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

April 1, 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 located over Spring Creek in College Township, Centre County was destroyed by flooding. Two bridge designs must be created in order to replace this bridge.

Objective. To quickly create two different types of bridges, a Warren Truss Bridge and a Howe Truss Bridge, that will be structurally and economically efficient to replace the previous bridge over spring creek.

Design Criteria. Bridge must have standard abutments, no piers (one span), deck material shall be medium strength concrete (0.23 meters thick), no cable anchorages and designed for the load of two trucks (225kN) with one in each traffic lane. The bridge deck elevation shall be set at 20 meters and the deck span shall be exactly 40 meters.

Technical Approach.

Phase 1: Economic Efficiency. Bridge must be designed to be as affordable as possible, in order to do this similar inexpensive materials must be used in order to cut production costs. The geometrical design of the bridge will also reduce the number of struts needed while optimizing the overall strength of the structure. Data from from program simulation (Engineering Encounters Bridge Design 2015) was used to predict what the cost would be.

Phase 2: Structural Efficiency. Using the design simulator, various materials could be tested in order to decide what should be used and where they should be used. to be able to determine an optimal bridge design, two scaled prototypes were built using Popsicle sticks for struts and Polyvinyl acetate glue (PVA) for joints. Using a maximum of 60 members, simple Warren and Howe Bridges were constructed. These bridges were loaded until catastrophic failure so that the structural efficiency could be calculated.

Results.

Phase 1: Economic Efficiency. Warren Bridge cost was $193,152.57. Howe Bridge cost was $213,532.82. View Attachment 1 for more information.

Phase 2: Structural Efficiency. Warren bridge structural efficiency was 406.8. The Howe Truss Bridge Structural efficiency was 366.5. View Attachment 2 for more information.

Best Solution. The Warren truss bridge had the lowest cost and was therefore more economically efficient. (see figures 1 and 4) The Warren truss bridge had a structural efficiency of 406.8 for design team 1. The geometric mean of the Warren bridge was 340.2 for all 7 design teams. The Howe truss bridge had a structural efficiency of 366.5 for design team 1. The geometric mean of of the Howe bridge was 299.2 for all design teams. Since the Warren was clearly superior in both structural and economic efficiency, it is the best solution to the problem. If the total cost of the Warren bridge is divided by the structural efficiency, the design efficiency is found to be $474/unit of structural efficiency. According to tables 1 and 4, the Warren bridge had significantly lower material and product cost due to the use of less material. Based on all of these different data, the Warren bridge is the superior option.

Conclusions and Recommendations. After load testing each bridge design, it was determined that the Warren Truss bridge was the most economically and structurally efficient. The Warren bridge used less members and held more than the Howe bridge. It is recommended that when designing and building the bridge that all joints are properly secured especially the floor and ceiling. This will prevent leaning and assist in the strength of the bridge.

Respectfully,

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ATTACHMENT 1

Phase 1: Economic Efficiency

Howe Truss. Two different forms of hollow tubing was primarily used for the main members of our bridge. 2,996.7 kg of the Carbon Steel Hollow Tubes were used, and 3,165.0 kg of the Quenched and Tempered Steel Hollow tubes. Comparatively, only 1675.2 kg of High Strength Low Alloy Steel Solid bars were used, and only 157.0 kg of the Quenched and Tempered Steel Solid bars. This was done to minimize cost, while still fitting the safety requirement. Hollow tubing is shown to have a higher compression strength than that of solid bars, and this information was used in order to utilize these hollow bars in compression areas. Although hollow tubes are slightly more expensive per kilogram, they are also much stronger than solid bars, and through multiple trial and error efforts it was decided that the hollow tubing would provide a cheaper design. Our total cost for this bridge was $213,532.82, which is under the $225,000 goal that was set by the customer.

Warren Truss. Similar to the Howe Truss, hollow tubing was the primary source for the members in this bridge. 2,885.4 kg of Carbon Steel Hollow Tubes were used, and 2,296.4 kg of Quenched and Tempered Steel Hollow Tubes were used. Again, Hollow tubing is better for areas where a large compression strength is necessary. High Strength Low Alloy Steel Solid bars were only used for 1,513.5 kg, and Carbon Steel Solid bars were only used for 263.3 kg. Truss bridges used more compression than tension, and since hollow tubing is better at sustaining this type of pressure, hollow tubing utilized more in the design. Although Quenched and Tempered Steel Hollow bars are $7.70/kg compared to High Strength Low Allow Steel bars being only $5.60/kg, the compression strength per dollar is much greater on the Q&T bars. This is why the Q&T bars were utilized so much in the design of the Warren Bridge. The final cost for this bridge was $193,152.57, easily under the $225,000 goal set by the customer.

ATTACHMENT 2

Phase 2: Structural Efficiency

Howe Truss.

Prototype Bridge. 59 Popsicle sticks were used to construct the bridge. PVA glue was used for the majority of the joints excluding the floor and ceiling struts where hot glue was used. When gluing joints, the surface of the wood was scratched in order for the glue to sink deeper in the wood and create a stronger hold. A cure time was allowed for the glue so that it would get stronger over time. The bridge's final dimensions were 13.5 inches in length, 4 in height, and 4.5 in width. (Figure 3)

Load Testing. The load testing was carried out by placing the bridge on two boards and placing a wooden block on top connected to a bucket which hung below. Sand was poured into the bucket until the bridge failed. The bucket was then weighed and this load at failure was recorded. The Howe Truss Bridge was able to support 63.5 pounds before failing. By dividing the load at failure by the weight of the bridge, the structural efficiency was found to be 366.5. This was the third greatest structural efficiency in the class with the minimum being 194.0 and the maximum being 631.8. (Data are displayed in Table 7)

Forensic Analysis. The Howe truss bridge failed due to weakness in the glue joints. The main cause of this failure was due to improper gluing of the floor and ceiling struts. When gluing these members the structure itself was not perfectly vertical, causing the bridge to lean and collapse to one side under stress. The minimal use of members between the trusses caused minor leaning and caused extra stresses on these joints. From figure 4, it can be seen that no members actually failed. The glue holding the members together was what failed.

Results. Figure 7 displays the structural efficiencies of all design teams as a bar graph.

Warren Truss.

Prototype Bridge. 52 Popsicle sticks were used to construct the bridge. PVA glue was used for the majority of the joints excluding the floor and ceiling struts where hot glue was used. When gluing joints, the surface of the wood was scratched in order for the glue to sink deeper in the wood and create a stronger hold. A cure time was allowed for the glue so that it would get stronger over time. The bridge's final dimensions were 13.5 inches in length, 4 in height, and 4.5 in width. (Figure 4)

Load Testing. The load testing was carried out by placing the bridge on two boards and placing a wooden block on top connected to a bucket which hung below. Sand was poured into the bucket until the bridge failed. The bucket was then weighed and this load at failure was recorded. The Warren Truss Bridge was able to support 64.3 pounds before failing. By dividing the load at failure by the weight of the bridge, the structural efficiency was found to be 406.8. This was the third greatest structural efficiency in the class with the minimum being 188.4 and the maximum being 648.2. (Data are displayed in Table 8)

Forensic Analysis. The Warren truss bridge failed after holding a load of 64.3 lbs. The main cause of this failure was due to improper gluing of the floor and ceiling struts. When gluing these members the structure itself was not perfectly vertical, causing the bridge to lean and collapse to one side

under stress. Neither the PVA glue joints or the members themselves broke to cause the failure. Another cause of the bridge failure was the use of hot glue, which does not need a long cure time or maintain its rigidity for very long. This would cause the floor and ceiling joints to be more flexible and also contribute to leaning.

Results. Figure 8 displays the structural efficiencies of all the design teams as a bar graph.

TABLES

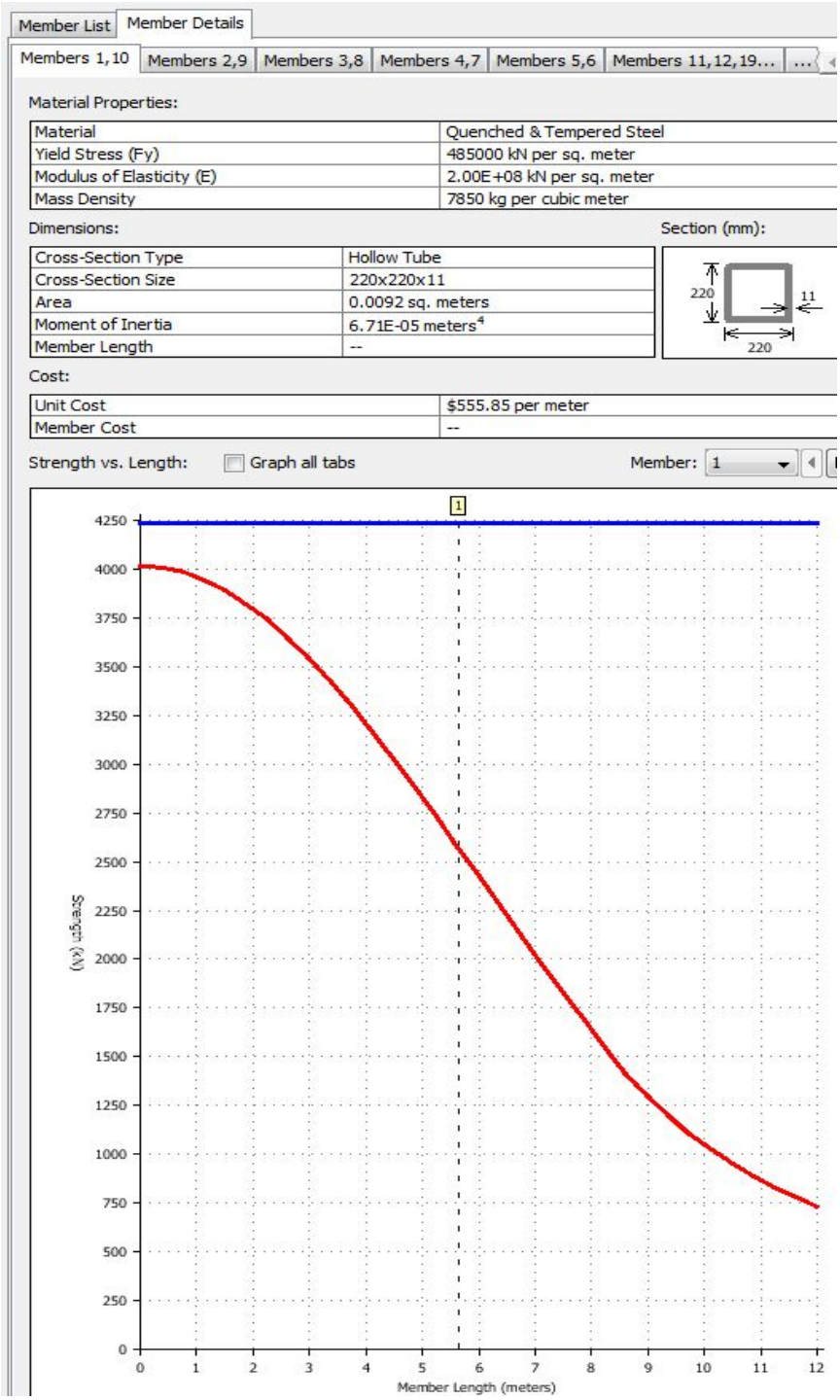
Table 1
Cost Calculation Report from Bridge Designer 2015 for the Howe Truss Bridge

Table 1			
Howe Truss Bridge			
Cost Calculation Report from Bridge Designer 2016			
Type of Cost	**Item**	**Cost Calculation**	**Cost**
Material Cost (M)	Carbon Steel Hollow Tube	(2995.7 kg) x ($6.30 per kg) x (2 Trusses) =	$37,745.75
	High-Strength Low-Alloy Steel Solid Bar	(1675.2 kg) x ($5.60 per kg) x (2 Trusses) =	$18,762.13
	Quenched & Tempered Steel Solid Bar	(157.0 kg) x ($6.00 per kg) x (2 Trusses) =	$1,884.00
	Quenched & Tempered Steel Hollow Tube	(3165.0 kg) x($7.70 per kg) x (2 Trusses) =	$48,740.94
Connection Cost (C)		(20 Joints) x (400.0 per joint) x (2 Trusses) =	$16,000.00
Product Cost (P)	2 – 50x50 mm Quenched & Tempered Steel Bar	(%s per Product)	$1,000.00
	4 – 70x70 mm High-Strength Low-Alloy Steel Bar	(%s per Product)	$1,000.00
	6 – 75x75 mm High-Strength Low-Alloy Steel Bar	(%s per Product)	$1,000.00
	2 – 80x80x4 mm Quenched & Tempered Steel Tube	(%s per Product)	$1,000.00
	3 – 90x90x4 mm Quenched & Tempered Steel Tube	(%s per Product)	$1,000.00
	2 – 100x100x5 mm Quenched & Tempered Steel Tube	(%s per Product)	$1,000.00
	2 - 130x130x6 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	2 – 160x160x8 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	2 – 180x180x9 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	6 – 180x180x9 mm Quenched & Tempered Steel Tube	(%s per Product)	$1,000.00
	2 – 190x190x9 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	2 – 190x190x9 mm Quenched & Tempered Steel Tube	(%s per Product)	$1,000.00
	2 – 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+P+C+S**	$107, 132.82 + $16,000.00+ $13,000.00 + $77, 400.00 =	$213, 532.82

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

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	220x220x11	6	1956	2566	OK	0	4237	OK
2	CS	Hollow Tube	130x130x6	8	150	184	OK	320	707	OK
3	CS	Hollow Tube	190x190x9	9	600	679	OK			OK
4	CS	Hollow Tube	160x160x8	10	252	303	OK	192	1155	OK
5	CS	Hollow Tube	180x180x9	10	389	485	OK	69	1462	OK
6	CS	Hollow Tube	180x180x9	10	354	485	OK	104	1462	OK
7	CS	Hollow Tube	160x160x8	10	230	303	OK	258	1155	OK
8	CS	Hollow Tube	190x190x9	9	574	679	OK	0	1548	OK
9	CS	Hollow Tube	130x130x6	8	141	184	OK	344	707	OK
10	QTS	Hollow Tube	220x220x11	6	1920	2566	OK	0	4237	OK
11	HSS	Solid Bar	70x70	4	0	196	OK	1390	1606	OK
12	HSS	Solid Bar	70x70	4	0	196	OK	1412	1606	OK
13	HSS	Solid Bar	75x75	4	0	258	OK	1620	1844	OK
14	HSS	Solid Bar	75x75	4	0	258	OK	1644	1844	OK
15	HSS	Solid Bar	75x75	4	0	258	OK	1709	1844	OK
16	HSS	Solid Bar	75x75	4	0	258	OK	1635	1844	OK
17	HSS	Solid Bar	75x75	4	0	258	OK	1600	1844	OK
18	HSS	Solid Bar	75x75	4	0	258	OK	1377	1844	OK
19	HSS	Solid Bar	70x70	4	0	196	OK	1358	1606	OK
20	HSS	Solid Bar	70x70	4	0	196	OK	0	1606	OK
21	QTS	Hollow Tube	190x190x9	5	1737	1784	OK	0	3002	OK
22	QTS	Hollow Tube	180x180x9	4	1455	1884	OK	0	2836	OK
23	QTS	Hollow Tube	180x180x9	4	1670	1884	OK	0	2836	OK
24	QTS	Hollow Tube	180x180x9	4	1644	1924	OK	0	2836	OK
25	QTS	Hollow Tube	180x180x9	4	1635	1924	OK	0	2836	OK
26	QTS	Hollow Tube	180x180x9	4	1649	1884	OK	0	2836	OK
27	QTS	Hollow Tube	180x180x9	4	1419	1884	OK	0	2836	OK
28	QTS	Hollow Tube	190x190x9	5	1697	1784	OK	0	3002	OK
29	QTS	Solid Bar	50x50	0	0	51	OK	343	1152	OK
30	QTS	Hollow Tube	100x100x5	7	0	91	OK	775	875	OK
31	QTS	Hollow Tube	80x80x4	8	0	29	OK	464	560	OK
32	QTS	Hollow Tube	90x90x4	9	0	33	OK	610	634	OK
33	QTS	Hollow Tube	90x90x4	9	0	33	OK	620	634	OK
34	QTS	Hollow Tube	90x90x4	9	0	33	OK	578	634	OK
35	QTS	Hollow Tube	80x80x4	8	0	29	OK	443	560	OK
36	QTS	Hollow Tube	100x100x5	7	0	91	OK	753	875	OK
37	QTS	Solid Bar	50x50	4	0	51	OK	335	1152	OK

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



Member List | Member Details

Members 1,10 | Members 2,9 | Members 3,8 | Members 4,7 | Members 5,6 | Members 11,12,19... | ...

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	Hollow Tube
Cross-Section Size	220x220x11
Area	0.0092 sq. meters
Moment of Inertia	6.71E-05 meters^4
Member Length	--

Section (mm):

Cost:

Unit Cost	$555.85 per meter
Member Cost	--

Strength vs. Length: Graph all tabs Member: 1

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

Warren Truss Bridge			
Cost Calculation Report from Bridge Designer 2016			
Type of Cost	**Item**	**Cost Calculation**	**Cost**
Material Cost (M)	Carbon Steel Solid Bar	(265.3 kg) x ($4.30 per kg) x (2 Trusses) =	$2,281.84
	Carbon Steel Hollow Tube	(2885.4 kg) x ($6.30 per kg) x (2 Trusses) =	$36,355.89
	High-Strength Low-Alloy Steel Solid Bar	(1513.5 kg) x ($5.60 per kg) x (2 Trusses) =	$16, 950.98
	Quenched & Tempered Steel Hollow Tube	(2296.4 kg) x ($7.70 per kg) x (2 Trusses) =	$35, 363.87
Connection Cost (C)		(21 Joints) x ($400.0 per joint) x (2 Trusses) =	$16,800.00
Product Cost (P)	2 – 65x65 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	2 – 70x70 mm High-Strength Low-Alloy Steel Bar	(%s per Product)	$1,000.00
	6 – 80x80 mm High-Strength Low-Alloy Steel Bar	(%s per Product)	$1,000.00
	2 – 100x100x5 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	6 – 120x120x60 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	7 – 140x140x7 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	3 – 150x150x7 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	11 – 190x190x9 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+P+C+S**	$90,952.57 + $16,800.00 + $8,000.00 + $77,400.00 =	$193,152.57

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

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	190x190x9	4	1546	1959	OK	0	3002	OK
2	QTS	Hollow Tube	190x190x9	4	1842	2071	OK	0	3002	OK
3	QTS	Hollow Tube	190x190x9	4	2044	2071	OK	0	3002	OK
4	QTS	Hollow Tube	190x190x9	4	2022	2071	OK	0	3002	OK
5	QTS	Hollow Tube	190x190x9	4	1912	2110	OK	0	3002	OK
6	QTS	Hollow Tube	190x190x9	4	2011	2071	OK	0	3002	OK
7	QTS	Hollow Tube	190x190x9	4	2018	2071	OK	0	3002	OK
8	QTS	Hollow Tube	190x190x9	4	1796	2071	OK	0	3002	OK
9	QTS	Hollow Tube	190x190x9	4	1510	1959	OK	0	3002	OK
10	CS	Solid Bar	65x65	4	0	145	OK	923	1003	OK
11	HSS	Solid Bar	70x70	4	0	196	OK	1516	1606	OK
12	HSS	Solid Bar	80x80	4	0	334	OK	1859	2098	OK
13	HSS	Solid Bar	80x80	4	0	334	OK	1928	2098	OK
14	HSS	Solid Bar	80x80	4	0	334	OK	1836	2098	OK
15	HSS	Solid Bar	80x80	4	0	334	OK	1844	2098	OK
16	HSS	Solid Bar	80x80	4	0	334	OK	1939	2098	OK
17	HSS	Solid Bar	80x80	4	0	334	OK	1859	2098	OK
18	HSS	Solid Bar	70x70	4	0	196	OK	1500	1606	OK
19	CS	Solid Bar	65x65	4	0	145	OK	902	1003	OK
20	QTS	Hollow Tube	190x190x9	4	1664	2232	OK	0	3002	OK
21	CS	Hollow Tube	150x150x7	5	500	576	OK	0	951	OK
22	CS	Hollow Tube	150x150x7	6	468	487	OK	0	951	OK
23	CS	Hollow Tube	120x120x6	7	149	175	OK	269	650	OK
24	CS	Hollow Tube	120x120x6	8	0	137	OK	540	650	OK
25	CS	Hollow Tube	120x120x6	8	69	137	OK	363	650	OK
26	CS	Hollow Tube	120x120x6	8	102	137	OK	330	650	OK
27	CS	Hollow Tube	120x120x6	8	0	137	OK	599	650	OK
28	CS	Hollow Tube	120x120x6	7	132	175	OK	338	650	OK
29	CS	Hollow Tube	150x150x7	6	447	487	OK	15	951	OK
30	CS	Hollow Tube	140x140x7	5	483	500	OK	0	884	OK
31	QTS	Hollow Tube	190x190x9	4	1626	2232	OK	0	3002	OK
32	CS	Hollow Tube	140x140x7	4	0	665	OK	829	884	OK
33	CS	Hollow Tube	140x140x7	5	0	500	OK	730	884	OK
34	CS	Hollow Tube	100x100x5	6	0	112	OK	392	451	OK
35	CS	Hollow Tube	140x140x7	7	283	325	OK	124	884	OK
36	CS	Hollow Tube	140x140x7	7	298	325	OK	109	884	OK
37	CS	Hollow Tube	100x100x5	6	0	112	OK	374	451	OK
38	CS	Hollow Tube	140x140x7	5	0	500	OK	708	884	OK
39	CS	Hollow Tube	140x140x7	4	0	665	OK	810	884	OK

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

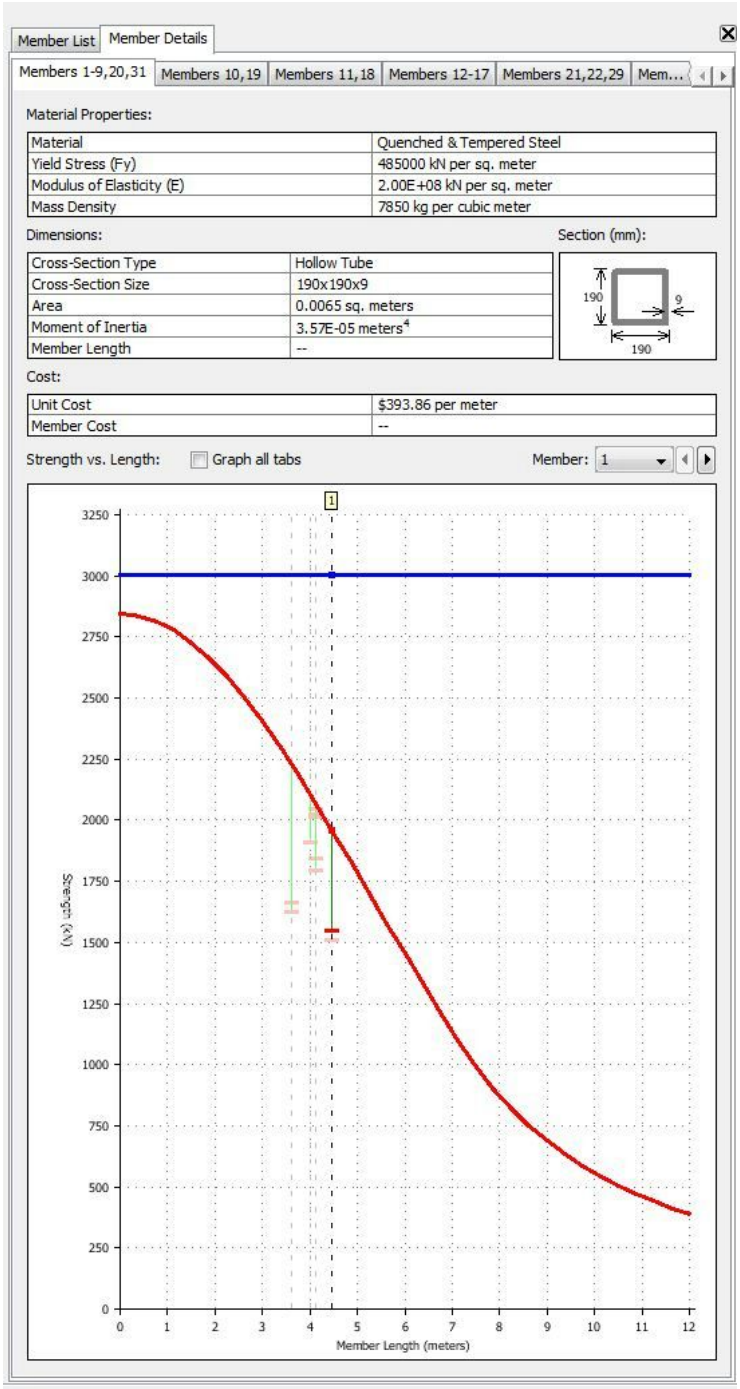


Table 7
Load Test Results for the Howe Truss Bridge

Design Team Number	Howe Truss Bridge Weight (grams)	Bridge Weight (lbs.)	Load at Failure (lbs.)	Structural Efficiency
1	78.6	0.17328156	63.5	366.455611318365
2	77.9	0.17173834	46.2	269.013896372819
3	73.2	0.16137672	67.6	418.895612700518
4	77.9	0.17173834	108.5	631.775059663439
5	73.7	0.16247902	33.9	208.642321944088
6	72.7	0.16027442	32.6	203.401141616984
7	85.1	0.18761146	36.4	194.017998687287

Table 8
Load Test Results for the Warren Truss Bridge

Design Team Number	Warren Truss Bridge Weight (grams)	Bridge Weight (lbs.)	Load at Failure (lbs.)	Structural Efficiency
1	71.7	0.15806982	64.3	406.782268746811
2	82.1	0.18099766	78	430.944797849873
3	80.2	0.17680892	114.6	648.157344097798
4	82.4	0.18165904	56.6	311.572713364554
5	80.9	0.17835214	33.6	188.391347589101
6	63.2	0.13933072	32.7	234.693397120176
7	80.6	0.17769076	59.9	337.102503247777

FIGURES

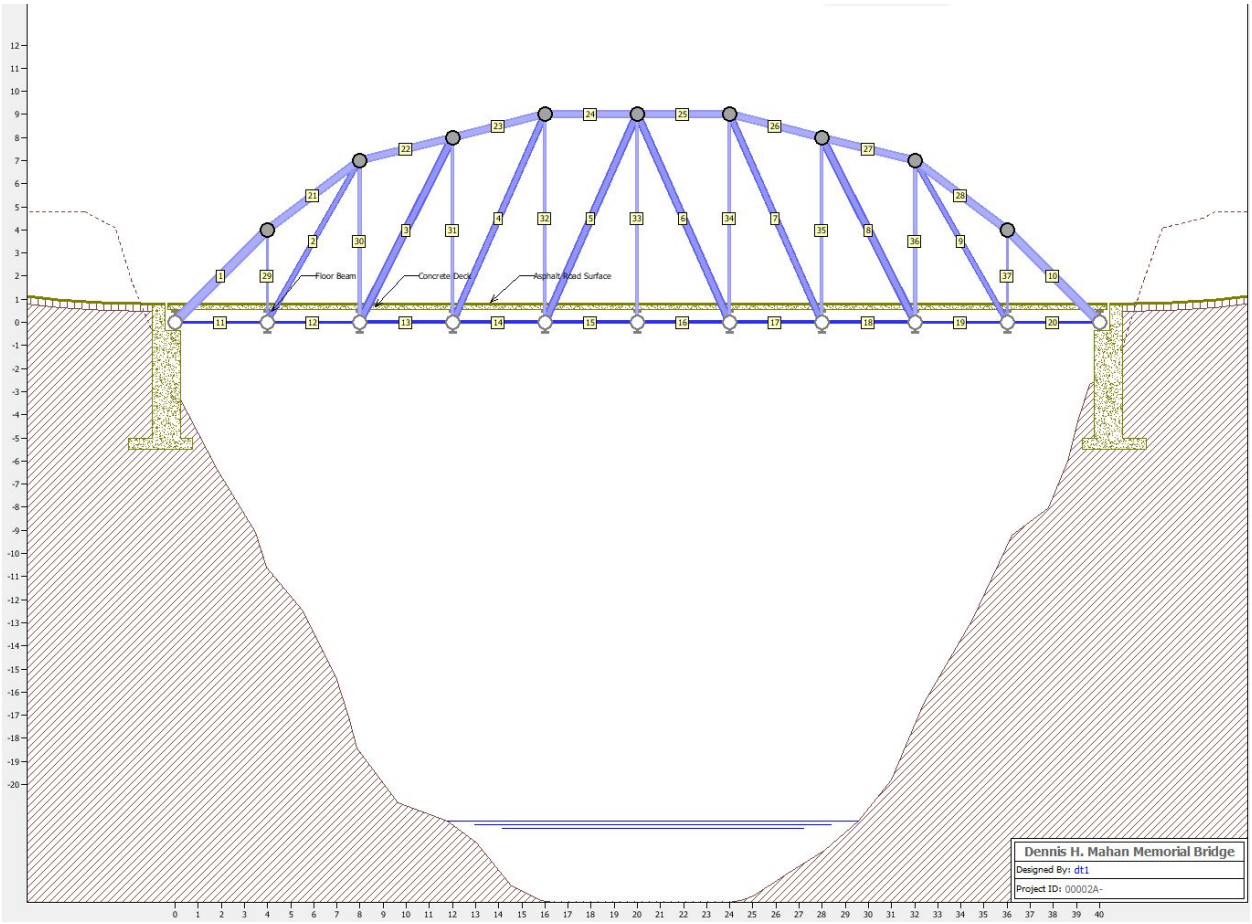


Figure 1. Howe Truss Bridge Model from Bridge Designer 2015

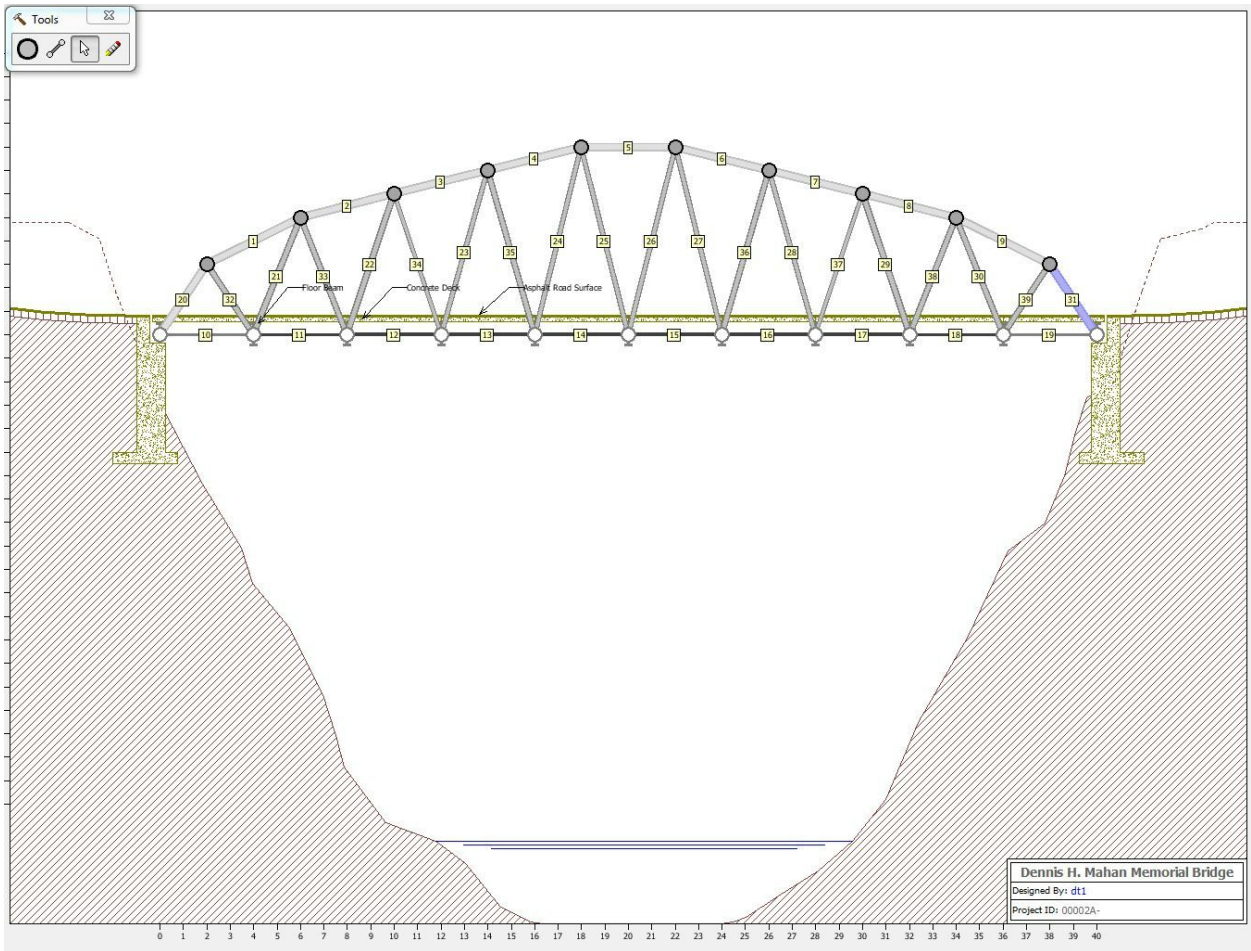


Figure 2. Warren Truss Bridge Model from Bridge Designer 2015

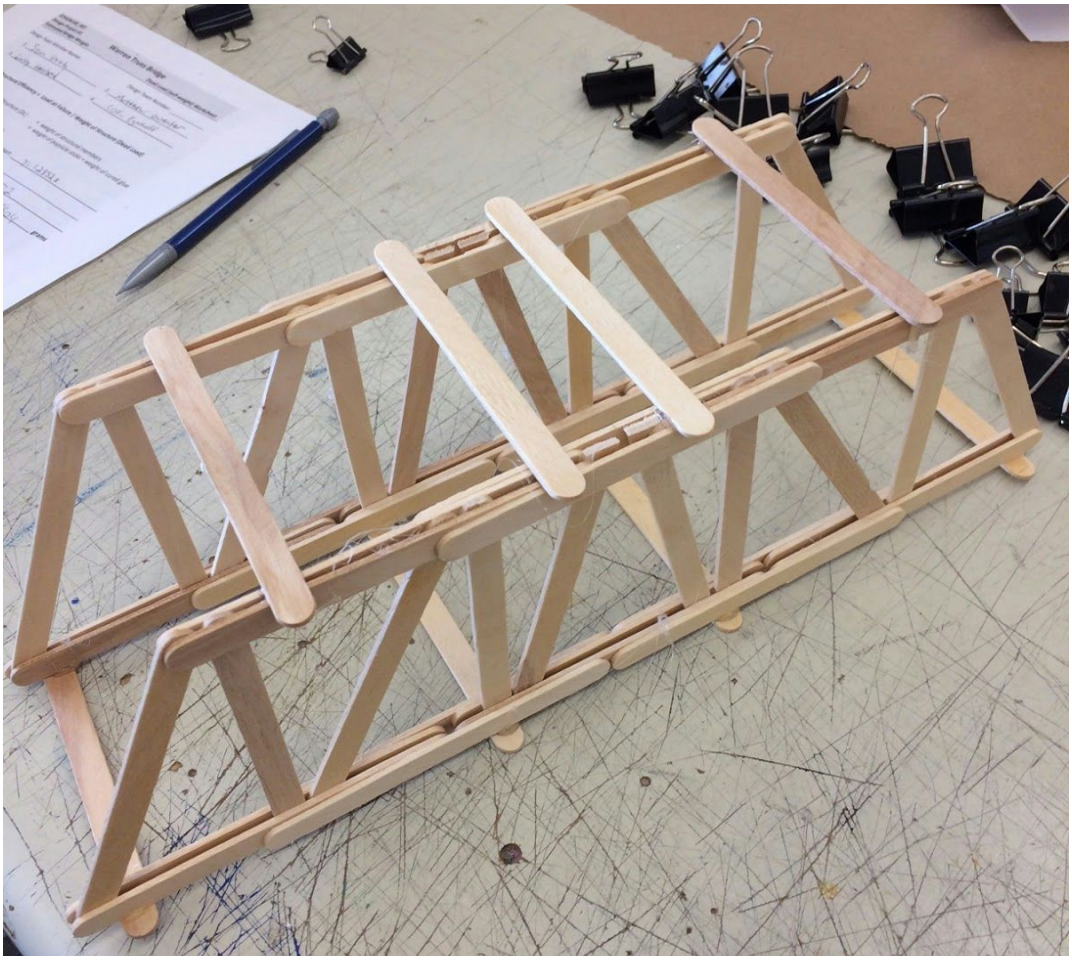


Figure 3. Howe Truss Bridge Prototype before Load Testing

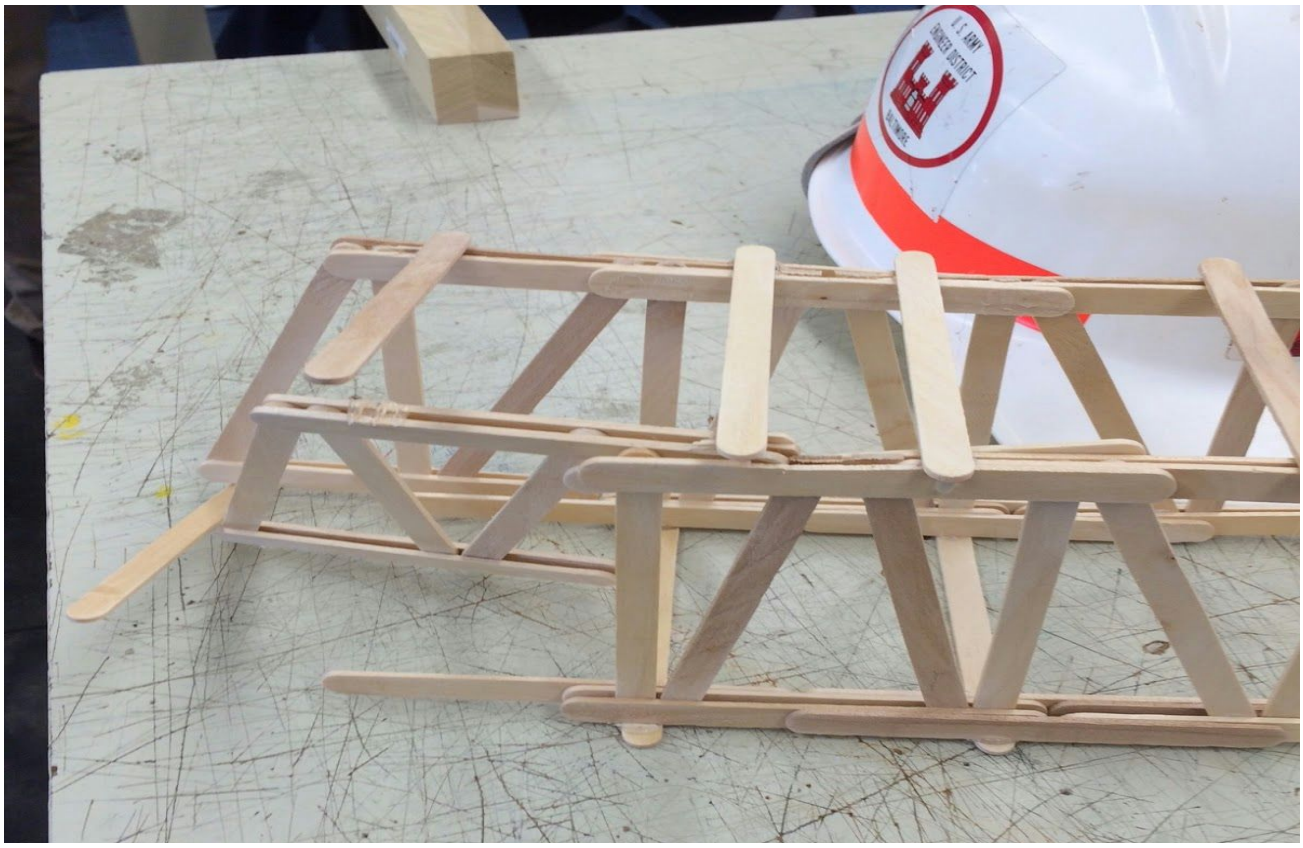


Figure 4. Howe Truss Bridge Prototype Failure after Load Testing

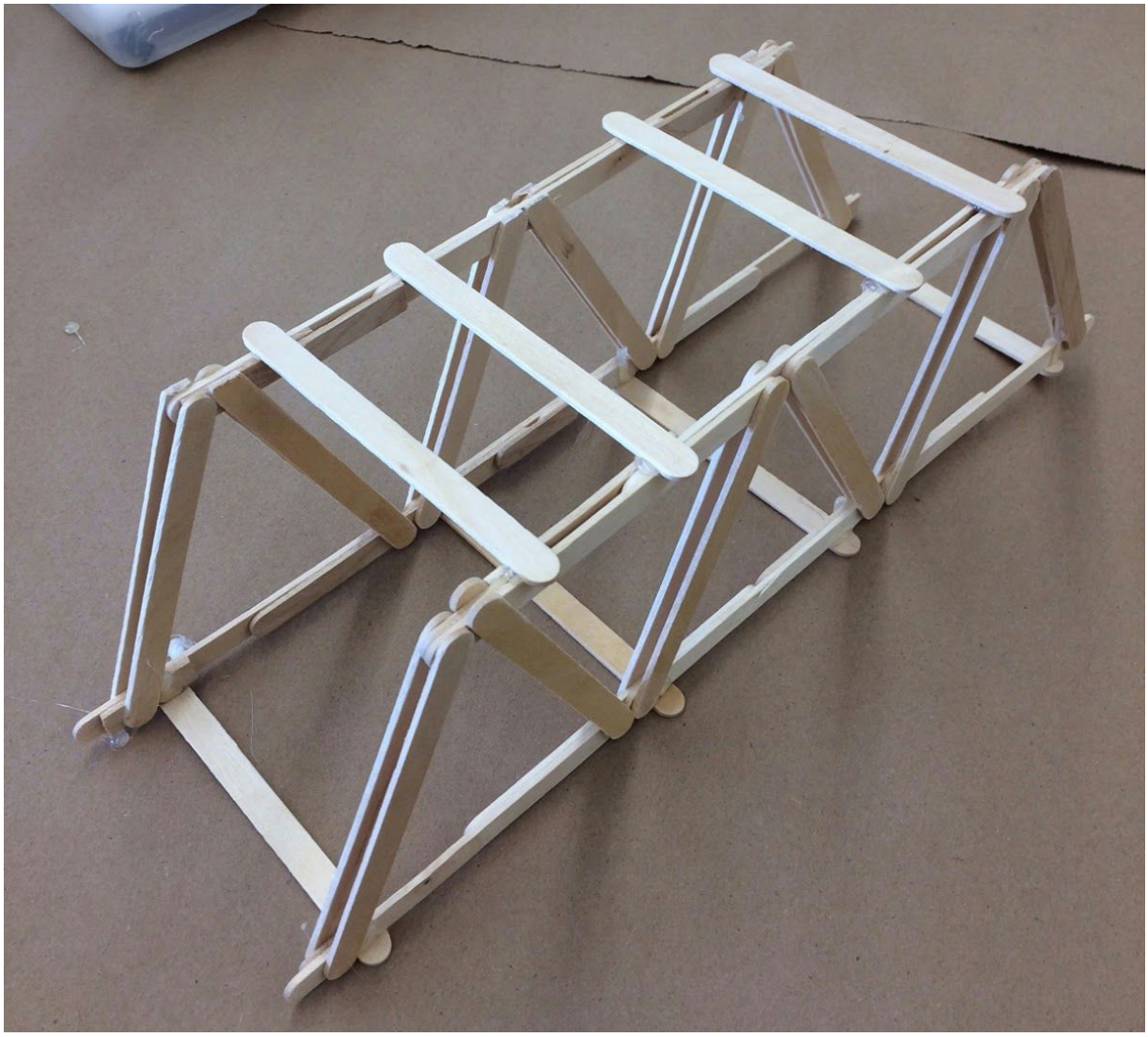


Figure 5. Warren Truss Bridge Prototype before Load Testing

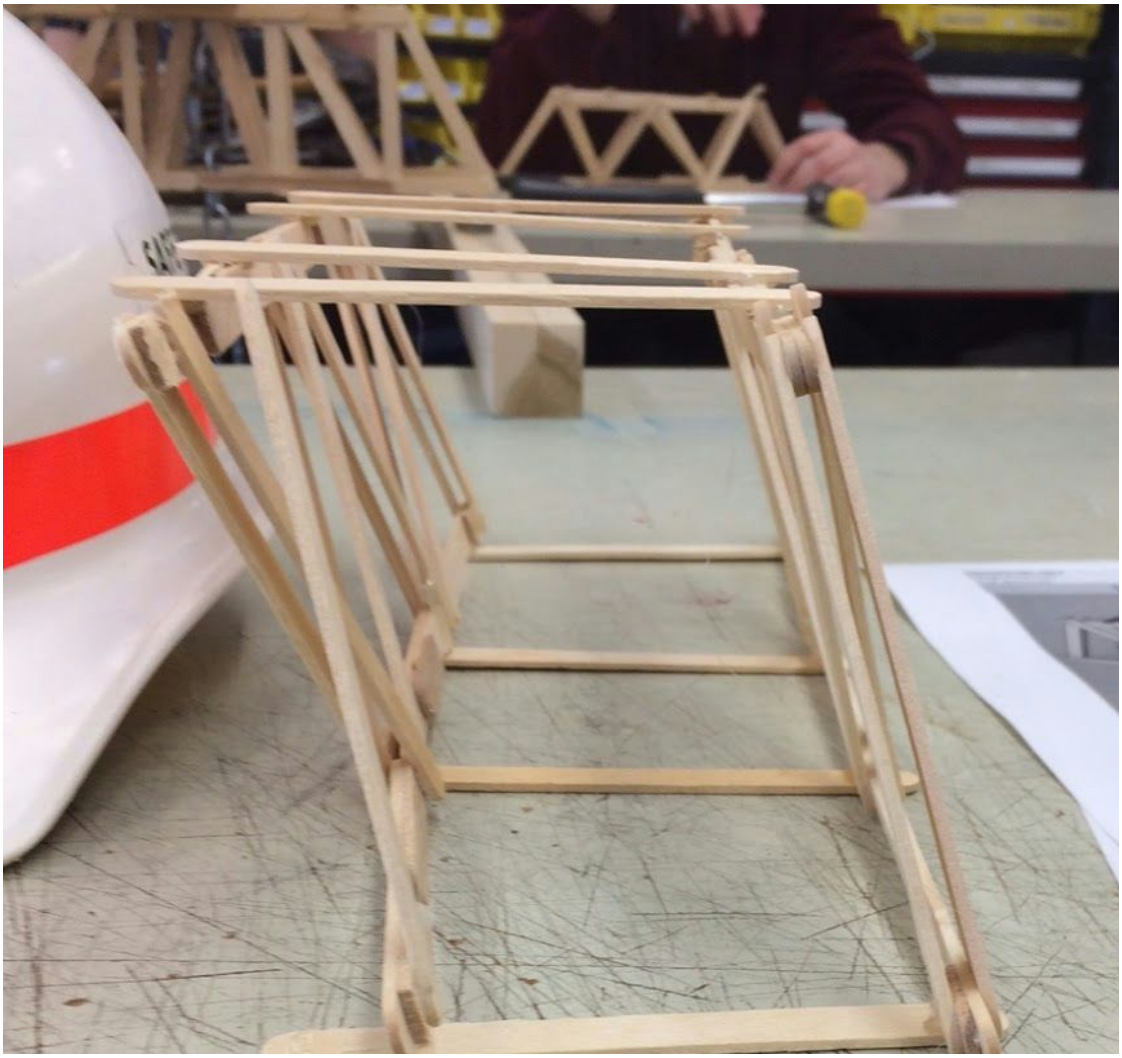


Figure 6. Warren Truss Bridge Prototype Failure after Load Testing

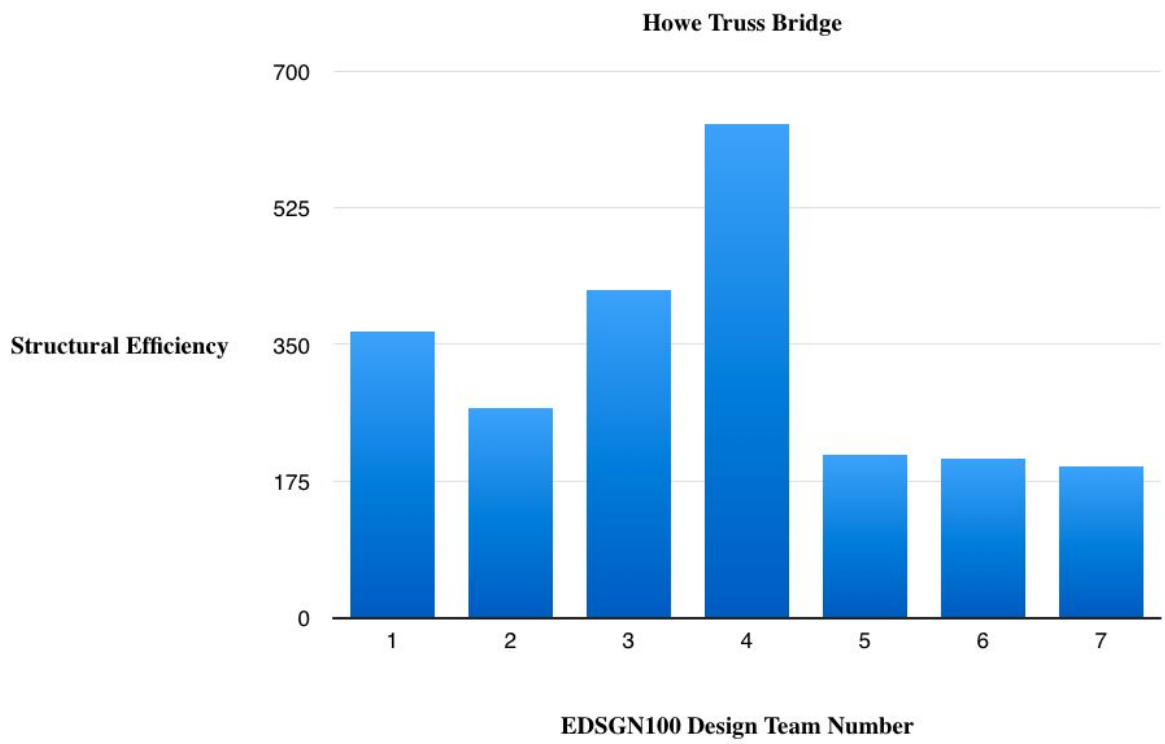


Figure 7. Howe Truss Bridge Structural Efficiencies

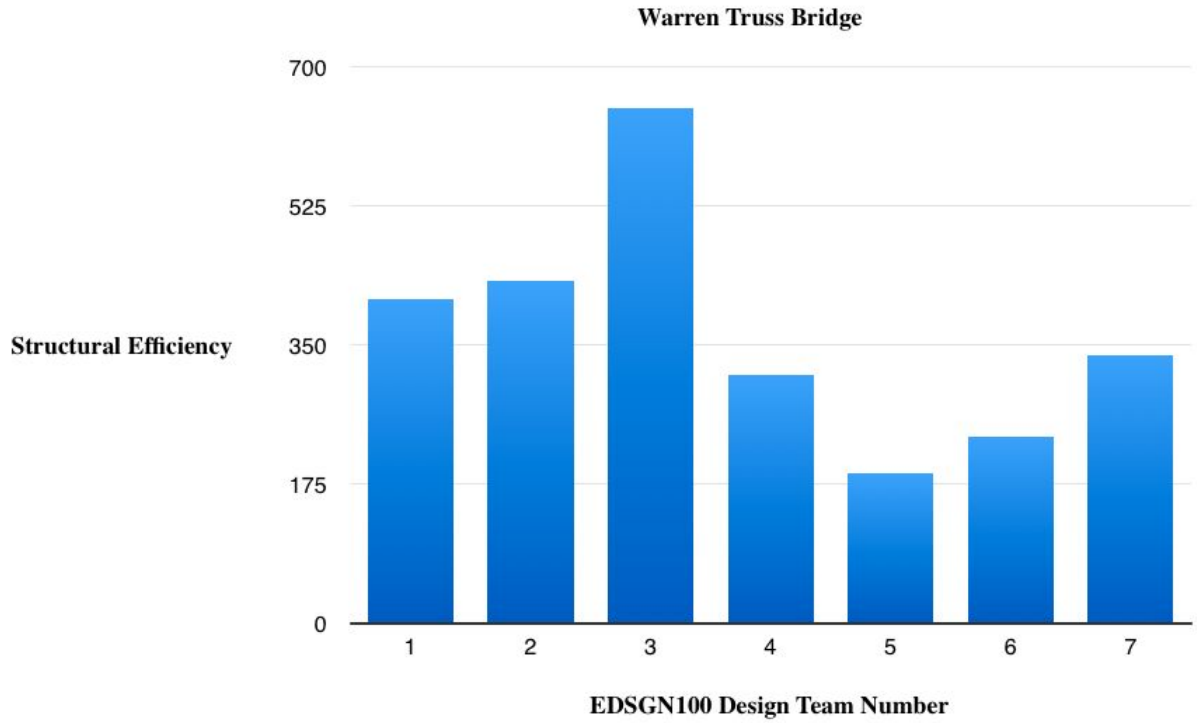


Figure 8. Warren Truss Bridge Structural Efficiencies