PENNSTATE

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March 24, 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. A bridge over Spring Creek along Puddintown Road in College Township, Centre County (PA) recently collapsed due to local flooding. This bridge is part of an essential roadway that provides the citizens of College Township and beyond with easy access to necessary amenities, including the Mount Nittany Medical Center. Local traffic is now disrupted and re-routed, making State College residents under several difficulties.

Objective. To create an effective replacement for the bridge quickly and efficiently to restore normal traffic flow and safer conditions.

Design Criteria. According to PennDOT District 2-0, both the designed Warren and Howe bridges should have standard abutments, no piers (one span), medium strength concrete for deck material, no cable anchorages, and must be able to support two AASHTO H20-44 trucks (225kN of Force) (one in each lane). The deck elevation should be 20 meters and the bridge span should be 40 meters. Other criteria are selected by the EDSGN 100 team.

Technical Approach.

Phase 1: Economic Efficiency. The economic efficiency of the bridge will be determined by using the Bridge Designer 2016 software based on the criteria listed below.

The Bridge Designer 2016 software is used to perform a systematic and iterative analysis for the design of the optimized Warren and Howe Through Truss bridges to keep their costs as low as possible as well as ensure that the bridges can handle the combination of their own weight (dead load) and the standard truck loading (live load).

Phase 2: Structural Efficiency. Prototypes of both the Howe and Warren truss bridges will be tested in a lab to catastrophic failure. The truss bridge type that exhibits the best

structural efficiency, which is determined by dividing the load that the bridge supports by the weight of the prototype itself, will be determined from the results of the testing. The objective of the lab is to decide and report on which prototype is the most effective at dissipating the load. The bridge prototypes will be constructed using no more than 60, 4-1/2 x 3/8 x 1/12 inch standard white birch popsicle sticks. The popsicle sticks were connected by Elmer's white glue for all structural members, and the struts were connected by hot glue.

The testing for the prototypes will involve loading the top center chords of the bridge with a loading block that will be attached to a dead load. Beforehand, an estimate of the bridge weight will be performed based on a weight study of the elements that compose the prototype. However, all prototypes will be accurately measured directly before they are load tested. The load that caused them to fail will then be measured on a scale right after the bridge fails.

The design team must then conduct a thorough investigation of the causes of their bridges' failure. The investigation shall explore why, where, and how the bridges failed. The investigation should be documented with photographs sketches, measurements, analyses, and by any other means that the design team finds suitable for their analysis. All of the members should be identified before the bridge fails to make for an easier investigation upon failure. After the cause of the failure is determined, a recommendation for design improvement should be issued.

Results.

Phase 1: Economic Efficiency (see Attachment 1)

Generally the Warren bridge is more economically efficient compared to the Howe bridge (with the cost of about $207,000 and $214,000, respectively)

Phase 2: Structural Efficiency(see Attachment 2)

Overall, through load testing results, the Warren bridges is more structurally efficient than the Howe bridges.

Best Solution.

Through analysis of economic efficiencies, the Warren bridge is shown to be a better decision. The Warren bridge has the lower overall, production and material cost but higher connection cost due to the greater number of joints. (see Tables 1 and 4)

The Warren bridge is also structurally more efficient. Both the geomean and arithmetic means are greater for the Warren bridge, demonstrating a superiority in structural efficiency. In addition, one of the Warren bridges of the design teams has the highest overall structural efficiency, a rating of 648. The only potential drawback is that one of the Warren bridges also has the lowest structural efficiency, 188, leading to a larger range of structural efficiency for the Warren bridges. (see in Tables 7 and 8)

Afterwards, the Warren has lower design efficiency, of $613.9/S.E compared to that of $1,104.6/S.E of the Howe bridge, as calculated by dividing the total cost by the structural efficiency. Having a lower design efficiency rating is better because each unit of structural efficiency is more economical.

Ultimately, the Warren bridge is more constructible due to its lower production cost. The Warren bridge has a product cost $1,000 lower than the Howe bridge because it employs only 7 instead of 8 different types of members. In all aspects, the Warren is proven to be a superior choice.

Conclusions and Recommendations.

After considering all of the different factors and efficiency analyses, it is clear that the Warren bridge fulfills all design criteria more effectively than the Howe bridge. It is more economical, more structurally efficient, has lower design efficiency, and is more constructible. The next steps in the process should be to have an experienced professional engineer review the design and make necessary adjustments to finalize the design.

Respectfully,

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ATTACHMENT 1

Phase 1: Economic Efficiency

Howe Truss.

The Howe bridge is generally less economically efficient than the Warren bridge, according to Tables 1 and 4.

Detailed cost calculations of the Howe bridge are presented in Table 1. The bridge is made from quenched & tempered steel and has the total cost of $214,000. While the Howe bridge has higher material costs ($108,600), it also has a lower connection cost ($16,000). Its product cost is $1,000 higher than that of the Warren bridge due to various dimensions of the members used. Finally, without pier or cable anchorage, the site cost is kept low and equal to that of the Warren ($81,400).

The virtual load test results of the Howe bridge can be referred to Table 2. The structural member with the highest compression force/strength ratio (of 0.98) is member number 24. From Figure 1, member number 24 is the third diagonal member from the leftmost chord.

Warren Truss.

The Warren bridge is generally more economical than the Howe bridge, according to Table 1 and 4.

Detailed cost calculations of the Warren bridge are presented in Table 4. Among the total cost of $207,000, the material cost is about $101,700 due to the use of quenched and tempered steel, the highest quality material. However, using the strongest material is overall more economically efficient than using lower quality materials in greater and more varied sizes. The connection cost, the total cost of the joints, is $16,800, and the product cost is $7,000 which is higher than expected because 7 different types of members are used. The site cost is kept low because there is no pier or cable anchorage cost, as per the design criteria. Finally, the costs for deck, excavation, and abutment are about $81,400.

Table 5 lists the load test results from the virtual test of the members. Member number 4 is shown with the highest compression force/strength ratio, of 0.98. Its member detail report can be found in Table 6. From Figure 2, member number 4 is the third member from the left on the top chord of the bridge. During the design process, the top and bottom chords in the middle of the bridge were found to experience the highest tension (or compression) force/strength ratio and were thus replaced with equivalent members that were greater in sizes. Hence the highest compression force/strength ratio in member 4, which is not in the middle of the bridge, is expected.

ATTACHMENT 2

Phase 2: Structural Efficiency

Howe Truss.

Prototype Bridge. A picture of the Howe bridge prior to load-testing can be found in Figures 3.

The materials used in the construction of the bridge were the wooden Popsicle sticks for chords, Elmer's glue for body joints, and hot glue for gluing struts and floor beams. The prototyped bridge consisted of 56 Popsicle sticks, with final dimensions as approximate 13.2 inches in length, 4.4 inches in width, and 4.4 inches in height.

Load Testing. The results for the Howe bridge's load testing can be found in Table 7.

To load test, the bridge was attached to a block that was attached to increasing live load. The load was gradually increased by the addition of sand and other available loads.

The prototyped bridge failed at 36.4 lbs. of sand and had structural efficiency of 194, which is below the average of 327 and the geometric mean of 299. In fact, our Howe bridge is the one with lowest structural efficiency among all the design teams.

Forensic Analysis. A picture of the Howe bridge latter to load-testing can be referred to as Figure 4.

The bridge collapsed due to a split in the middle vertical member and the breakage of the middle top and bottom chords and the floor beams on one truss. The bridge also failed at 4 other joints, including 2 of the floor beams and 2 of the struts. One main reason for the failure of the bridge is that the verticals and the diagonals in each truss weren't parallel to each other, leading to one truss exposed to more weight than the other.

Results. The structural efficiencies of all of the Howe bridges are statistically presented in Table 7, and graphically in Figure 7.

Warren Truss.

Prototype Bridge. A picture of Warren bridge before testing can be found in Figures 5.

The prototype bridge was constructed from 60 popsicle sticks as member chords and Elmer's glue for joints. Hot glue was used to secure the final 8 struts of the bridge right before testing. The horizontal top and bottom chords and the vertical members were connected by the end posts first before the diagonal members were glued together. The struts and floor beams were then originally and mistakenly connected with Elmer's glue, but it was realized that hot glue should have been used. The floor beams and struts were removed and re-glued using hot glue just twenty minutes before load testing. The final dimensions of the Warren bridge are approximately 3.8 inches high, 13.25 inches long, and 4.4 inches wide.

Load Testing. The results of load testing of all design teams can be found in Table 8.

To load test, the bridge was attached to a block that was hooked up to a live load. The load was gradually increased by adding sand, hammers, and other available loads.

As results were shown in Table 8, our Warren bridge failed at 59.9 lbs. of sand and had structural efficiency of 337 which was slightly below both the average structural efficiency rating (366) and the geometric mean (341). So overall our bridge slightly underperformed compared to the average of all design teams.

Forensic Analysis. An image of the Warren bridge after testing can be found as Figure 6.

One of the reasons the bridge failed is the lack of glue (or joint connection). As demonstrated in Figure 6, the failed joint lay in the center of the bottom chord. It was found that that joint was not glued because no glue residue was observed. The joint was able to adhere to the whole structure thanks to adjacent members and joints, but the lack of joint connection at such point led to a decrease in the whole structure integrity and the quick failure of the bridge in load testing. Another plausible reason is the wrong glue used for floor beams and struts prior to load testing. In fact, the beams and struts were removed and re-glued by hot glue about twenty minutes before load testing, so they were not dried and cured enough to sustain the whole structure.

Results. The structural efficiencies of all of the Warren bridges are statistically presented in Table 8, and graphically in Figure 8.

TABLES

Table 1
Howe Truss Bridge
Cost Calculation Report from Bridge Designer 2016

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Quenched & Tempered Steel Solid Bar	(2191.7 kg) x ($6.00 per kg) x (2 Trusses) =	26,300.64
	Quenched & Tempered Steel Hollow Tube	(5346.3 kg) x ($7.70 per kg) x (2 Trusses) =	82,333.69
Connection Cost (C)		(20 Joints) x (400.0 per joint) x (2 Trusses) =	16,000.00
Product Cost (P)	6 - 60x60 mm Quenched & Tempered Steel Bar	(%s per Product) =	1,000.00
	2 - 70x70 mm Quenched & Tempered Steel Bar	(%s per Product) =	1,000.00
	6 - 80x80 mm Quenched & Tempered Steel Bar	(%s per Product) =	1,000.00
	6 - 140x140x7 mm Quenched & Tempered Steel Tube	(%s per Product) =	1,000.00
	5 - 160x160x8 mm Quenched & Tempered Steel Tube	(%s per Product) =	1,000.00
	2 - 170x170x8 mm Quenched & Tempered Steel Tube	(%s per Product) =	1,000.00
	6 - 200x200x10 mm Quenched & Tempered Steel Tube	(%s per Product) =	1,000.00
	4 - 220x220x11 mm Quenched & Tempered Steel Tube	(%s per Product) =	1,000.00
Site Cost (S)	Deck Cost	(10 4-meter panels) x ($5,100.00 per panel) =	51,000.00
	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**	**$108,634.33 + $16,000.00 + $8,000.00 + $81,400.00 =**	**214,034.33**

Table 2.
Howe Truss Bridge
Load test Results Report from Bridge Designer 2016

#	Material Type	Cross Section	Size (mm)	Length (m)	Compression Force	Compression Strength	Compression Status	Tension Force	Tension Strength	Tension Status
1	QTS	Hollow Tube	200x200 x10	5.66	1638.75	1930.33	OK	0	3501.7	OK
2	QTS	Solid Bar	60x60	4	0	105.53	OK	1158.77	1658.7	OK
3	QTS	Solid Bar	70x70	4	0	195.5	OK	2059.45	2257.67	OK
4	QTS	Solid Bar	80x80	4	0	333.51	OK	2700.58	2948.8	OK
5	QTS	Solid Bar	80x80	4	0	333.51	OK	2465.46	2948.8	OK
6	QTS	Solid Bar	80x80	4	0	333.51	OK	2561.91	2948.8	OK
7	QTS	Solid Bar	80x80	4	0	333.51	OK	2561.91	2948.8	OK
8	QTS	Solid Bar	80x80	4	0	333.51	OK	2449.08	2948.8	OK
9	QTS	Solid Bar	80x80	4	0	333.51	OK	2659.61	2948.8	OK
10	QTS	Solid Bar	70x70	4	0	195.5	OK	1998	2257.67	OK
11	QTS	Solid Bar	60x60	4	0	105.53	OK	1126.89	1658.7	OK
12	QTS	Hollow Tube	160x160 x8	4	1158.77	1390.76	OK	0	2241.09	OK
13	QTS	Hollow Tube	200x200 x10	4	2059.45	2530.55	OK	0	3501.7	OK
14	QTS	Hollow Tube	220x220 x11	4.12	2783.69	3164.71	OK	0	4237.06	OK
15	QTS	Hollow Tube	220x220 x11	4	2465.46	3209.27	OK	0	4237.06	OK
16	QTS	Hollow Tube	220x220 x11	4	2449.08	3209.27	OK	0	4237.06	OK
17	QTS	Hollow Tube	220x220 x11	4.12	2741.47	3164.71	OK	0	4237.06	OK
18	QTS	Hollow Tube	200x200 x10	4	1998	2530.55	OK	0	3501.7	OK
19	QTS	Hollow Tube	160x160 x8	4	1126.89	1390.76	OK	0	2241.09	OK
20	QTS	Hollow Tube	200x200 x10	5.66	1593.66	1930.33	OK	0	3501.7	OK
21	QTS	Solid Bar	60x60	4	0	105.53	OK	1154.78	1658.7	OK
22	QTS	Hollow Tube	200x200 x10	5.66	1347.81	1930.33	OK	0	3501.7	OK
23	QTS	Solid Bar	60x60	4	0	105.53	OK	947.47	1658.7	OK

24	QTS	Hollow Tube	170x170 x8	5.66	1054.81	1074.13	OK	0	2388.53	OK
25	QTS	Hollow Tube	140x140 x7	4	237.99	935.47	OK	64.87	1715.83	OK
26	QTS	Hollow Tube	140x140 x7	6.4	0	419.79	OK	647.61	1715.83	OK
27	QTS	Hollow Tube	140x140 x7	5	0	685.56	OK	532.27	1715.83	OK
28	QTS	Hollow Tube	160x160 x8	6.4	422.65	716.15	OK	113.87	2241.09	OK
29	QTS	Hollow Tube	160x160 x8	5	0	1096.25	OK	569.82	2241.09	OK
30	QTS	Hollow Tube	160x160 x8	6.4	381.82	716.15	OK	154.7	2241.09	OK
31	QTS	Hollow Tube	140x140 x7	5	0	685.56	OK	500.38	1715.83	OK
32	QTS	Hollow Tube	140x140 x7	6.4	0	419.79	OK	739.41	1715.83	OK
33	QTS	Hollow Tube	140x140 x7	4	284.08	935.47	OK	56.9	1715.83	OK
34	QTS	Hollow Tube	170x170 x8	5.66	1009.72	1074.13	OK	0	2388.53	OK
35	QTS	Solid Bar	60x60	4	0	105.53	OK	915.59	1658.7	OK
36	QTS	Hollow Tube	200x200 x10	5.66	1302.71	1930.33	OK	0	3501.7	OK
37	QTS	Solid Bar	60x60	4	0	105.53	OK	1122.89	1658.7	OK

Table 3.
Howe Truss Bridge
Member Details Report from Bridge Designer 2016
Member with the Highest Compression Force/Strength Ratio

Member 24

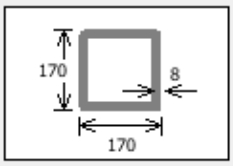
Material Properties:

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	Hollow Tube
Cross-Section Size	170x170x8
Area	0.0052 sq. meters
Moment of Inertia	2.27E-05 meters^4
Member Length	5.66 meters

Section (mm):



Cost:

Unit Cost	$313.35 per meter
Member Cost	$1772.56

Strength vs. Length: Graph all tabs Member:

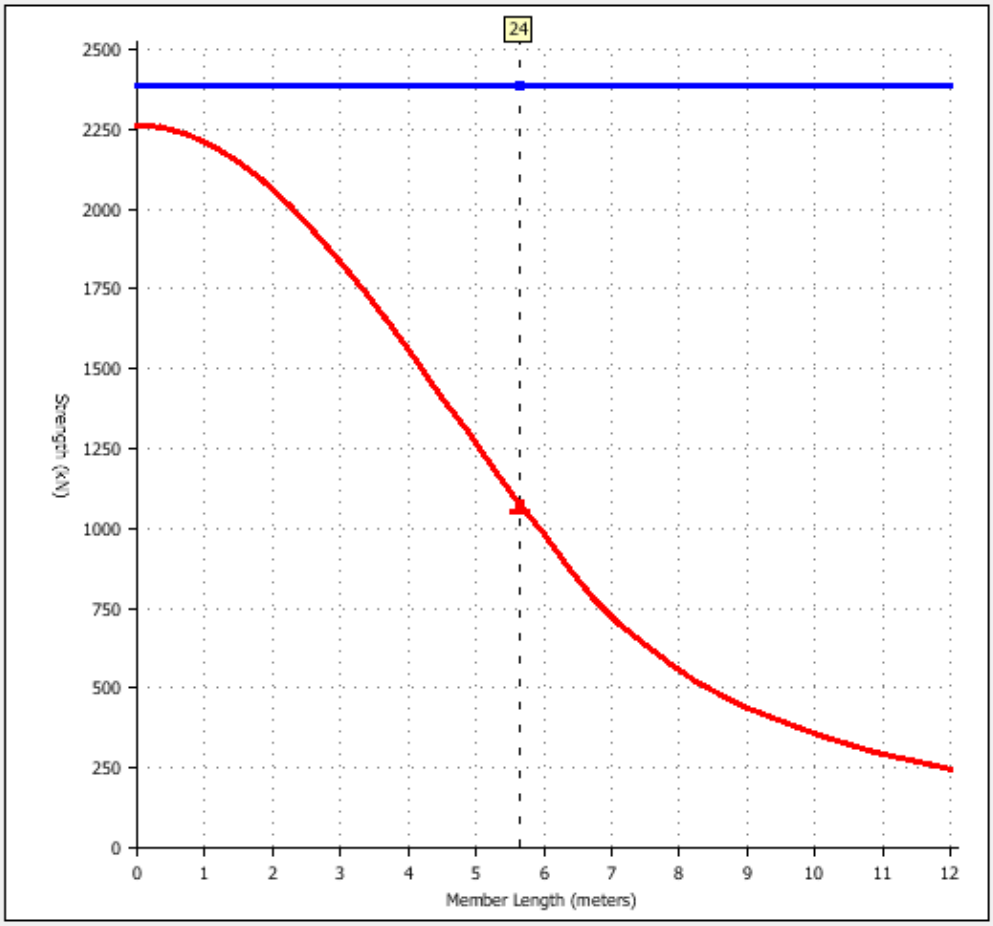


Table 4
Warren Truss Bridge
Cost Calculation Report from Bridge Designer 2016

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Quenched & Tempered Steel Solid Bar	(3399.0 kg) x ($6.00 per kg) x (2 Trusses) =	$40,788.34
	Quenched & Tempered Steel Hollow Tube	(3954.9 kg) x ($7.70 per kg) x (2 Trusses) =	$60,905.32
Connection Cost (C)		(21 Joints) x (400.0 per joint) x (2 Trusses) =	$16,800.00
Product Cost (P)	6 - 55x55 mm Quenched & Tempered Steel Bar	(%s per Product) =	$1,000.00
	12 - 80x80 mm Quenched & Tempered Steel Bar	(%s per Product) =	$1,000.00
	6 - 130x130x6 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	2 - 140x140x7 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	6 - 180x180x9 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	6 - 190x190x9 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	1 - 200x200x10 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
Site Cost (S)	Deck Cost	(10 4-meter panels) x ($5,100.00 per panel) =	$51,000.00
	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**	**$101,693.67 + $16,800.00 + $7,000.00 + $81,400.00 =**	**$206,893.67**

Table 5
Warren Truss Bridge
Load Test Results Report from Bridge Designer 2016

#	Material Type	Cross Section	Size (mm)	Length (m)	Compression Force	Compression Strength	Compression Status	Tension Force	Tension Strength	Tension Status
1	QTS	Hollow Tube	180x180 x9	4.47	1295.22	1769.4	OK	0	2836.38	OK
2	QTS	Hollow Tube	180x180 x9	4	1156.77	1923.61	OK	0	2836.38	OK
3	QTS	Hollow Tube	190x190 x9	4.12	1883.79	2071.38	OK	0	3002.25	OK
4	QTS	Hollow Tube	190x190 x9	4.12	2021.47	2071.38	OK	0	3002.25	OK
5	QTS	Hollow Tube	190x190 x9	4.12	1990.76	2071.38	OK	0	3002.25	OK
6	QTS	Hollow Tube	190x190 x9	4.12	1827.49	2071.38	OK	0	3002.25	OK
7	QTS	Hollow Tube	180x180 x9	4	1124.88	1923.61	OK	0	2836.38	OK
8	QTS	Hollow Tube	180x180 x9	4.47	1259.57	1769.4	OK	0	2836.38	OK
9	QTS	Hollow Tube	180x180 x9	4.47	1066.59	1769.4	OK	0	2836.38	OK
10	QTS	Solid Bar	55x55	4.47	0	59.61	OK	1291.4	1393.77	OK
11	QTS	Solid Bar	55x55	4.47	0	59.61	OK	550.4	1393.77	OK
12	QTS	Hollow Tube	130x130 x6	5.39	338.6	412.1	OK	83.79	1371.19	OK
13	QTS	Solid Bar	80x80	5.39	73.86	184.01	OK	271.73	2948.8	OK
14	QTS	Solid Bar	80x80	6.32	81.51	133.41	OK	339.59	2948.8	OK
15	QTS	Hollow Tube	130x130 x6	6.32	0	298.77	OK	562.05	1371.19	OK
16	QTS	Hollow Tube	130x130 x6	6.32	0	298.77	OK	528.44	1371.19	OK
17	QTS	Solid Bar	80x80	6.32	66.23	133.41	OK	415.98	2948.8	OK
18	QTS	Solid Bar	80x80	5.39	134.02	184.01	OK	256.12	2948.8	OK
19	QTS	Hollow Tube	130x130 x6	5.39	319.52	412.1	OK	157.33	1371.19	OK
20	QTS	Solid Bar	55x55	4.47	0	59.61	OK	530.59	1393.77	OK
21	QTS	Hollow Tube	180x180 x9	4.47	1030.94	1769.4	OK	0	2836.38	OK
22	QTS	Solid Bar	55x55	4.47	0	59.61	OK	1255.75	1393.77	OK
23	QTS	Solid Bar	55x55	4	0	74.51	OK	579.24	1393.77	OK

24	QTS	Solid Bar	80x80	4	0	333.51	OK	1581.39	2948.8	OK
25	QTS	Solid Bar	80x80	4	0	333.51	OK	1860.19	2948.8	OK
26	QTS	Solid Bar	80x80	4	0	333.51	OK	1872.63	2948.8	OK
27	QTS	Solid Bar	80x80	4	0	333.51	OK	2037.85	2948.8	OK
28	QTS	Solid Bar	80x80	4	0	333.51	OK	2048.47	2948.8	OK
29	QTS	Solid Bar	80x80	4	0	333.51	OK	1886.28	2948.8	OK
30	QTS	Solid Bar	80x80	4	0	333.51	OK	1860.19	2948.8	OK
31	QTS	Solid Bar	80x80	4	0	333.51	OK	1560.91	2948.8	OK
32	QTS	Solid Bar	55x55	4	0	74.51	OK	563.3	1393.77	OK
33	QTS	Hollow Tube	190x190 x9	4	2050.36	2110.37	OK	0	3002.25	OK
34	QTS	Hollow Tube	200x200 x10	4	2129.91	2530.55	OK	0	3501.7	OK
35	QTS	Hollow Tube	190x190 x9	4	2036.71	2110.37	OK	0	3002.25	OK
36	QTS	Hollow Tube	140x140 x7	6.32	349.28	430.29	OK	92.33	1715.83	OK
37	QTS	Hollow Tube	130x130 x6	6.32	97.75	298.77	OK	343.87	1371.19	OK
38	QTS	Hollow Tube	130x130 x6	6.32	131.36	298.77	OK	310.25	1371.19	OK
39	QTS	Hollow Tube	140x140 x7	6.32	315.67	430.29	OK	125.94	1715.83	OK

Table 6
Warren Truss Bridge
Member Details Report from Bridge Designer 2016
Member with the Highest Tension Force/Strength Ratio

Member 4

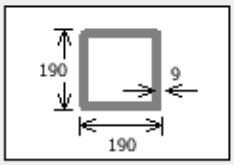
Material Properties:

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	Hollow Tube
Cross-Section Size	190x190x9
Area	0.0065 sq. meters
Moment of Inertia	3.57E-05 meters^4
Member Length	4.12 meters

Section (mm):



Cost:

Unit Cost	$393.86 per meter
Member Cost	$1623.92

Strength vs. Length: Graph all tabs Member:

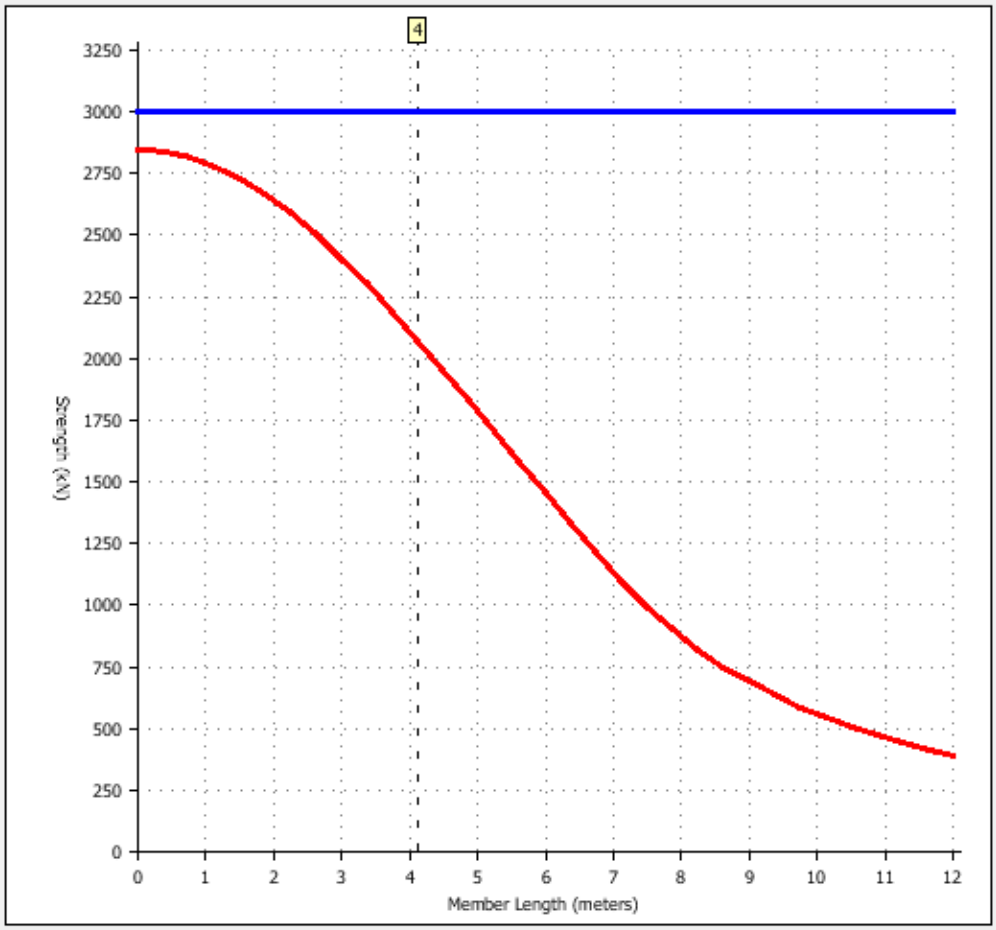


Table 7
Load Testing Results for the Howe Truss Bridge

EDSGN 100 Design Team #	Howe Bridge Weight (grams)	Bridge Weight (lbs)	Load at Failure (lbs)	Structural Efficiency
1	78.6	0.1733	63.5	366
2	77.9	0.1717	46.2	269
3	73.2	0.1614	67.6	419
4	77.9	0.1717	108.5	632
5	73.7	0.1625	33.9	209
6	72.7	0.1603	32.6	203
7	85.1	0.1876	36.4	194
			Max	**632**
			Min	**194**
			Average	**327**
			Range	**438**
			Geomean	**299**

Table 8
Load Testing Results for the Warren Truss Bridge

EDSGN 100 Design Team #	Warren Bridge Weight (grams)	Bridge Weight (lbs)	Load at Failure (lbs)	Structural Efficiency
1	71.1	0.1567	64.3	410
2	82.1	0.1810	78	431
3	80.2	0.1768	114.6	648
4	82.4	0.1817	56.6	312
5	80.9	0.1784	33.6	188
6	63.2	0.1393	32.7	235
7	80.6	0.1777	59.9	337
			Max	**648**
			Min	**188**
			Average	**366**
			Range	**460**
			Geomean	**341**

FIGURES

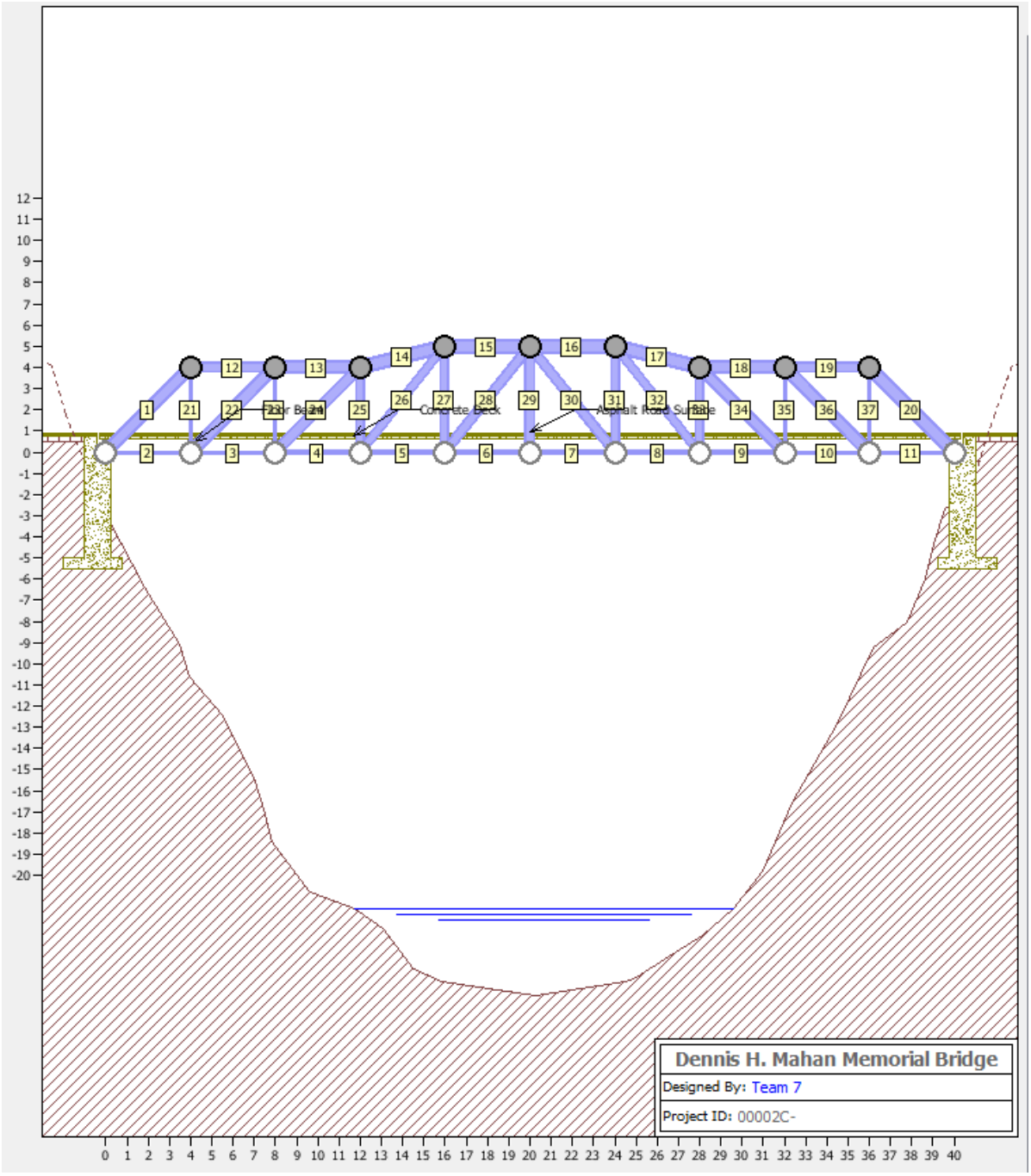


Figure 1. Howe Truss Bridge Model from Bridge Designer 2016

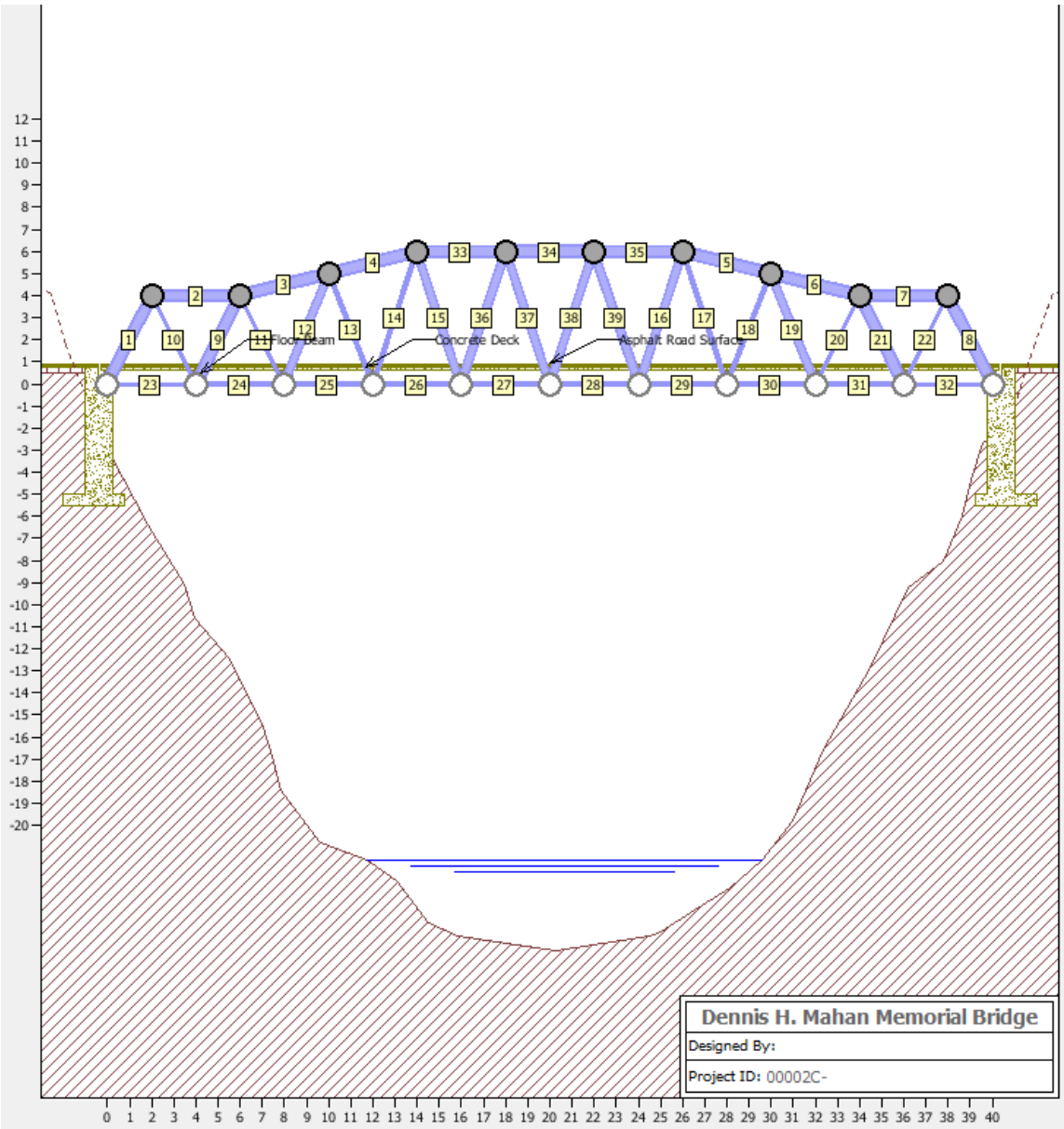


Figure 2. Warren Truss Bridge Model from Bridge Designer 2016

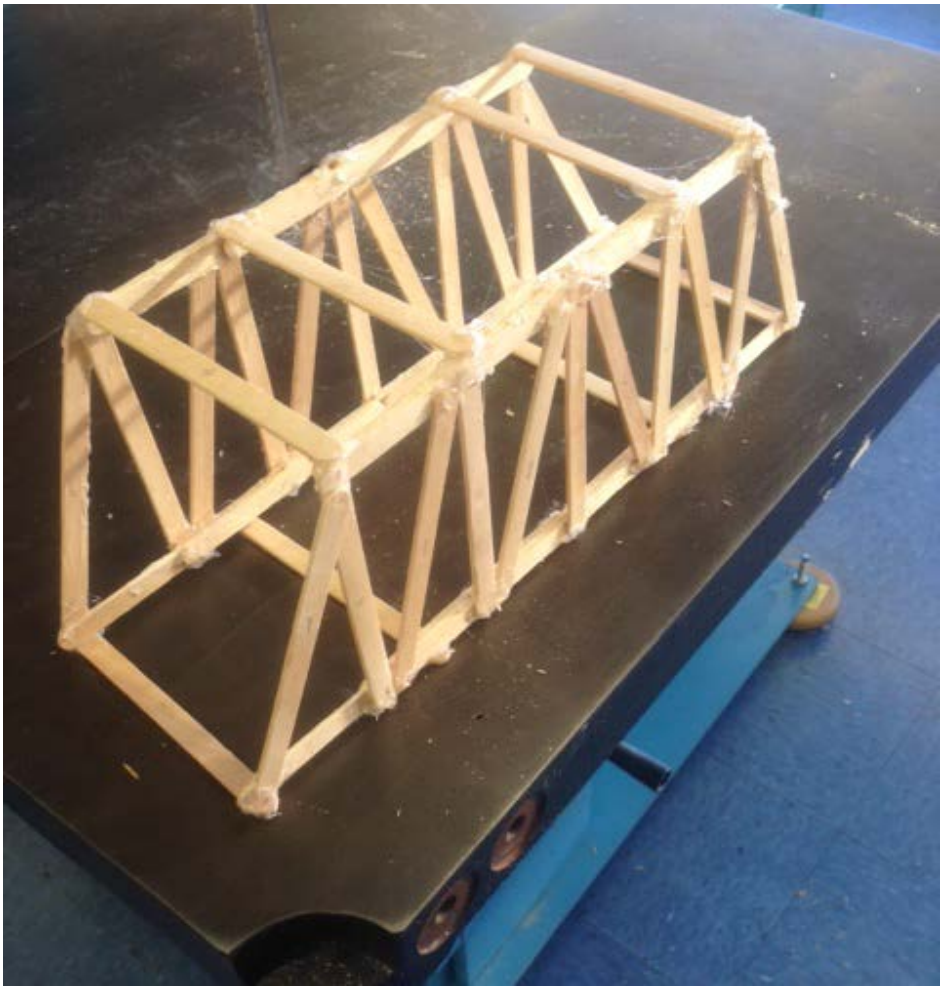


Figure 3. Howe Truss Bridge Prototype Failure before Load Testing

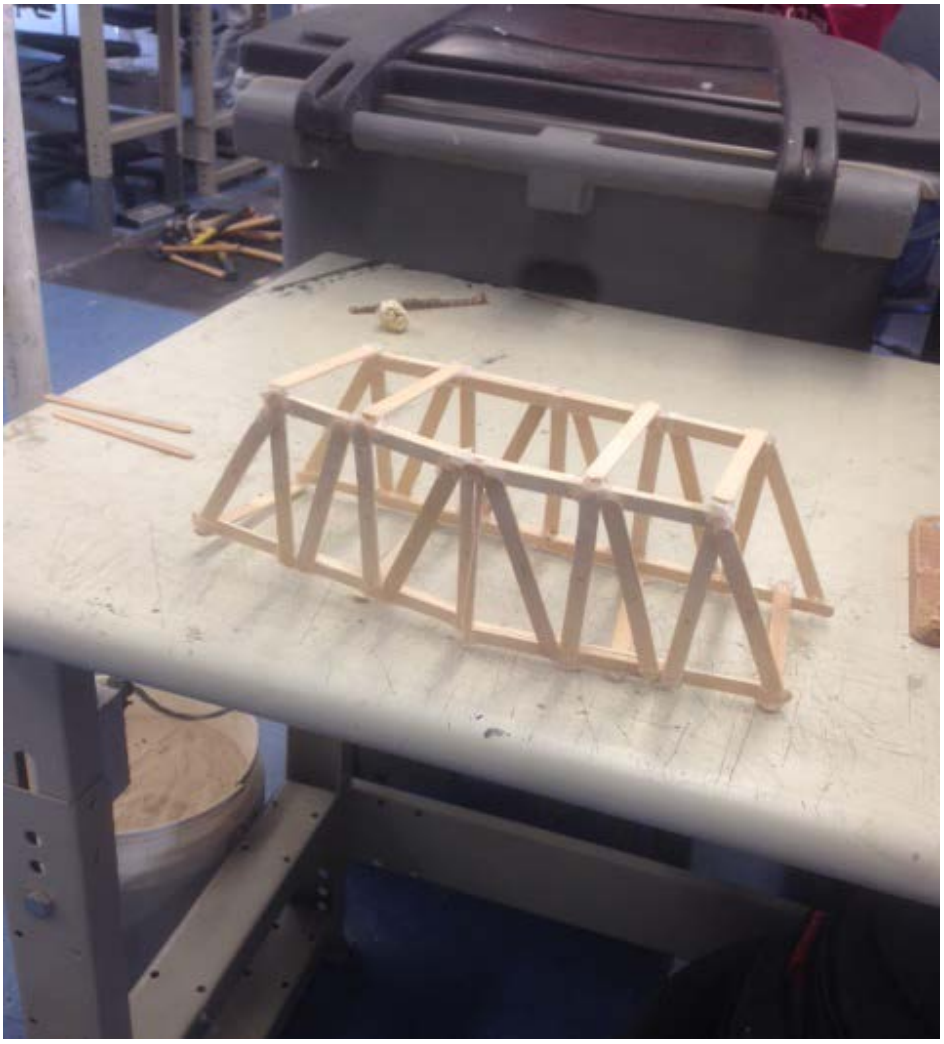


Figure 4. Howe Truss Bridge Prototype Failure after Load Testing

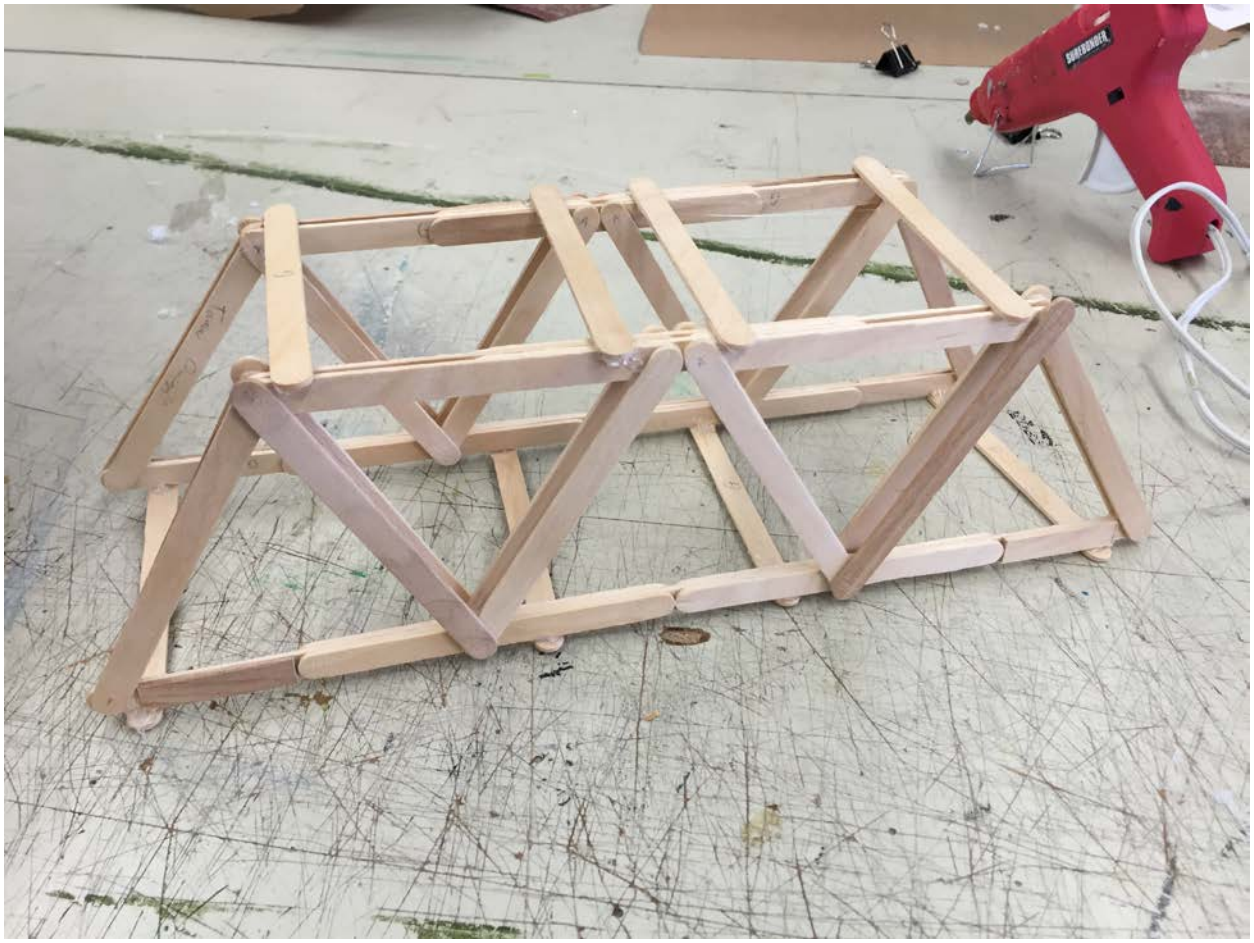


Figure 5. Warren Truss Bridge Prototype Failure before Load Testing

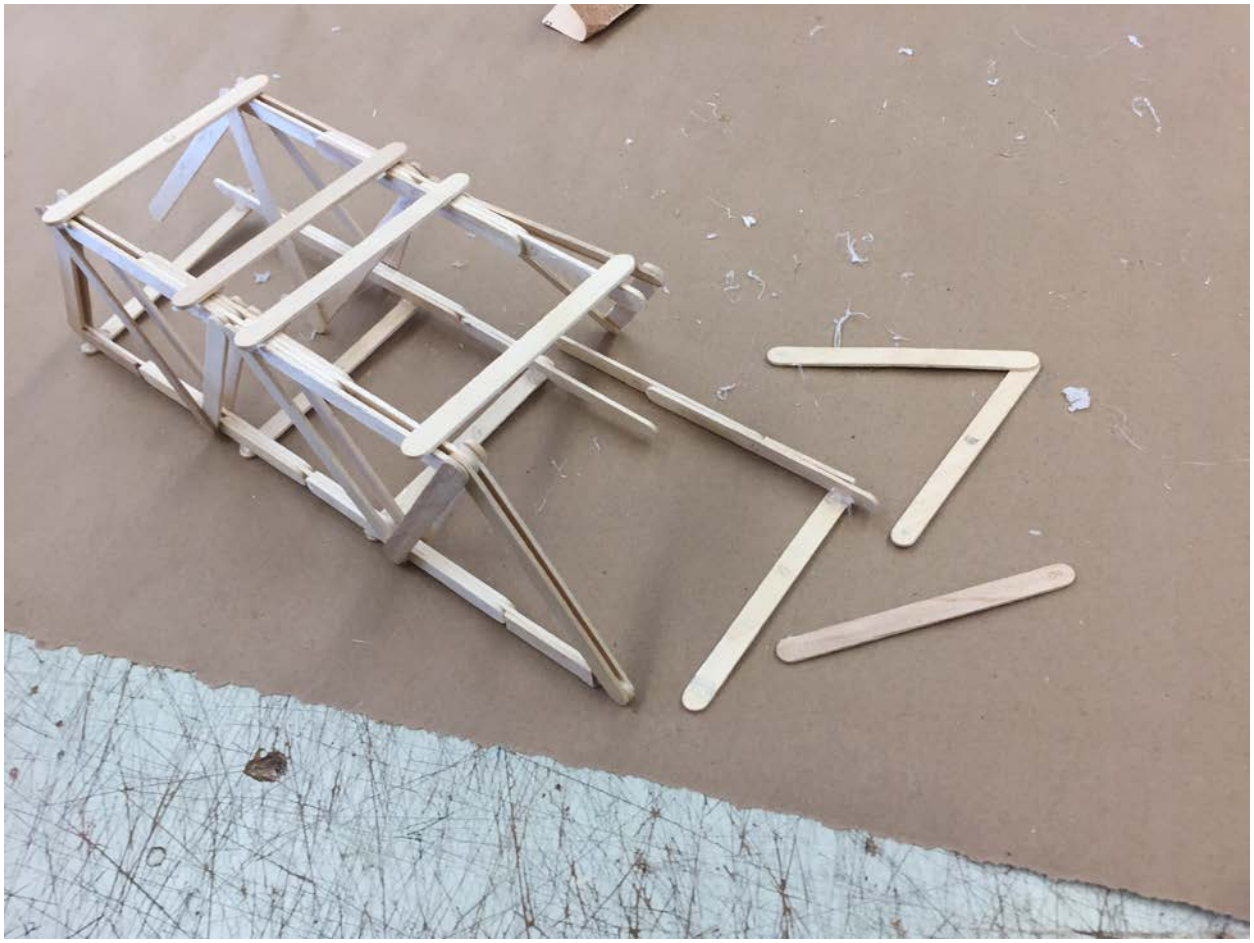


Figure 6. Warren Truss Bridge Prototype Failure after Load Testing

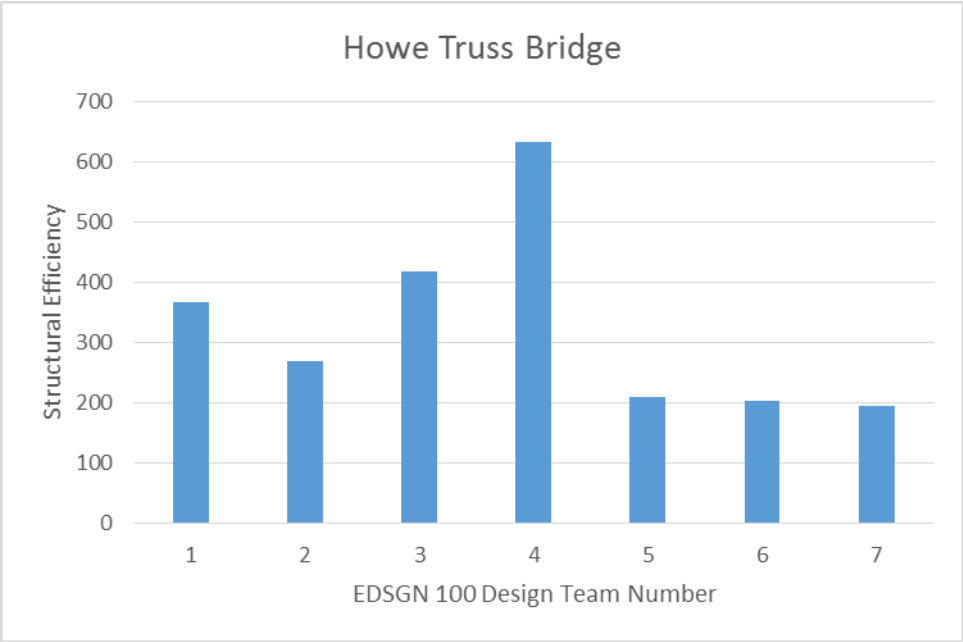


Figure 7. Howe Truss Bridge Structural Efficiencies

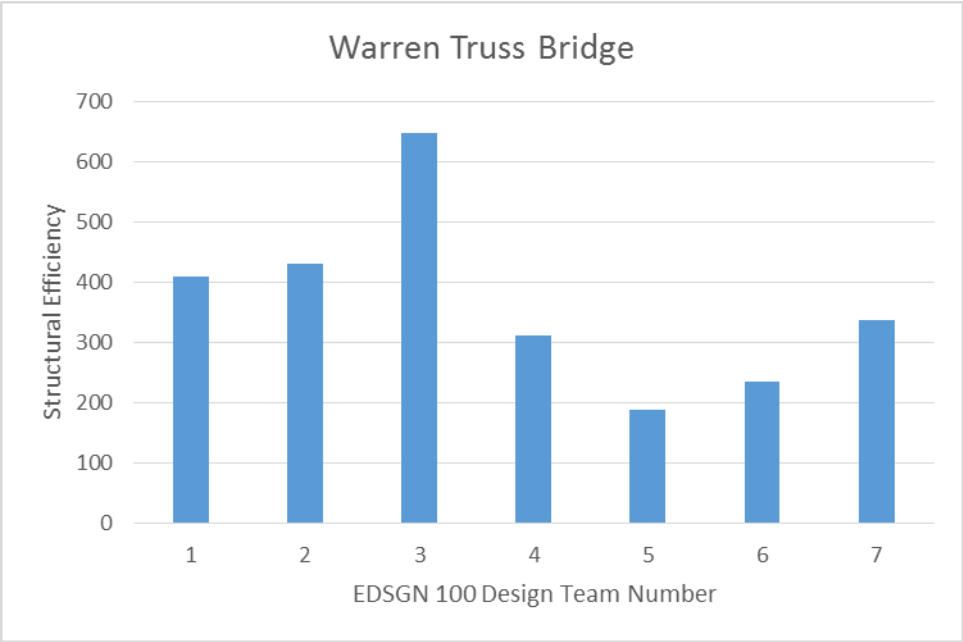


Figure 8. Warren Truss Bridge Structural Efficiencies