PENNSTATE

School of Engineering Design, Technology and Professional Programs
213 Hammond Building

October ##, 2015

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 100-year flood has destroyed the bridge located over Spring Creek in PennDOT Engineering District 2-0. This bridge is essential for vehicle transportation to the Mount Nittany Medical Center. Currently emergency vehicles cannot get to and from the medical center efficiently.

Objective. PennDOT Engineering District 2-0 has started an emergency, expedited project to quickly design a new bridge to replace the one destroyed by the flood.

Design Criteria. The bridge, being over a creek prone to flooding, has several specific qualifiers for its construction. To reduce chance of failure due to scour, the replacement bridge should be a single span, with no piers placed in the creek. The bridge type will either be a Howe or Warren Truss Bridge because neither requires piers and both can span long distances. More specifically, the bridge must include standard abutments, a 0.23m thick-medium strength concrete deck, no cable anchorages, a weight capacity equivalent to two AASHTO H20-44 trucks (one in each lane), and a length of 40 meters.

Technical Approach.

Phase 1: Economic Efficiency. In creating both the Howe and Warren Truss bridge design, the goal was to meet the design criteria while being as economically efficient as possible. To reduce price, different types of metal tubes (Carbon Steel Hollow Tube, High-Strength Low-Alloy Steel Hollow Tube, and Quenched & Tempered Steel Hollow Tube) and different sizes were used based on the size of the force on the member as well as if the force was tension or compression. Additionally, using the same type and size of member was helpful in reducing the price.

Phase 2: Structural Efficiency. In order to predict which bridge will be most efficient, Popsicle-stick prototypes of both the Warren and Howe truss bridge designs were made. For consistent results, each prototype bridge had a limit of sixty Popsicle sticks and the bridges' members were only allowed to be connected with Elmer's white glue. For the struts that attach the two trusses, hot glue will be used. Only eight Popsicle sticks may used as struts. The bridges will be approximately 13.5 inches in length, 4 inches in height, and 4.5 inches in width. Structural efficiency will be calculated by dividing the weight of load at failure by the weight of the bridge.

Results.

Phase 1: Economic Efficiency. After testing, it was determined that the Warren Truss Bridge ($232,745.35) was more economically efficient than the Howe Truss Bridge ($257,705.37). See attachment 1and its related tables and figures for more information.

Phase 2: Structural Efficiency. After testing, it was determined that the design team's Howe Truss Bridge(329lbs.) was more structurally efficient than the Warren Truss Bridge(323lbs.). See attachment 2 and its related tables and figures for more information.

Best Solution. The Warren Truss Bridge Model was more economically efficient than the Howe Truss Bridge Model by $24,960.02. However, the Howe Model was more structurally efficient than the Warren Model by 6lbs. In addition, the Howe models' had a higher structural efficiency average than the Warren models' by 28lbs. The Warren Model is about 11% less expensive than the Howe and, according to the Design Teams' average, the Howe Model only supports an additional 8% of weight.

Conclusions and Recommendations. Due to the aforementioned data, the design team finds the Warren Truss Bridge to be best fit to replace the bridge destroyed by the flood at Spring Creek. The economic efficiency of this bridge outweighs the barely superior structural efficiency of the Howe Truss Bridge. As a next step, the design team recommends that the design of the Warren be refined in order to lighten the bridge while maintaining it's failure load. This could be accomplished with different types or sizes of steel tubes and bar.

Respectfully,

Adam Granito
Engineering Student
EDSGN100 Section 001
Design Team 5
Team Money Team
College of Engineering
Penn State University

Michael Barychewsky
Engineering Student
EDSGN100 Section 001
Design Team 5
Team Money Team
College of Engineering
Penn State University

Ryan King
Engineering Student
EDSGN100 Section 001
Design Team 5
Team Money Team
College of Engineering
Penn State University

Jacob McCann
Engineering Student
EDSGN100 Section 001
Design Team 5
Team Money Team
College of Engineering
Penn State University

ATTACHMENT 1

Phase 1: Economic Efficiency

Howe Truss. For the Howe Truss, it was found to be most economically efficient to used carbon steel hollow tubing for the entire bridge. The use of the same type of metal helped significantly reduce the product cost. In total, the Howe Truss bridge came out at a cost of $257,705.37.

Warren Truss. For the Warren Truss, a different approach was taken. Instead of using the same type of member for the entire bridge, the design team experimented with using different types of metals. This allowed us to use the smallest possible members in the design of the bridge because the design team took advantage of the unique strengths and weaknesses of each bridge. For instance, the floor beams beneath the deck are a combination of High-Strength Low-Alloy Steel and Quenched & Tempered Steel. This was found to be more economically efficient than using only one type of steel. The Warren Truss came to a total cost of $232,745.35.

ATTACHMENT 2

Phase 2: Structural Efficiency

Howe Truss This prototype had a structural efficiency of 325, which was slightly below average. Most of the Popsicle sticks were used and the design team used a fairly traditional design except for one particular deviation.

Prototype Bridge. For the Howe Truss bridge prototype, the design team used Popsicle sticks, Elmer's glue, and hot glue (for struts only). The construction of the Howe used a fairly traditional design. The most significant deviation from a normal Howe was the reinforcement of the members in the center of the Howe Truss Bridge. The reinforced members are visible in figure 3. The Howe Truss Bridge used 60 Popsicle sticks (8 of which were used for struts). The bridge weighed in at 81.4 grams. The bridge was 13.19 inches in length, 3.81 inches in width, and 4.44 inches in height.

Load Testing. Team 3 had the greatest structural efficiency at 604 while team 2 had the lowest structural efficiency at 205. Our Howe Bridge's structural efficiency was 325, slightly below the average of 357. For all of the structural efficiency data, see table 7.

Forensic Analysis. The Howe Truss Bridge failed in several ways once it reached its load limit. One of the ways it failed was a diagonal disengaged from a vertical, causing a section of one of the truss sections to disconnect. In addition, the floor beam broke at the center of the bridge on both truss sections and, lastly, the end post of one of the truss sections separated from the top chord. The vertical to diagonal and end post to top chord failures were due to weakness in the glue, while the floor beam failures were due to weakness in the Popsicle sticks. These points of failure can be viewed in figure 4.

Results The Howe Prototype had a structural efficiency of 325, which was slightly below average. For a visual representation of the load testing results, which is presented in table 7, see figure 7.

Warren Truss. This prototype had a structural efficiency of 323, which was slightly below average. Most of the Popsicle sticks were used and the design team used a fairly traditional design.

Prototype Bridge. For the Warren Truss Bridge prototype, the design team used Popsicle sticks, Elmer's glue, and hot glue (for struts only). The bridge design is pretty standard for a Warren. The team attempted to maximize the amount of triangles that could be fit within the limits of the dimensions. The bridge used 58 Popsicle sticks (7 of which were used for struts). The bridge weighed 85.3 grams. The bridge was 13.06 inches in length, 3.62 inches in width, and 4.44 inches in height.

Load Testing. Team 3 had the greatest structural efficiency at 494 while team 4 had the lowest structural efficiency at 203. Our Howe Bridge's structural efficiency was 323, slightly below the average of 329. For all of the structural efficiency data, see table 8.

Forensic Analysis.

The Warren Truss Bridge Model's failure is much less complex than the Howe Model's. Both of the truss sections remained intact except for some slight bending in the middle. However, the two truss sections were essentially separated from each other. The points at which the bridge failed were where the struts and top chord were adhered. 6/7 Struts failed because the hot glue was not strong enough to hold the bridge together. At the last remaining strut the Popsicle stick fracture due to a weak spot in the stick. These points of failure can be seen in figure 6.

Results The Warren Prototype had a structural efficiency of 323, which was slightly below average. For a visual representation of the load testing results, which is presented in table 8, see figure 8.

TABLES

Table 1. Howe Truss Bridge
Cost Calculation Report from Bridge Designer 2015

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Carbon Steel Solid Bar	(10683.5 kg) x ($4.30 per kg) x (2 Trusses) =	$91,878.30
	Carbon Steel Hollow Tube	(4319.6 kg) x ($6.30 per kg) x (2 Trusses) =	$54,427.07
Connection Cost (C)		(20 Joints) x (500.0 per joint) x (2 Trusses) =	$20,000.00
Product Cost (P)	2 - 110x110 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	3 - 120x120 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	4 - 130x130 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	3 - 130x130x6 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	2 - 140x140 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	2 - 140x140x7 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	2 - 150x150 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	2 - 150x150x7 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	4 - 160x160 mm Carbon Steel Bar	(%s per Product) =	$1,000.00
	2 - 170x170x8 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	6 - 180x180x9 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	3 - 200x200x10 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	1 - 220x220x11 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	1 - 240x240x12 mm Carbon 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	(19,900 cubic meters) x ($1.00 per cubic meter) =	$19,900.00
	Abutment Cost	(2 standard abutments) x ($5,250.00 per abutment) =	$10,500.00
	Pier Cost	No pier =	$0.00
	Cable Anchorage Cost	No anchorages =	$0.00
Total Cost	M + C + P + S	$146,305.37 + $20,000.00 + $14,000.00 + $77,400.00	$257,705.37

Table 2. Howe Truss Bridge
Load Test Results from Bridge Designer 2015

#	Material Type	Cross Section	Size (mm)	Length (m)	Compression Force	Compression Strength	Compression Status	Tension Force	Tension Strength	Tension Status	#
1	CS	Hollow Tube	180x180x9	4.00	0.00	1165.88	OK	1433.42	1462.05	OK	1
2	CS	Solid Bar	110x110	4.00	0.00	1181.16	OK	2547.48	2873.75	OK	2
3	CS	Solid Bar	120x120	4.00	0.00	1606.24	OK	3341.16	3420.00	OK	3
4	CS	Solid Bar	130x130	4.00	0.00	2091.29	OK	3813.04	4013.75	OK	4
5	CS	Solid Bar	130x130	4.00	0.00	2091.29	OK	3962.84	4013.75	OK	5
6	CS	Solid Bar	130x130	4.00	0.00	2091.29	OK	3962.84	4013.75	OK	6
7	CS	Solid Bar	130x130	4.00	0.00	2091.29	OK	3791.27	4013.75	OK	7
8	CS	Solid Bar	120x120	4.00	0.00	1606.24	OK	3297.69	3420.00	OK	8
9	CS	Solid Bar	110x110	4.00	0.00	1181.16	OK	2482.44	2873.75	OK	9
10	CS	Hollow Tube	180x180x9	4.00	0.00	1165.88	OK	1398.78	1462.05	OK	10
11	CS	Solid Bar	120x120	4.00	1433.42	1606.24	OK	0.00	3420.00	OK	11
12	CS	Solid Bar	140x140	4.00	2547.48	2633.62	OK	0.00	4655.00	OK	12
13	CS	Solid Bar	160x160	4.00	3341.16	3881.59	OK	0.00	6080.00	OK	13
14	CS	Solid Bar	160x160	4.00	3813.04	3881.59	OK	0.00	6080.00	OK	14
15	CS	Solid Bar	160x160	4.00	3791.27	3881.59	OK	0.00	6080.00	OK	15
16	CS	Solid Bar	160x160	4.00	3297.69	3881.59	OK	0.00	6080.00	OK	16
17	CS	Solid Bar	140x140	4.00	2482.44	2633.62	OK	0.00	4655.00	OK	17
18	CS	Hollow Tube	200x200x10	4.00	1398.78	1487.26	OK	0.00	1805.00	OK	18
19	CS	Solid Bar	150x150	5.66	2027.17	2062.08	OK	0.00	5343.75	OK	19
20	CS	Hollow Tube	180x180x9	4.00	0.00	1165.88	OK	1422.54	1462.05	OK	20
21	CS	Hollow Tube	240x240x12	5.66	1649.57	2028.51	OK	0.00	2599.20	OK	21
22	CS	Hollow Tube	170x170x8	4.00	0.00	962.60	OK	1155.06	1231.20	OK	22
23	CS	Hollow Tube	200x200x10	5.66	1270.56	1293.53	OK	0.00	1805.00	OK	23
24	CS	Hollow Tube	150x150x7	4.00	0.00	704.11	OK	885.96	950.95	OK	24
25	CS	Hollow Tube	180x180x9	5.66	889.52	981.36	OK	0.00	1462.05	OK	25
26	CS	Hollow Tube	130x130x6	4.00	0.00	482.45	OK	615.92	706.80	OK	26
27	CS	Hollow Tube	150x150x7	5.66	508.09	550.30	OK	84.40	950.95	OK	27
28	CS	Hollow Tube	130x130x6	4.00	0.00	482.45	OK	624.38	706.80	OK	28
29	CS	Hollow Tube	140x140x7	5.66	464.82	474.03	OK	127.66	884.45	OK	29
30	CS	Hollow Tube	180x180x9	5.66	846.14	981.36	OK	0.00	1462.05	OK	30

31	CS	Hollow Tube	200x200x10	5.66	1227.01	1293.53	OK	0.00	1805.00	OK	31
32	CS	Hollow Tube	130x130x6	4.00	0.00	482.45	OK	585.24	706.80	OK	32
33	CS	Hollow Tube	140x140x7	4.00	0.00	630.23	OK	855.22	884.45	OK	33
34	CS	Hollow Tube	170x170x8	4.00	0.00	962.60	OK	1124.27	1231.20	OK	34

Table 3.
Howe Truss Bridge
Member Details Report From Bridge Designer 2015
Member with the highest Compression (or Tension) Force/Strength Ratio

Member List | Member Details

Member 29

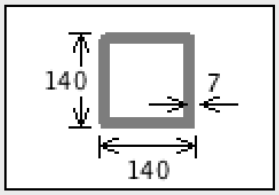
Material Properties:

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	Hollow Tube
Cross-Section Size	140x140x7
Area	0.0037 sq. meters
Moment of Inertia	1.10E-05 meters^4
Member Length	5.66 meters

Section (mm):



Cost:

Unit Cost	$184.17 per meter
Member Cost	$1041.83

Strength vs. Length: Graph all tabs Member:

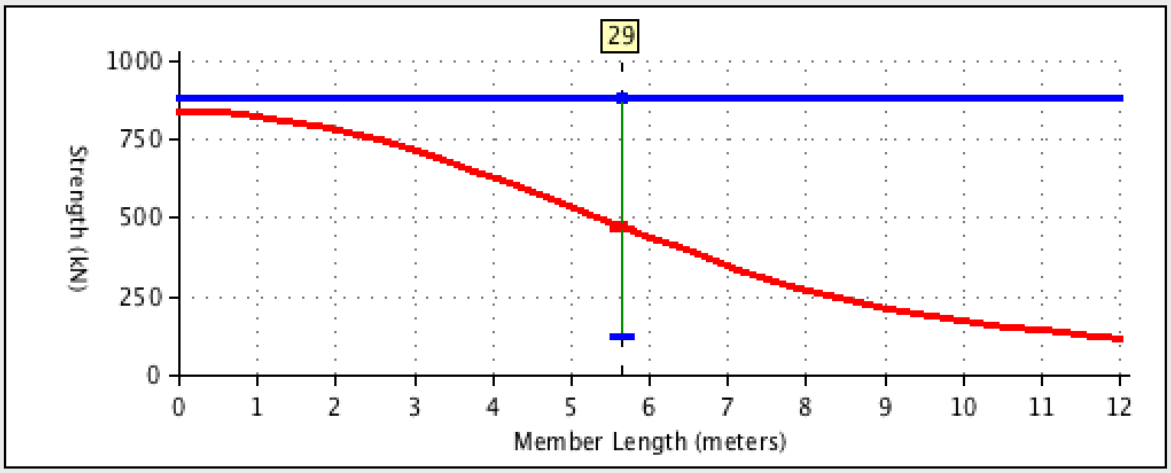


Table 4. Warren Truss Bridge
Cost Calculation Report from Bridge Designer 2015

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Carbon Steel Hollow Tube	(1300.5 kg) x ($6.30 per kg) x (2 Trusses) =	$16,385.68
	High-Strength Low-Alloy Steel Hollow Tube	(5232.4 kg) x ($7.00 per kg) x (2 Trusses) =	$73,253.60
	Quenched & Tempered Steel Hollow Tube	(2448.4 kg) x ($7.70 per kg) x (2 Trusses) =	$37,706.07
Connection Cost (C)		(16 Joints) x (500.0 per joint) x (2 Trusses) =	$16,000.00
Product Cost (P)	4 - 100x100x5 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	1 - 130x130x6 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	3 - 140x140x7 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	1 - 150x150x7 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	5 - 160x160x8 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	1 - 170x170x8 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	2 - 200x200x10 mm Carbon Steel Tube	(%s per Product) =	$1,000.00
	2 - 220x220x11 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	2 - 220x220x11 mm Quenched & Tempered Steel Tube	(%s per Product) =	$1,000.00
	4 - 240x240x12 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00

	2 - 260x260x13 mm High-Strength Low-Alloy Steel Tube	(%s per Product) =	$1,000.00
	2 - 280x280x14 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	(19,900 cubic meters) x ($1.00 per cubic meter) =	$19,900.00
	Abutment Cost	(2 standard abutments) x ($5,250.00 per abutment) =	$10,500.00
	Pier Cost	No pier =	$0.00
	Cable Anchorage Cost	No anchorages =	$0.00
Total Cost	M + C + P + S	$127,345.35 + $16,000.00 + $12,000.00 + $77,400.00 =	$232,745.35

Table 5. Warren Truss Bridge
Load Test Results from Bridge Designer 2015

#	Material Type	Cross Section	Size (mm)	Length (m)	Compression Force	Compression Strength	Compression Status	Tension Force	Tension Strength	Tension Status	#
1	CS	Hollow Tube	200x200x10	5.66	1245.89	1293.53	OK	0.00	1805.00	OK	1
2	CS	Hollow Tube	140x140x7	5.66	0.00	474.03	OK	866.85	884.45	OK	2
3	CS	Hollow Tube	150x150x7	5.66	507.24	550.30	OK	85.24	950.95	OK	3
4	CS	Hollow Tube	140x140x7	5.66	462.97	474.03	OK	129.52	884.45	OK	4
5	HSS	Hollow Tube	130x130x6	5.66	0.00	373.92	OK	822.15	975.38	OK	5
6	CS	Hollow Tube	200x200x10	5.66	1200.88	1293.53	OK	0.00	1805.00	OK	6
7	HSS	Hollow Tube	160x160x8	5.66	0.00	827.32	OK	1561.18	1594.18	OK	7
8	HSS	Hollow Tube	260x260x13	8.00	2417.91	2528.09	OK	0.00	4209.62	OK	8
9	QTS	Hollow Tube	280x280x14	8.00	3691.31	3741.86	OK	0.00	6863.33	OK	9
10	QTS	Hollow Tube	280x280x14	8.00	3712.37	3741.86	OK	0.00	6863.33	OK	10
11	HSS	Hollow Tube	260x260x13	8.00	2480.28	2528.09	OK	0.00	4209.62	OK	11
12	HSS	Hollow Tube	220x220x11	5.66	1975.38	2076.87	OK	0.00	3013.99	OK	12
13	HSS	Hollow Tube	220x220x11	5.66	1929.03	2076.87	OK	0.00	3013.99	OK	13
14	HSS	Hollow Tube	160x160x8	4.00	0.00	1117.80	OK	1364.03	1594.18	OK	14
15	HSS	Hollow Tube	160x160x8	4.00	0.00	1117.80	OK	1364.03	1594.18	OK	15
16	HSS	Hollow Tube	240x240x12	4.00	0.00	2972.71	OK	3214.70	3586.90	OK	16
17	HSS	Hollow Tube	240x240x12	4.00	0.00	2972.71	OK	3214.70	3586.90	OK	17
18	QTS	Hollow Tube	220x220x11	4.00	0.00	3209.27	OK	3861.57	4237.06	OK	18
19	QTS	Hollow Tube	220x220x11	4.00	0.00	3209.27	OK	3861.57	4237.06	OK	19
20	HSS	Hollow Tube	240x240x12	4.00	0.00	2972.71	OK	3256.52	3586.90	OK	20
21	HSS	Hollow Tube	240x240x12	4.00	0.00	2972.71	OK	3256.52	3586.90	OK	21
22	HSS	Hollow Tube	160x160x8	4.00	0.00	1117.80	OK	1396.80	1594.18	OK	22
23	HSS	Hollow Tube	160x160x8	4.00	0.00	1117.80	OK	1396.80	1594.18	OK	23
24	CS	Hollow Tube	140x140x7	4.00	0.00	630.23	OK	619.53	884.45	OK	24
25	HSS	Hollow Tube	170x170x8	5.66	0.00	947.42	OK	1606.33	1699.06	OK	25
26	HSS	Hollow Tube	100x100x5	4.00	0.00	273.05	OK	621.68	622.73	OK	26
27	HSS	Hollow Tube	100x100x5	4.00	0.00	273.05	OK	620.95	622.73	OK	27
28	HSS	Hollow Tube	100x100x5	4.00	0.00	273.05	OK	621.68	622.73	OK	28
29	HSS	Hollow Tube	100x100x5	4.00	0.00	273.05	OK	619.15	622.73	OK	29

Table 6.
Warren Truss Bridge
Member Details Report From Bridge Designer 2015
Member with the highest Compression (or Tension) Force/Strength Ratio

Member List | Member Details

Member 29

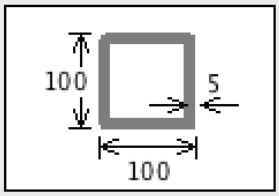
Material Properties:

Material	High-Strength Low-Alloy Steel
Yield Stress (Fy)	345000 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	100x100x5
Area	0.0019 sq. meters
Moment of Inertia	2.87E-06 meters^4
Member Length	4.00 meters

Section (mm):



Cost:

Unit Cost	$104.41 per meter
Member Cost	$417.62

Strength vs. Length: Graph all tabs Member:

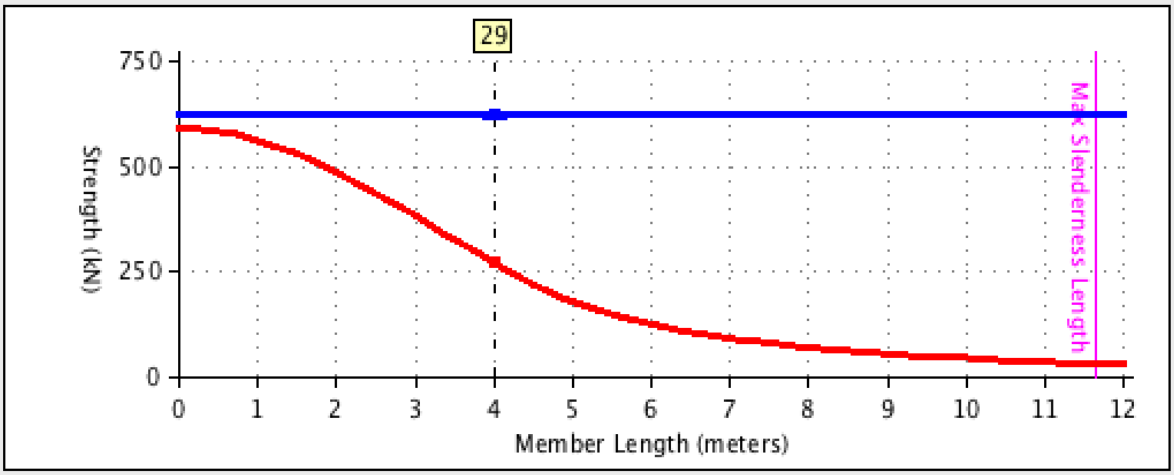


Table 7.
Howe Truss Bridge
Loading Results

Design Team No.	Bridge Weight (Grams)	Bridge Weight (lbs.)	Load at Failure (lbs.)	Structural efficiency
1	84.5	0.186	49.4	266
2	75.3	0.166	34.0	205
3	81.8	0.180	108.8	604
4	78.1	0.1683	77.9	463
5	81.4	0.1794	58.3	325
6	85.2	0.188	72.1	384
7	74.7	0.164	34.3	208
8	80.0	0.176	70.0	398

Minimum: 205
Maximum: 604
Range: 399
Mean: 357

Table 8.
Warren Truss Bridge
Loading Results

Design Team No.	Bridge Weight (Grams)	Bridge Weight (lbs.)	Load at Failure (lbs.)	Structural efficiency
1	85.3	0.1881	39	207
2	80.3	0.1770	55.1	311
3	83.4	0.1839	90.8	494
4	73.2	0.1614	32.7	203
5	85.3	0.1881	60.8	323
6	83.8	0.1847	70.4	381
7	75.5	0.1664	55.6	334
8	81.9	0.1806	68.4	379

Minimum: 203
Maximum: 494
Range: 291
Mean: 329

FIGURES

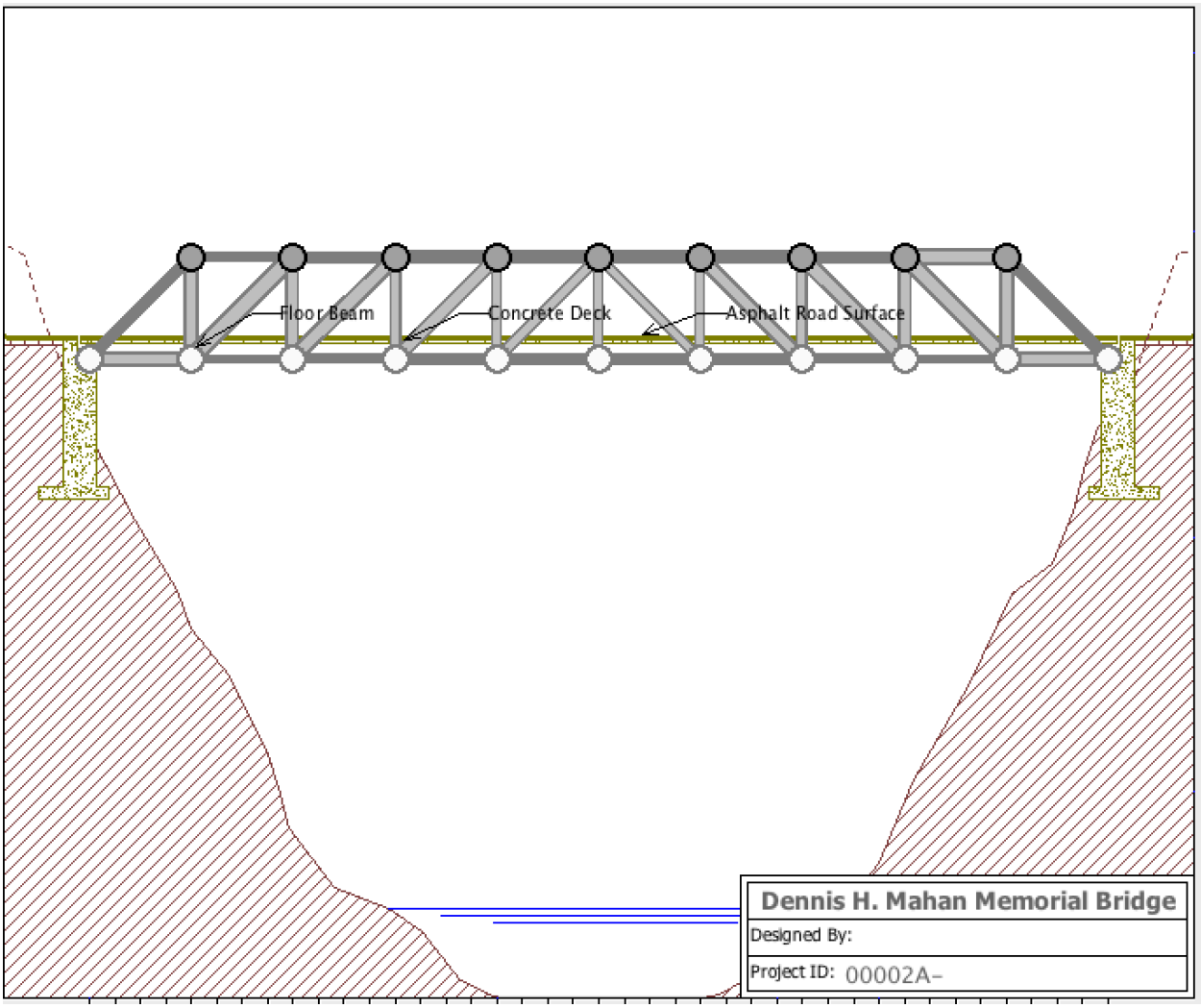


Figure 1. Howe Truss Bridge Model from Bridge Designer 2015

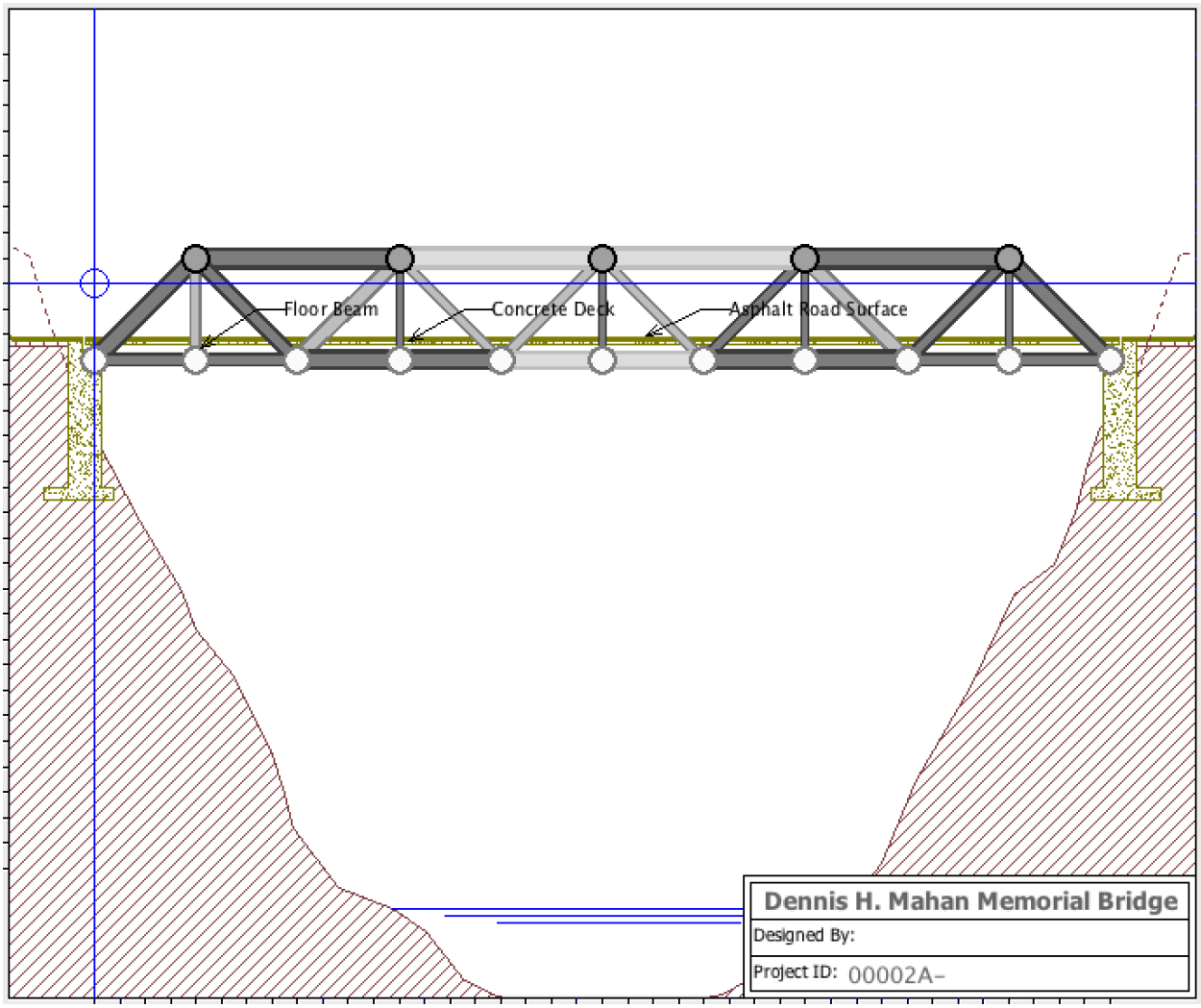


Figure 2. Warren Truss Bridge Model from Bridge Designer 2015

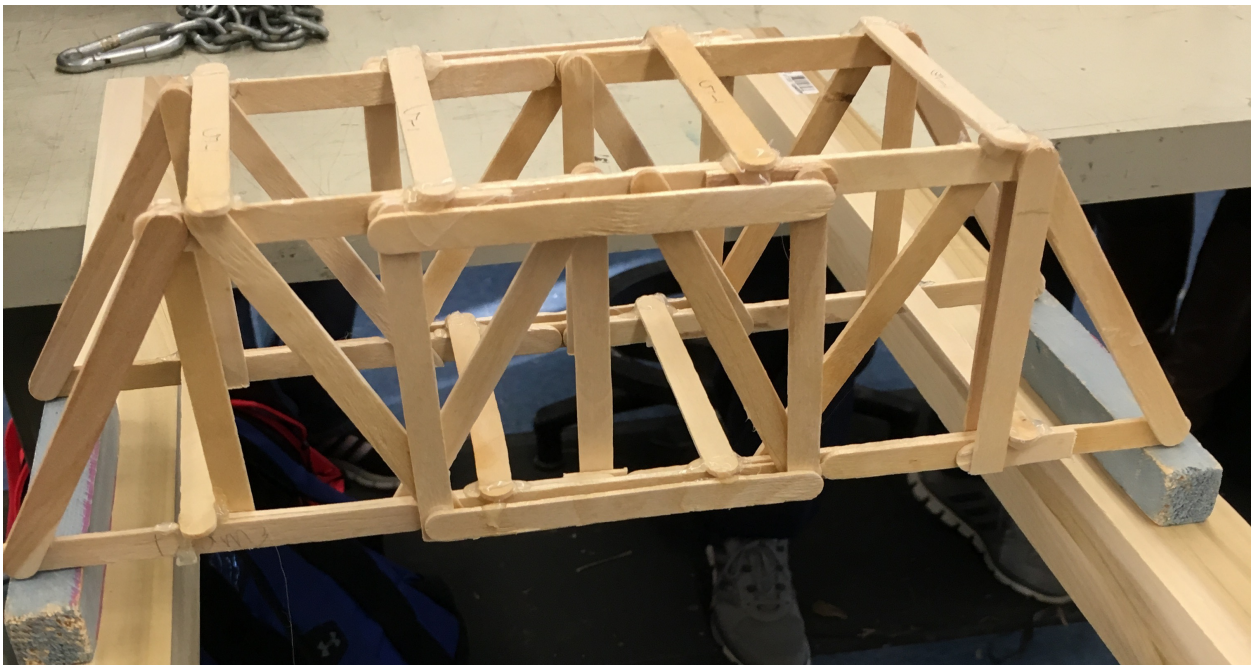


Figure 3. Howe Truss Bridge Prototype before Loading Testing

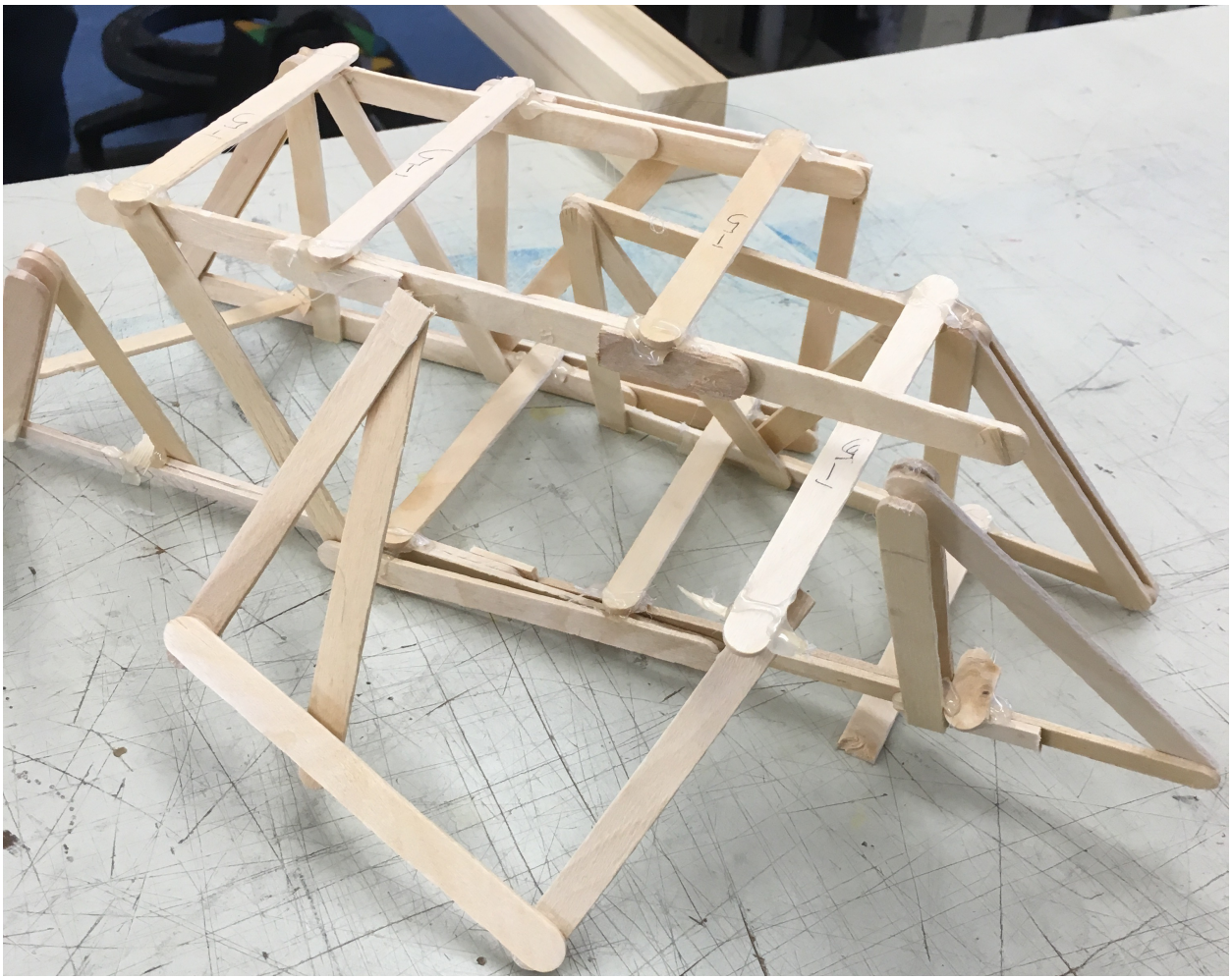


Figure 4. Howe Truss Bridge Prototype Failure after Load Testing

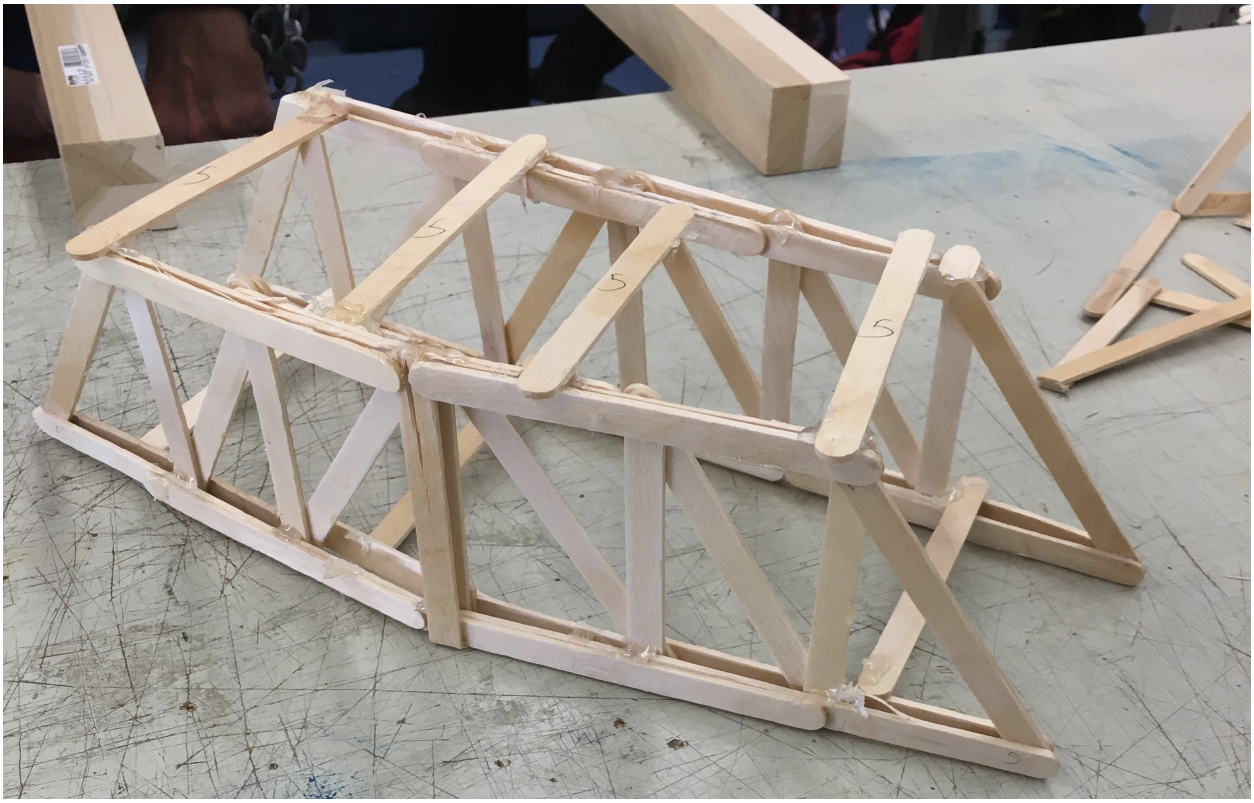


Figure 5. Warren Truss Bridge Prototype before Load Testing

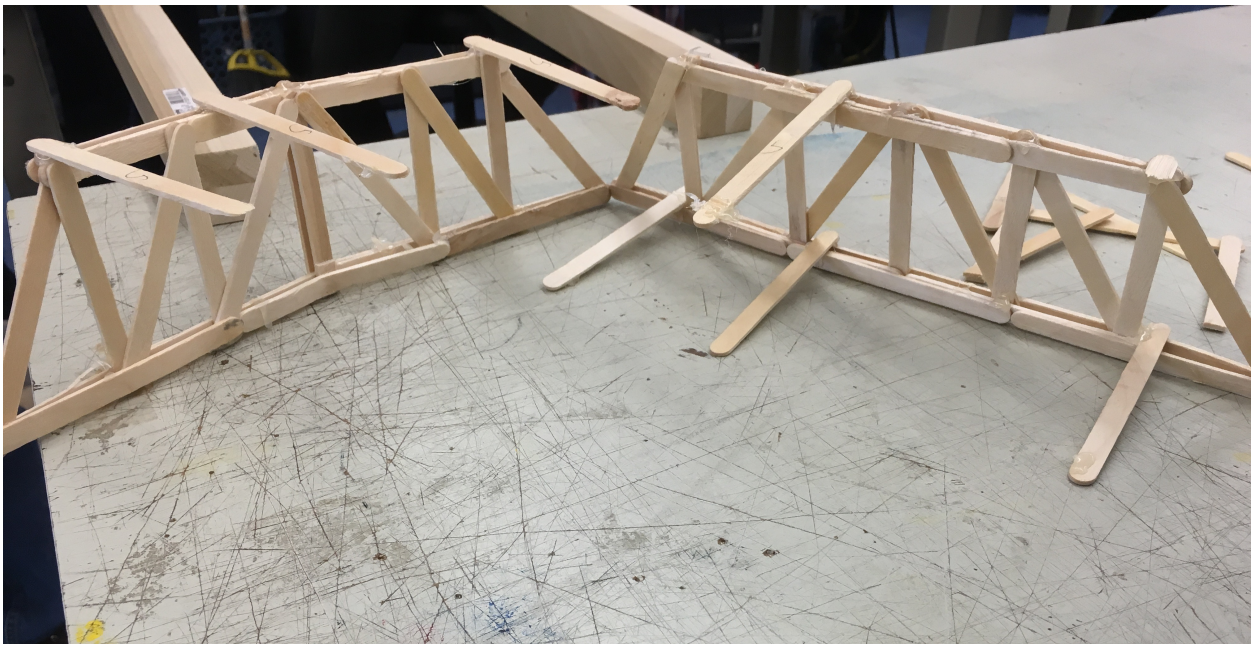


Figure 6. Warren Truss Bridge Prototype Failure after Load Testing

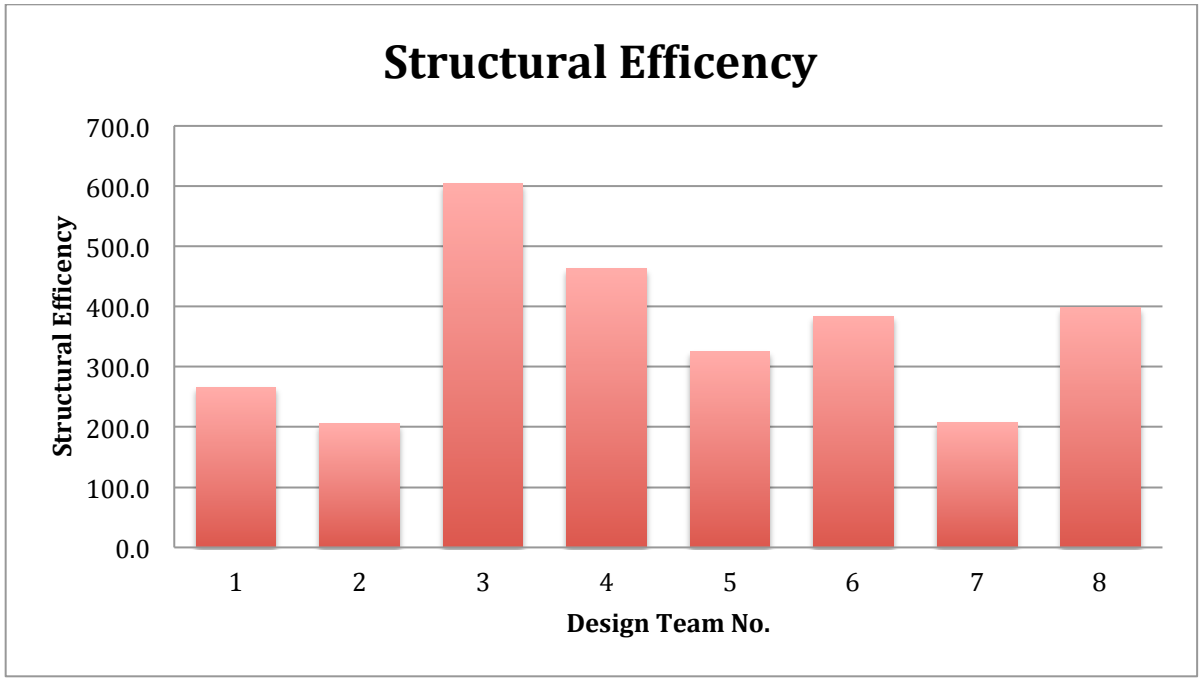


Figure 7. Howe Truss Bridge Structural Efficiencies

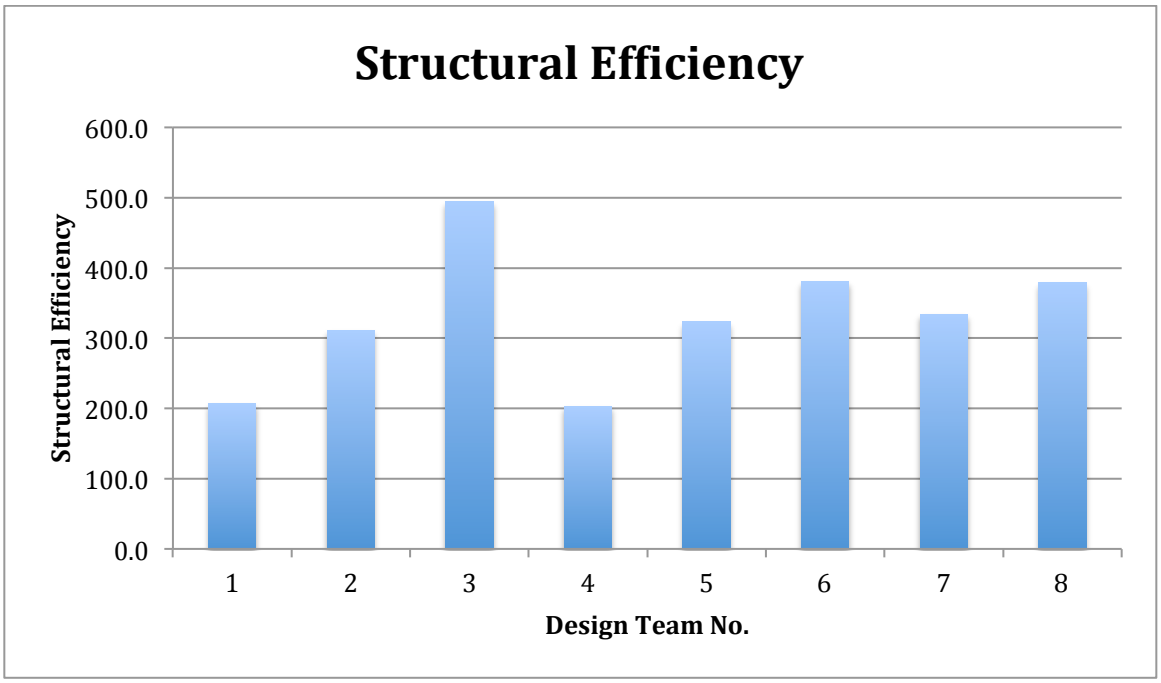


Figure 8. Warren Truss Bridge Structural Efficiencies