 design teams ranged from 32.6 to 101.1 pounds. Group 3 and Group 8 tied for the lowest amount of weight held by the prototype bridges at 32.6 pounds. The two groups also presented the lowest weight of the bridge prior to load testing at 66.6 pounds and 73.7 grams, respectively. Groups 1, 2, 4 and 5 had similar load testing results ranging between 52.3 pounds and 66.7 pounds. This consisted of about half a bucket of poured sand. Group 6 held an impressive 101 pounds, weighing in at the second highest amongst all other groups. During the load testing, tools and other objects were used on top of the full bucket of sand that hung below the bridge.

Group 3's structural efficiency, load at failure divided by the weight of the bridge, was 222. This number lay in the lower percentage of structural efficiencies compared to other EDSGN 100 design teams, which had a mean of 334. The structural efficiencies ranged from 201 to 555. The minimum of 201 was a result of Group 8's poor load testing outcome. A trend can be seen in Table 7, where the heavier bridges seemed to carry more weight and have a higher structural efficiency. The two lightest bridges held the lowest structural efficiencies. Also, the top structural efficiencies were given by the bridges were the heaviest. It would be expected that the design of the bridge would directly correlate to the effectiveness of it, but as seen through the load testing results, the weight of the bridge has a very large impact on the overall results of the bridge.

Forensic Analysis. The Howe Truss bridge had two major flaws, which lead to the failure of the bridge. First, was the uneven distribution of weight due to very slight faults at the two ends of the bridge. The Popsicle sticks were measured correctly and matched the mock bridge design exactly. However, what was not taken into consideration was the plane at which the Popsicle sticks would reside on at the end joints. It was planned to connect them by gluing the two sticks one on top of the other, but after construction, the two Popsicle sticks were found to be on the same plane. Thus, a Popsicle stick was cut to act as a joint, connecting the two Popsicle sticks at the end. This connection can be seen in Figure 3. The issue with this was that it caused most of the weight to be directly put on the outer Popsicle sticks on each end instead of the even combination all Popsicle sticks throughout the bridge. As the load weight was increased, the added joint was not able to support the bridge and resulted in a failure, as seen in Figure 4. The bridge failed at 4 spots on the right end of the bridge, causing it to completely detach from the rest of the bridge. The horizontal bottom Popsicle stick connecting the two sides of the bridge shot down and the truss followed not far behind. On the left side, the added end joint, along with the two Popsicle sticks attached to it, failed as a unit and detached from the bridge.

The second flaw was the fact that the bridge was simply too light. There were only 48 Popsicle sticks used, which is a small amount given the capability to use up to 60 total. This resulted in a bridge that was non-supportive of itself. If there happened to be one minor flaw in calculation, construction, or in the Popsicle stick itself, the bridge was not able to back itself up. There was no support for each Popsicle stick. If one failed, the entire bridge failed. It can be seen in Figure 4 that there was not one Popsicle stick that is separated, missing, or broken. There are many failures throughout the bridge, which all escalated from the root cause of poor weight distribution as mentioned earlier. If there were more support for the end joints, a failure may have been prevented or delayed.

Results. The prototype Howe bridges have the lowest geomean weight held of the two types of bridges as shown in Table 7. The structural efficiencies of the Howe bridges is also much lower as shown in Figure 7. As a result of this, there is the Howe bridge is the weaker of the two and is not as effective.

Warren Truss.

Prototype Bridge. The standard (4-1/2 x 3/8 x 1/12 inch) wooden (white birch) Popsicle (craft) sticks and Elmer's white glue only were the main materials used for the warren truss. Hot glue was used only to attach no more than eight (8) struts/floor beams between the two adjacent truss sections. The bridge was first built by differentiated the Popsicle stick and classified each of them best on their features (best, moderate, bad). The best Popsicle stick will be the bottom cord and the vertical. All the bad Popsicle sticks were left to be the top chord. Each of the Popsicle sticks were glued together and clamps were used to ensure that there is no gap between the sticks. After being glued, they were left for a week to let chemical reaction to occur thus ensuring the sticks closely intact to each other. The final touch to the bridge was gluing the top chord by using the hot glue. Finally, the warren truss has the dimensions of 13.5 inches in length, 4-1/8 inches in height and width. The weight of the warren truss is 73g.

Load Testing. The structural efficiency of group 3 warren truss is 299.50. The SE of group 3 is below the average since the average is 415.35. The minimum SE of Section 002 (EDSGN100) is 237.18 while the highest is 732.90. Thus the range of SE is 273.18<SE<732.90.

design team #	height (inches)	width (inches)	length (inches)	actual bridge weight (grams)	load at failure (grams)	structural efficiency
1	4.000	4.250	13.25	80.10	27079.46	338.07
2	4.000	4.250	13.25	78.60	18642.65	237.18
3	4.125	4.125	13.50	73.00	21863.15	299.50
4	3.750	4.500	13.50	57.60	24539.35	426.03
5	4.000	4.000	13.50	73.90	34835.89	471.39
6	4.000	4.111	13.50	82.50	60463.86	732.90
7	4.000	4.250	13.50	72.60	29211.35	402.36
				Average structural efficiency		415.35

Forensic Analysis. Upon failure of the bridge, the cause of the failure was analyzed. It is concluded that the bridge underwent torque stress which caused the bottom chord to twist. This twisting action, which the Popsicle sticks were not designed to handle, put too much strain against the grain of the wood and caused the bottom chord to crack and then splinter as shown in Figure 6. Also upon failure, the deck was cracked at the glue joints which suggests that this torque affecting the deck as well. One of the deck struts was broken off completely from both bottom chords. The torque was most likely a result from the asymmetry of the bridge as both sides did not have an equal load.

Results. The prototype Warren bridges have both the highest structural efficiency and the highest geomean of structural efficiency as show in Figure 8. Because of these values, it can be determined that the Warren bridge design was the better bridge type based on the prototype results.

TABLES

Table 1
Cost Calculation Report from Bridge Designer 2015 for the Howe Truss Bridge

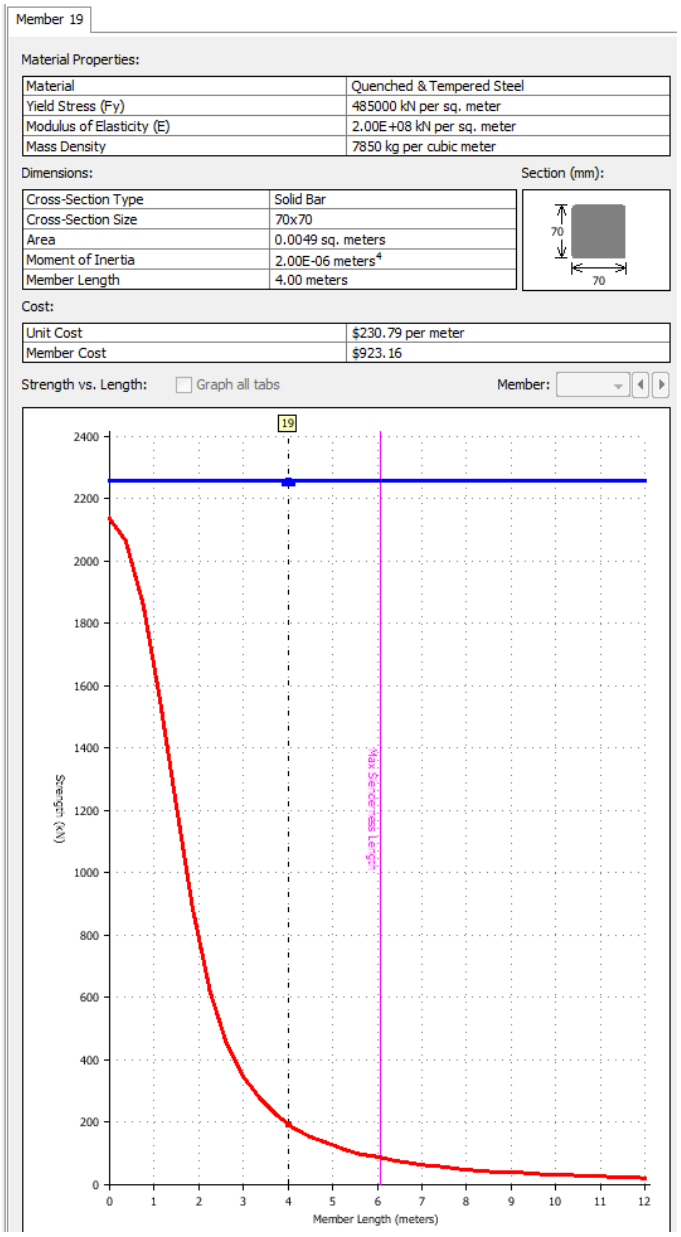
Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Carbon Steel Hollow Tube	(1300.9 kg) x ($6.30 per kg) x (2 Trusses) =	$16,390.81
	Quenched & Tempered Steel Solid Bar	(1538.6 kg) x ($6.00 per kg) x (2 Trusses) =	$18,463.20
	Quenched & Tempered Steel Hollow Tube	(3230.0 kg) x ($7.70 per kg) x (2 Trusses) =	$49,742.13
Connection Cost (C)		(20 Joints) x (400.0 per joint) x (2 Trusses) =	$16,000.00
Product Cost (P)	10 - 70x70 mm Quenched & Tempered Steel Bar	(%s per Product) =	$1,000.00
	1 - 70x70x3 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	7 - 90x90x4 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	1 - 100x100x5 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	3 - 110x110x5 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	2 - 120x120x6 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	3 - 140x140x7 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	7 - 200x200x10 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	3 - 220x220x11 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
Site Cost (S)	Deck Cost	(10 4-meter panels) x ($4,700.00 per panel) =	$47,000.00
	Excavation Cost	(19,400 cubic meters) x ($1.00 per cubic meter) =	$19,400.00
	Abutment Cost	(2 standard abutments) x ($5,500.00 per abutment) =	$11,000.00
	Pier Cost	No pier =	$0.00
	Cable Anchorage Cost	No anchorages =	$0.00
Total Cost	M + C + P + S	$84,596.14 + $16,000.00 + $9,000.00 + $77,400.00 =	$186,996.14

Table 2
Load Test Results Report from Bridge Designer 2015 for the Howe Truss Bridge

#	Material Type	Cross Section	Size (mm)	Length (m)	Compression Force	Compression Strength	Compression Status	Tension Force	Tension Strength	Tension Status
1	QTS	Hollow Tube	220x220x11	4.72	2599.36	2940.68	OK	0	4237.06	OK
2	QTS	Hollow Tube	220x220x11	4.47	2464.43	3034.68	OK	0	4237.06	OK
3	QTS	Hollow Tube	200x200x10	4.19	2279.48	2464.52	OK	0	3501.7	OK
4	QTS	Hollow Tube	200x200x10	4.12	2301.07	2488.09	OK	0	3501.7	OK
5	QTS	Hollow Tube	200x200x10	4.01	2174.41	2527.87	OK	0	3501.7	OK
6	QTS	Hollow Tube	200x200x10	4.03	2258.65	2519.86	OK	0	3501.7	OK
7	QTS	Hollow Tube	200x200x10	4.07	2242.49	2506.57	OK	0	3501.7	OK
8	QTS	Hollow Tube	200x200x10	4.27	2398.31	2436.01	OK	0	3501.7	OK
9	QTS	Hollow Tube	200x200x10	4.37	2349.84	2402.75	OK	0	3501.7	OK
10	QTS	Hollow Tube	220x220x11	4.72	2538.71	2940.68	OK	0	4237.06	OK
11	QTS	Solid Bar	70x70	4	0	195.5	OK	2204.25	2257.67	OK
12	QTS	Solid Bar	70x70	4	0	195.5	OK	2175.72	2257.67	OK
13	QTS	Solid Bar	70x70	4	0	195.5	OK	2232.37	2257.67	OK
14	QTS	Solid Bar	70x70	4	0	195.5	OK	2170.17	2257.67	OK
15	QTS	Solid Bar	70x70	4	0	195.5	OK	2175.14	2257.67	OK
16	QTS	Solid Bar	70x70	4	0	195.5	OK	2175.14	2257.67	OK
17	QTS	Solid Bar	70x70	4	0	195.5	OK	2241.21	2257.67	OK
18	QTS	Solid Bar	70x70	4	0	195.5	OK	2204.08	2257.67	OK
19	QTS	Solid Bar	70x70	4	0	195.5	OK	2245.61	2257.67	OK
20	QTS	Solid Bar	70x70	4	0	195.5	OK	2152.82	2257.67	OK
21	QTS	Hollow Tube	90x90x4	2.5	0	358.32	OK	270.96	633.99	OK
22	QTS	Hollow Tube	90x90x4	4.5	0	131.23	OK	437.71	633.99	OK
23	QTS	Hollow Tube	70x70x3	5.75	19.85	28.5	OK	303.11	370.44	OK
24	QTS	Hollow Tube	90x90x4	6.75	0	58.32	OK	470.06	633.99	OK
25	QTS	Hollow Tube	90x90x4	7	0	54.23	OK	619.27	633.99	OK

26	QTS	Hollow Tube	100x100x5	6.5	101.92	106.04	OK	301.1	875.43	OK
27	QTS	Hollow Tube	90x90x4	5.75	0	80.38	OK	423.95	633.99	OK
28	QTS	Hollow Tube	90x90x4	4.25	27.25	147.12	OK	244.66	633.99	OK
29	QTS	Hollow Tube	90x90x4	2.5	0	358.32	OK	399.5	633.99	OK
30	CS	Hollow Tube	110x110x5	6.02	83.17	166.79	OK	466.47	498.75	OK
31	CS	Hollow Tube	140x140x7	7	262.23	349.86	OK	222.6	884.45	OK
32	CS	Hollow Tube	110x110x5	7.85	92.39	98.21	OK	372.96	498.75	OK
33	CS	Hollow Tube	140x140x7	8.06	260.2	264.79	OK	222.23	884.45	OK
34	CS	Hollow Tube	110x110x5	8.06	75.82	93.02	OK	434.75	498.75	OK
35	CS	Hollow Tube	140x140x7	7.63	226.26	295.48	OK	298.11	884.45	OK
36	CS	Hollow Tube	120x120x6	7	37.11	189.36	OK	519.27	649.8	OK
37	CS	Hollow Tube	120x120x6	5.84	254.44	269.7	OK	323.12	649.8	OK

Table 3
Member Details Report from Bridge Designer 2015 for the Howe Truss Bridge
Member with the Highest Compression Force/Strength Ratio



Member 19

Material Properties:

Material	Quenched & Tempered Steel
Yield Stress (Fy)	485000 kN per sq. meter
Modulus of Elasticity (E)	2.00E+08 kN per sq. meter
Mass Density	7850 kg per cubic meter

Dimensions:

Cross-Section Type	Solid Bar
Cross-Section Size	70x70
Area	0.0049 sq. meters
Moment of Inertia	2.00E-06 meters^4
Member Length	4.00 meters

Section (mm):

Cost:

Unit Cost	$230.79 per meter
Member Cost	$923.16

Strength vs. Length: Graph all tabs Member:

Table 4
Cost Calculation Report from Bridge Designer 2015 for the Warren Truss Bridge

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Carbon Steel Solid Bar	(3027.0 kg) x ($4.30 per kg) x (2 Trusses) =	$26,031.86
	Carbon Steel Hollow Tube	(524.9 kg) x ($6.30 per kg) x (2 Trusses) =	$6,613.94
	Quenched & Tempered Steel Hollow Tube	(4651.5 kg) x ($7.70 per kg) x (2 Trusses) =	$71,632.49
Connection Cost (C)		(21 Joints) x (400.0 per joint) x (2 Trusses) =	$16,800.00
Product Cost (P)	2 - 100x100x5 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	4 - 100x100x5 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	2 - 120x120 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	2 - 120x120x6 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	4 - 120x120x6 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	4 - 130x130 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	2 - 130x130x6 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	6 - 140x140x7 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	2 - 160x160x8 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	2 - 180x180x9 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	4 - 200x200x10 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	5 - 240x240x12 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
Site Cost (S)	Deck Cost	(10 4-meter panels) x ($4,700.00 per panel) =	$47,000.00
	Excavation Cost	(19,400 cubic meters) x ($1.00 per cubic meter) =	$19,400.00
	Abutment Cost	(2 standard abutments) x ($5,500.00 per abutment) =	$11,000.00
	Pier Cost	No pier =	$0.00
	Cable Anchorage Cost	No anchorages =	$0.00
Total Cost	M + C + P + S	$104,278.29 + $16,800.00 + $12,000.00 + $77,400.00 =	$210,478.29

Table 5
Load Test Results Report from Bridge Designer 2015 for the Warren Truss Bridge

#	Material Type	Cross Section	Size (mm)	Length (m)	Compression Force	Compression Strength	Compression Status	Tension Force	Tension Strength	Tension Status
1	QTS	Hollow Tube	180x180x9	2.83	1970.39	2273.53	OK	0	2836.38	OK
2	QTS	Hollow Tube	140x140x7	4	0	935.47	OK	1393.27	1715.83	OK
3	QTS	Hollow Tube	100x100x5	2.83	0	482.58	OK	768.16	875.43	OK
4	QTS	Hollow Tube	200x200x10	4.37	2113.66	2402.75	OK	0	3501.7	OK
5	QTS	Hollow Tube	160x160x8	4	0	1390.76	OK	2036.68	2241.09	OK
6	QTS	Hollow Tube	200x200x10	3.76	2557.2	2612.12	OK	0	3501.7	OK
7	QTS	Hollow Tube	240x240x12	4.25	3251.52	3863.49	OK	0	5042.45	OK
8	QTS	Hollow Tube	240x240x12	4	3712.35	3958.27	OK	0	5042.45	OK
9	QTS	Hollow Tube	240x240x12	4	3858.99	3958.27	OK	0	5042.45	OK
10	QTS	Hollow Tube	240x240x12	4	3691.85	3958.27	OK	0	5042.45	OK
11	QTS	Hollow Tube	240x240x12	4	3210.58	3958.27	OK	0	5042.45	OK
12	QTS	Hollow Tube	200x200x10	4.01	2498.3	2527.87	OK	0	3501.7	OK
13	QTS	Hollow Tube	200x200x10	4.37	2065.15	2402.75	OK	0	3501.7	OK
14	QTS	Hollow Tube	180x180x9	2.83	1925.21	2273.53	OK	0	2836.38	OK
15	CS	Hollow Tube	120x120x6	4.25	367.83	397.41	OK	86.39	649.8	OK
16	QTS	Hollow Tube	120x120x6	4.25	0	510.95	OK	1094.07	1260.61	OK
17	QTS	Hollow Tube	140x140x7	4.37	785.1	841.58	OK	0	1715.83	OK
18	QTS	Hollow Tube	120x120x6	4.59	0	441.08	OK	1005.97	1260.61	OK
19	QTS	Hollow Tube	140x140x7	4.47	694.23	814.77	OK	0	1715.83	OK
20	QTS	Hollow Tube	100x100x5	4.47	0	224.01	OK	687.52	875.43	OK
21	CS	Hollow Tube	130x130x6	4.47	401.32	444.49	OK	67.08	706.8	OK
22	CS	Hollow Tube	100x100x5	4.47	73.43	212.76	OK	394.97	451.25	OK
23	CS	Hollow Tube	100x100x5	4.47	109.05	212.76	OK	359.35	451.25	OK
24	CS	Hollow Tube	130x130x6	4.47	365.7	444.49	OK	102.7	706.8	OK
25	QTS	Hollow Tube	100x100x5	4.47	0	224.01	OK	651.9	875.43	OK

26	QTS	Hollow Tube	140x140x7	4.47	658.44	814.77	OK	0	1715.83	OK
27	QTS	Hollow Tube	120x120x6	4.47	0	464.52	OK	944.47	1260.61	OK
28	QTS	Hollow Tube	140x140x7	4.47	783.95	814.77	OK	0	1715.83	OK
29	QTS	Hollow Tube	120x120x6	4.25	0	510.95	OK	1074.09	1260.61	OK
30	CS	Hollow Tube	120x120x6	4.25	353.66	397.41	OK	122.75	649.8	OK
31	QTS	Hollow Tube	100x100x5	2.83	0	482.58	OK	750.48	875.43	OK
32	CS	Solid Bar	120x120	4	0	1606.24	OK	2758.33	3420	OK
33	CS	Solid Bar	130x130	4	0	2091.29	OK	3404.89	4013.75	OK
34	CS	Solid Bar	130x130	4	0	2091.29	OK	3707.38	4013.75	OK
35	CS	Solid Bar	130x130	4	0	2091.29	OK	3723.31	4013.75	OK
36	CS	Solid Bar	130x130	4	0	2091.29	OK	3425.33	4013.75	OK
37	CS	Solid Bar	120x120	4	0	1606.24	OK	2813.22	3420	OK
38	QTS	Hollow Tube	160x160x8	4	0	1390.76	OK	2014.75	2241.09	OK
39	QTS	Hollow Tube	140x140x7	4	0	935.47	OK	1361.33	1715.83	OK

Table 6
Member Details Report from Bridge Designer 2015 for the Warren Truss Bridge Member with the Highest Tension Force/Strength Ratio

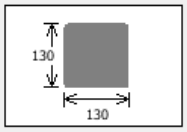
Material Properties:

Material	Carbon Steel
Yield Stress (Fy)	250000 kN per sq. meter
Modulus of Elasticity (E)	2.00E+08 kN per sq. meter
Mass Density	7850 kg per cubic meter

Dimensions:

Cross-Section Type	Solid Bar
Cross-Section Size	130x130
Area	0.0169 sq. meters
Moment of Inertia	2.38E-05 meters^4
Member Length	4.00 meters

Section (mm):



Cost:

Unit Cost	$570.46 per meter
Member Cost	$2281.84

Strength vs. Length: Graph all tabs Member:

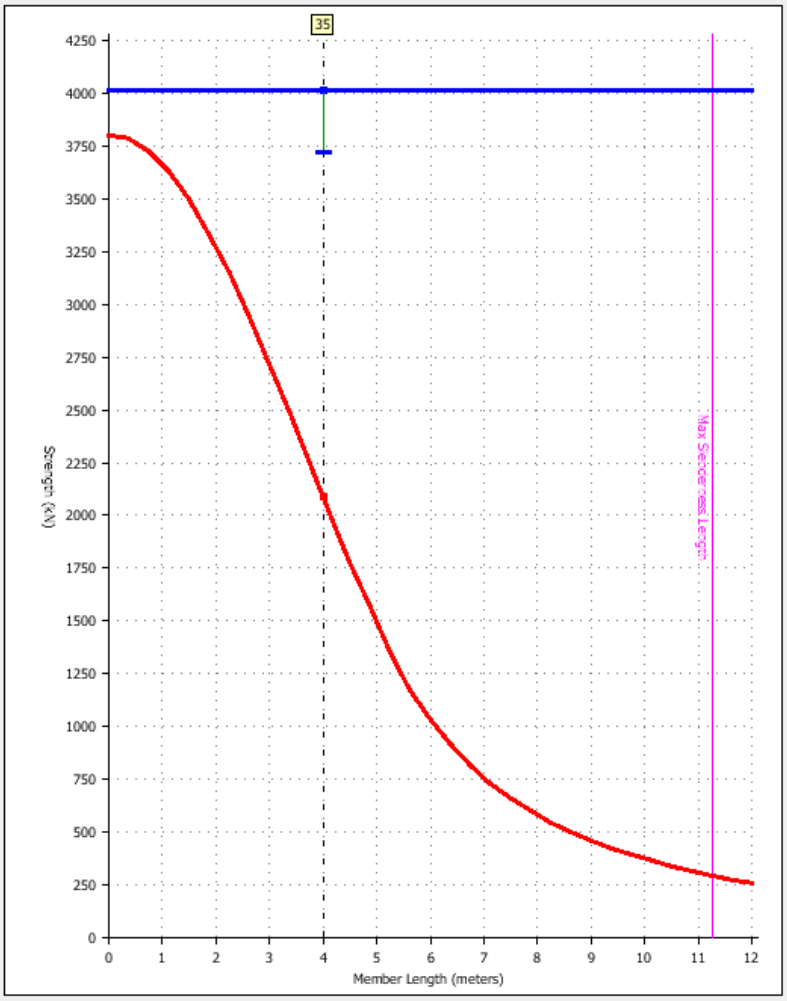


Table 7
Load Testing Results for the Howe Truss Bridge

Design Team	Weight (grams)	Load at Failure (pounds)	Weight (pounds)	Structural Efficiency		
1	83.8	65.3	0.185	353	334	Mean
2	80.8	57.4	0.178	322	322	Median
3	66.6	32.6	0.147	222	555	Max
4	80.8	66.7	0.178	374	201	Min
5	76.4	52.3	0.168	311	318	Geometric Mean
6	82.6	101.1	0.182	555		
8	73.7	32.6	0.162	201		

Table 8
Load Testing Results for the Warren Truss Bridge

Design Team	Weight grams	Load at Failure (pounds)	Weight (pounds)	Structural Efficency		
1	80.1	59.7	0.177	338	475	Mean
2	78.6	41.1	0.173	237	402	Median
3	73	48.2	0.161	299	1152	Max
4	57.6	54.1	0.127	426	237	Min
5	73.9	76.8	0.163	471	418	Geometric Mean
6	52.5	133.3	0.116	1152		
8	72.6	64.4	0.160	402		

FIGURES

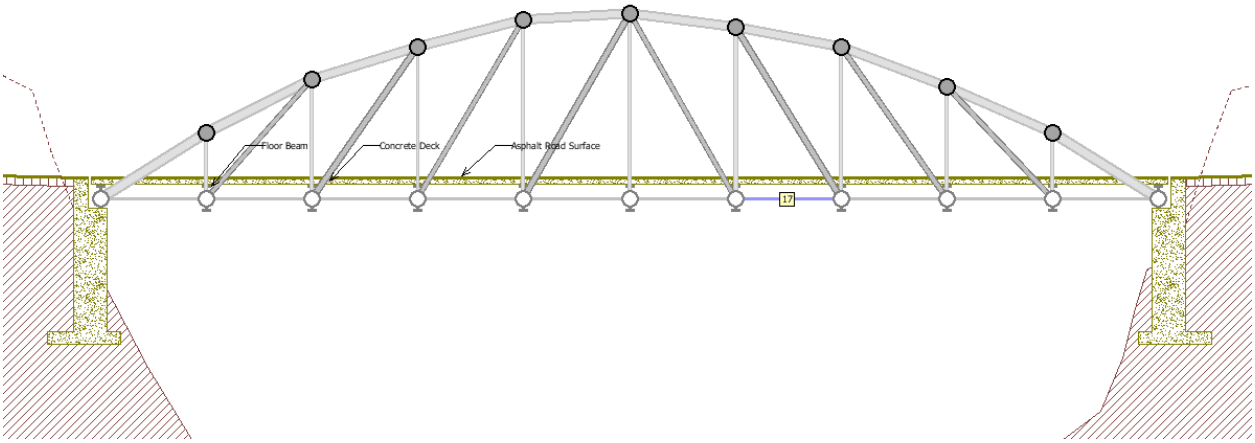


Figure 1. Howe Bridge Model from Bridge Designer 2015

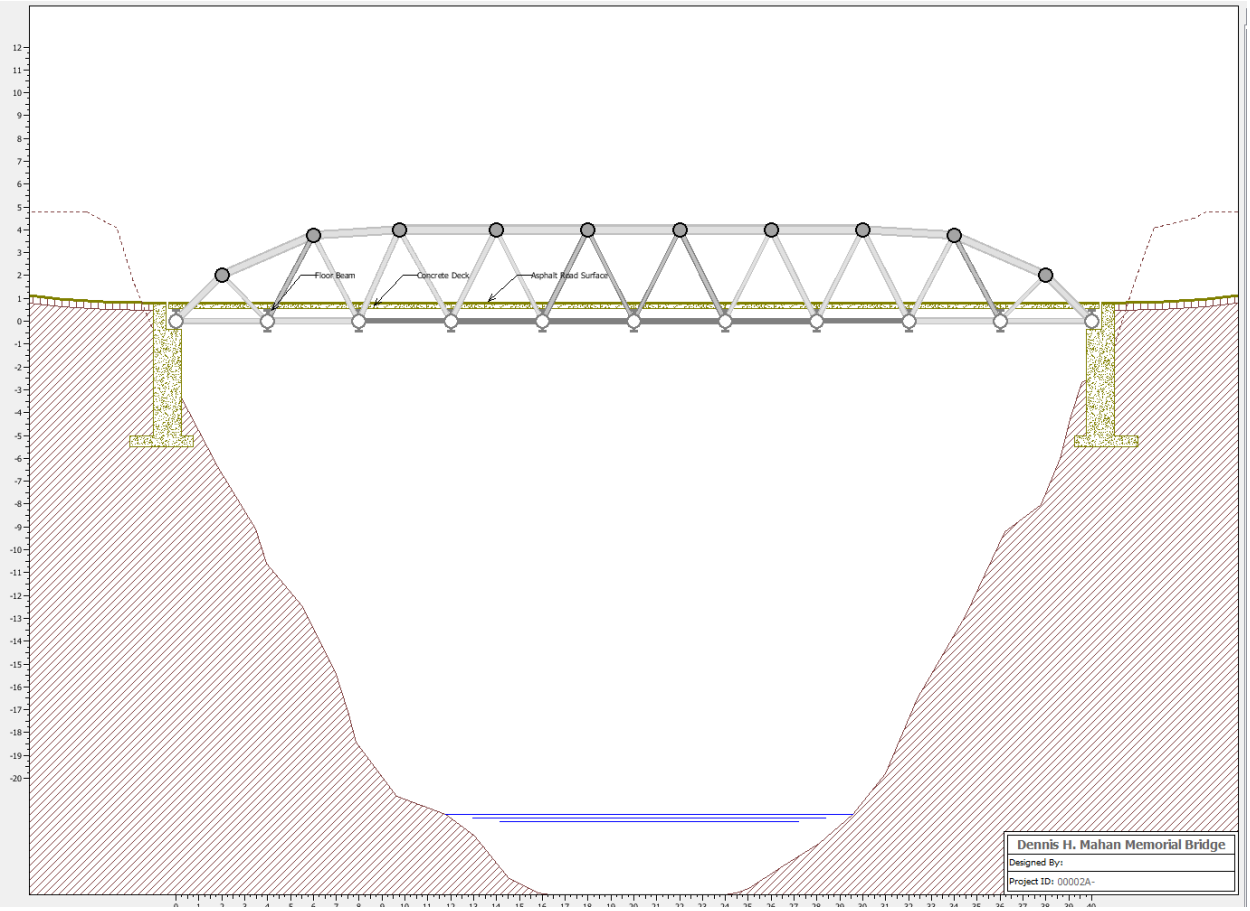


Figure 2. Warren Bridge Model from Bridge Designer 2015

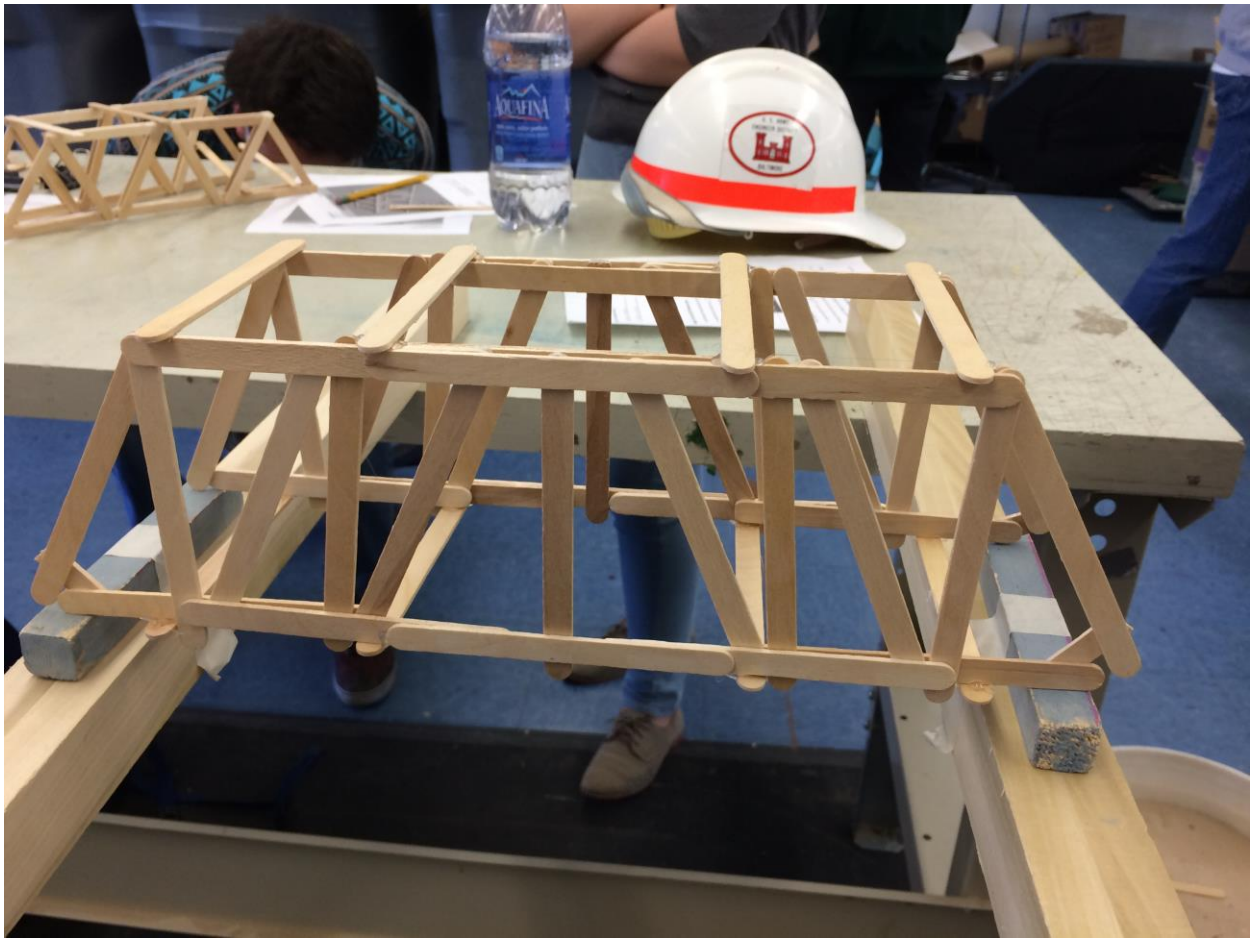


Figure 3. Howe Truss Bridge Prototype before Load Testing

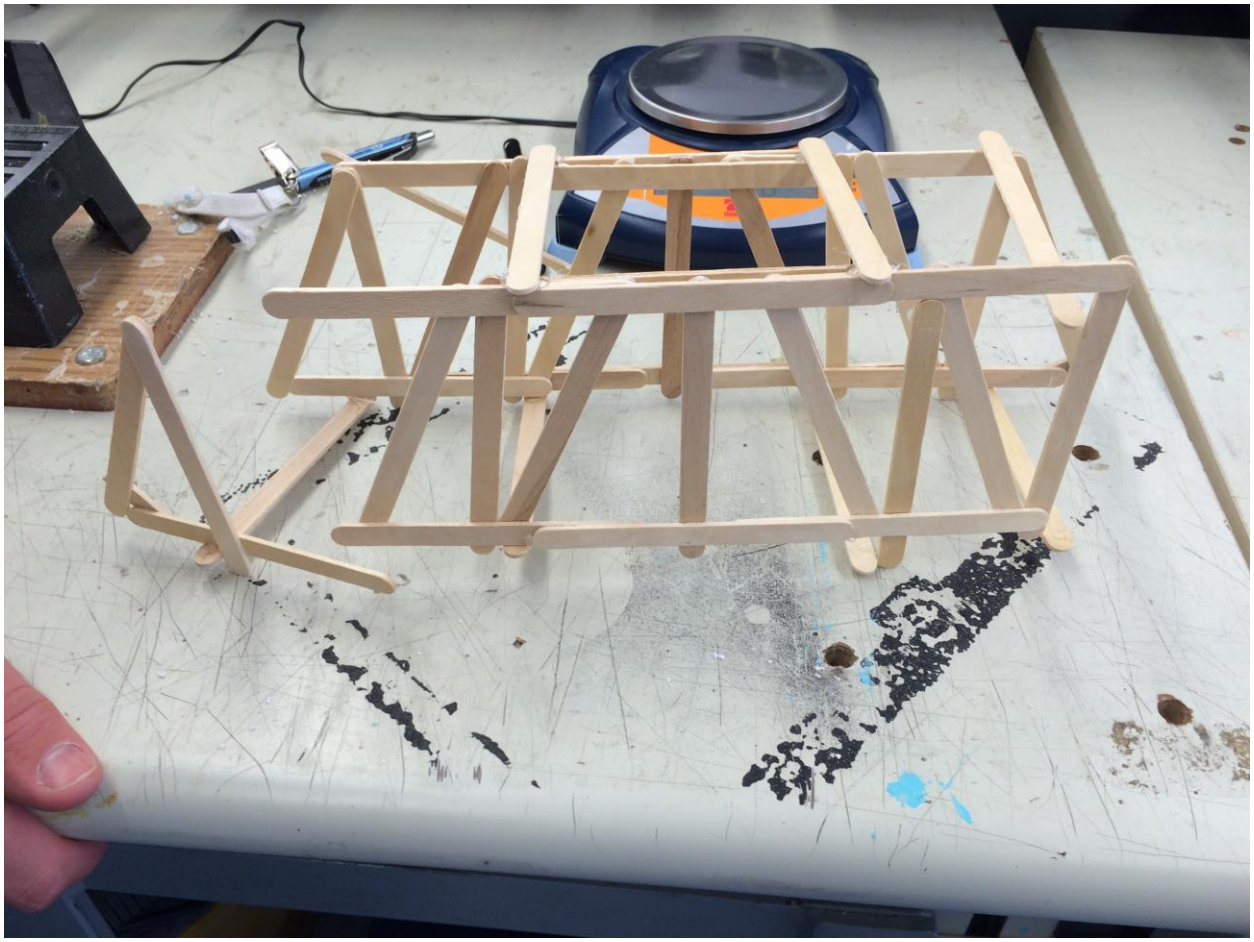


Figure 4. Howe Truss Bridge Prototype Failure after Load Testing

Figure 5. Warren Truss Bridge Prototype before Load Testing

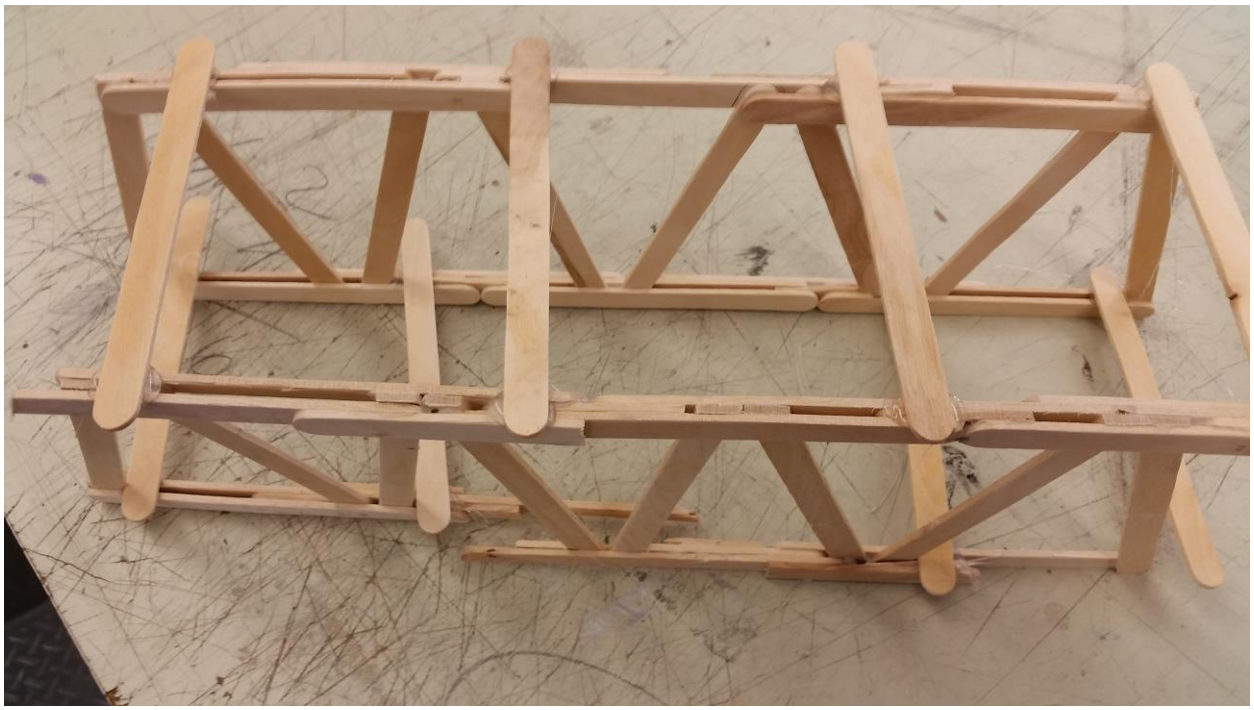


Figure 6. Warren Truss Bridge Prototype Failure after Load Testing

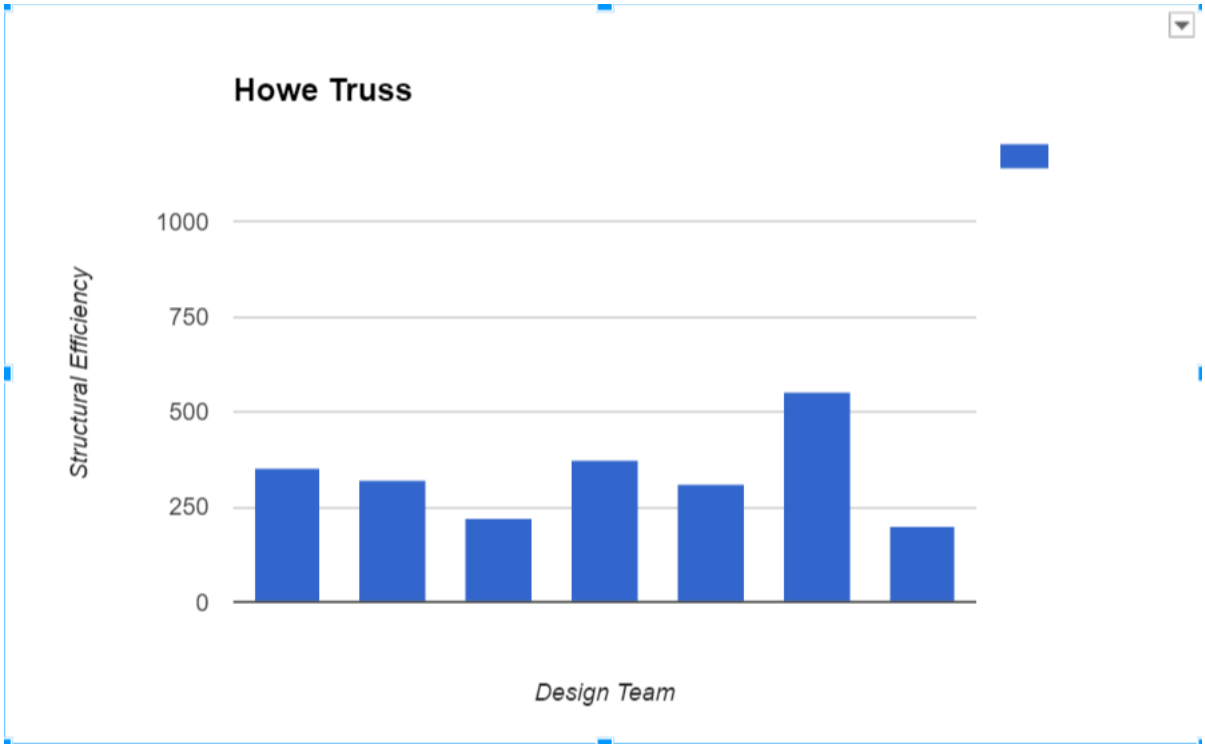


Figure 7. Howe Truss Bridge Structural Efficiencies

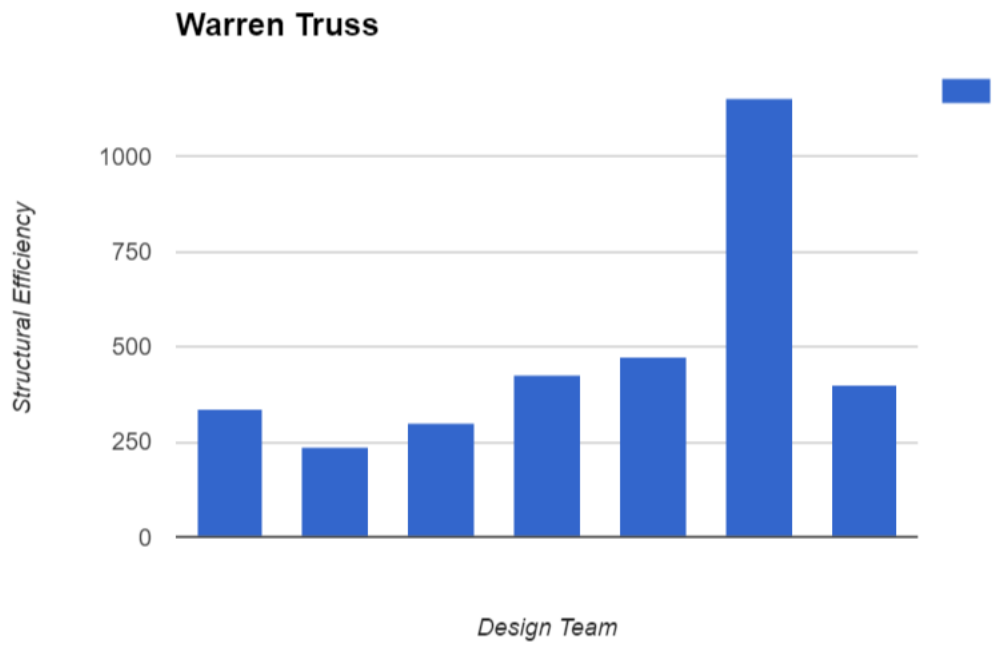


Figure 8. Warren Truss Bridge Structural Efficiencies