PENNSTATE

School of Engineering Design, Technology and Professional Programs
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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. Due to recent flooding, a heavily traveled bridge located in Pennsylvania Department of Transportation (PennDOT) Engineering District 2-0 has been destroyed. This failure of this bridge has put the residents of State College at risk since this bridge provided access for emergency vehicles travelling to the local hospital.

Objective. To quickly design an effective replacement to the destroyed vehicle bridge.

Design Criteria. The bridge must include standard abutments, no piers, medium strength concrete, no cables, and designed for a 450kN load. It must span 40 meters while the deck elevation is set at 20 meters.

Technical Approach.

Phase 1: Economic Efficiency. The cost of the replacement bridge will be estimated by the bridge design software used to design the bridge (Bridge Designer 2015).

Phase 2: Structural Efficiency. The structural efficiency is calculation of the load test results at failure of a prototype Howe and prototype Warren through truss bridge. The prototypes were constructed using Popsicle sticks and Elmer's white glue for the trusses and hot glue for the struts and floor beams. The load test was constructed using a block with a bucket of sand attached to it below. Sand was poured into the bucket until the bridge failed and the bucket was then massed.

Results.

Phase 1: Economic Efficiency. The cost of the bridge designs consisted of four parts including the material cost, connection cost, product cost, and site cost. The material had the

largest influence on the total cost while the site cost, connection cost and product cost followed. The Warren Truss Bridge's cost totaled to be $246,958 while the Howe Truss Bridge's cost accumulated up to $239,096 (See Attachment 1 for further details).

Phase 2: Structural Efficiency. The structural efficiencies for the Howe and Warren Truss Bridges were 354 lb/lb and 338 lb/lb respectively. Compared to the other design teams the Howe Truss Bridge performed better than the geometric mean while the Warren Truss Bridge was less effective than the geometric mean (See Attachment 2 for further details).

Best Solution. The Howe Truss Bridge and Warren Truss Bridge cost $239,096 and $246,958 respectively. The Howe Truss Bridge is $7,862 cheaper compared to the Warren Truss Bridge. However, each bridge did not hold an identical load. The structural efficiency of the Howe Truss Bridge was calculated to be 354 while the Warren Truss Bridge was found to be 338. The optimal choice of a bridge would minimize the cost per utility. The design efficiency of the bridges is calculated by dividing the structural efficiency into the economic efficiency. The Howe Truss Bridge is the clear choice with a design efficiency of $675 per unit of structural efficiency versus the Warren Truss Bridge having a design efficiency of $731 per unit of structural efficiency. The constructability values of each bridge are almost identical with a slight advantage to the Warren Truss Bridge as it uses one less type of product than the Howe Truss Bridge.

Conclusions and Recommendations. Moving forward, the solution of this problem is to construct a through truss bridge to avoid a repeat scenario of a flood destroying the structure. The optimal truss type for this situation is the Howe Truss, as it provides the highest design efficiency. In conclusion, PennDOT should begin the process of seeking permits, acquiring materials, and hiring labor to complete the bridge.

Respectfully,

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ATTACHMENT 1

Phase 1: Economic Efficiency

Howe Truss. For the Howe Truss Bridge, the cost was determined to be $239,096 as seen in Table 1. The most expensive part of the bridge construction was the material costs for the trusses. The primary material used was the carbon steel solid bar, which had a cheap price per mass however they were very heavy. The next most prominent material was the carbon steel hollow tubes, which were the most expensive per mass but were relatively light given their hollow nature. Lastly, the least used material was the quenched & tempered steel solid bar which were slightly cheaper than the carbon steel hollow tubes and referencing Table 2, it is obvious they could support the strongest tensile forces.

Next, the connection and product costs totaled $30,000.00. This includes the cost of procuring different types of materials as well as connecting each member during the assembly. Another significant expense for the bridge was the site cost coming to $77,400. Within the site cost includes the price of assembling the decks, excavating the required area to put the bridge in place, and the abutments on either end to keep the bridge sturdy.

Warren Truss. For the Warren Truss Bridge, the cost was higher than that of the Howe Truss Bridge at $246,958 as seen in Table 4. Again, the most expensive portion of the bridge construction was the material costs for the trusses. The primary material utilized for the trusses was the carbon steel solid bar. The bridge contains 11,635.6 kg of the relatively cheap carbon steel solid bars. The carbon steel hollow tubes used in the design were significantly less prominent in the design with only 2,280.9 kg used. A few quenched & tempered steel solid bars and hollow tubes were used but were crucial for their extraordinary tension strength as seen in Table 5.

The connection and product costs for the Warren Truss Bridge totaled slightly less than the Howe Truss Bridge at $29,800. This bridge had one more joint but one less product type required to be procured. The site cost for the Warren Truss Bridge was the same as the Howe since they have identical dimensions and use the same abutments.

ATTACHMENT 2

Phase 2: Structural Efficiency

Howe Truss. The structural efficiency for the Howe Truss Bridge was 354 lb/lb as seen in Table 7. This number was attained by dividing the load at failure by the weight of the bridge.

Prototype Bridge. The prototype Howe Truss Bridge was created using wood glue, Popsicle sticks, and hot glue for attaching the floor beams and struts. Joints were lightly sanded to allow the glue to bind more firmly with the Popsicle sticks. The prototype can be observed prior to its demise in Figure 3.

Load Testing. The maximum structural efficiency was a whopping 555 and the minimum was a dismal 201. The geometric mean of all design teams' Howe Truss Bridges was 318 so this prototype proved to be effective at 354. The range of the groups' bridges was 354, showing a great deal of variance between the design teams. As seen in Table 7, this prototype failed at 65.3 lbs, which ranked third amongst the class.

Forensic Analysis. The primary cause of failure was joints to the floor beams and struts were not glued effectively, and as a result the right joints as seen in figure 4 were ripped apart and allowed for the bridge to contort and forces to perpendicular to the sticks.

Results. See Figure 7 for a comparison of groups' structural efficiencies.

Warren Truss. The structural efficiency for the Warren Truss Bridge was 338 lb/lb as displayed in Table 8. This was calculated by taking the load at failure and dividing it by the bridge weight.

Prototype Bridge. The prototype Warren Truss Bridge was created using wood glue, Popsicle sticks, and hot glue for attaching the floor beams and struts. Joints were lightly sanded to allow the glue to bind more firmly with the Popsicle sticks. The prototype can be observed prior to its demise in Figure 5.

Load Testing. The maximum structural efficiency calculated was an astounding 733 and the minimum was 237. The geometric mean of all design teams' Warren Truss Bridges was 392 so this prototype was less operational at 338. The range of the groups' bridges was 496, which is skewed by design team 6's Bridge. As seen in Table 8, this prototype failed at 59.7 lbs, which ranked fifth amongst the class.

Forensic Analysis. The main cause of failure for the bridge was the fracture of the end floor beam. This fracture compromised the structural integrity of the design and then many of the joints between the trusses and struts failed ultimately leading to the demise of the Warren Truss Bridge.

Results. See Figure 8 for a comparison of groups' structural efficiencies.

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 Solid Bar	(6769.1 kg) x ($4.30 per kg) x (2 Trusses)	$58,213.87
	Carbon Steel Hollow Tube	(3553.2 kg) x ($6.30 per kg) x (2 Trusses)	$44,770.51
	Quenched & Tempered Steel Solid Bar	(2392.7 kg) x ($6.00 per kg) x (2 Trusses)	$28,712.16
Connection Cost (C)		(20 Joints) x ($400 per joint) x (2 Trusses) =	$16,000.00
Product Cost (P)	2-60x60	($1,000.00 per Product) =	$1,000.00
	5-65x65	($1,000.00 per Product) =	$1,000.00
	2-75x75	($1,000.00 per Product) =	$1,000.00
	2-80x80	($1,000.00 per Product) =	$1,000.00
	2-80x80	($1,000.00 per Product) =	$1,000.00
	2-90x90	($1,000.00 per Product) =	$1,000.00
	4-100x100	($1,000.00 per Product) =	$1,000.00
	2-120x120	($1,000.00 per Product) =	$1,000.00
	2-140x140	($1,000.00 per Product) =	$1,000.00
	2-150x150x7	($1,000.00 per Product) =	$1,000.00
	4-160x160	($1,000.00 per Product) =	$1,000.00
	2-190x190x9	($1,000.00 per Product) =	$1,000.00
	2-200x200x10	($1,000.00 per Product) =	$1,000.00
	4-240x240x12	($1,000.00 per Product) =	$1,000.00
Site Cost (S)	Deck Cost	(10 4-meter panels) x ($4,700 per panel) =	$47,000.00
	Excavation Cost	(19,400 cubic meters) x ($1.00 per cubic meter) =	$19,400.00
	Abutment	(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**	**$131,696.54 + $16,000 + $14,000 + $77,400.00 =**	**$239,096**

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	Solid Bar	60x60	4.00	0.00	105.53	OK	1420.82	1658.70	OK
2	QTS	Solid Bar	80x80	4.00	0.00	333.51	OK	2527.29	2948.80	OK
3	QTS	Solid Bar	90x90	4.00	0.00	534.22	OK	3315.70	3732.08	OK
4	QTS	Solid Bar	100x100	4.00	0.00	814.24	OK	3784.85	4607.50	OK
5	QTS	Solid Bar	100x100	4.00	0.00	814.24	OK	3934.16	4607.50	OK
6	QTS	Solid Bar	100x100	4.00	0.00	814.24	OK	3934.16	4607.50	OK
7	QTS	Solid Bar	100x100	4.00	0.00	814.24	OK	3764.36	4607.50	OK
8	QTS	Solid Bar	90x90	4.00	0.00	534.22	OK	3274.73	3732.08	OK
9	QTS	Solid Bar	80x80	4.00	0.00	333.51	OK	2465.85	2948.80	OK
10	QTS	Solid Bar	60x60	4.00	0.00	105.53	OK	1388.94	1658.70	OK
11	CS	Tube	240x240	5.66	2009.35	2028.51	OK	0.00	2599.20	OK
12	CS	Solid Bar	120x120	4.00	1420.82	1606.24	OK	0.00	3420.00	OK
13	CS	Solid Bar	140x140	4.00	2527.29	2633.62	OK	0.00	4655.00	OK
14	CS	Solid Bar	160x160	4.00	3315.70	3881.59	OK	0.00	6080.00	OK
15	CS	Solid Bar	160x160	4.00	3784.85	3881.59	OK	0.00	6080.00	OK
16	CS	Solid Bar	160x160	4.00	3764.36	3881.59	OK	0.00	6080.00	OK
17	CS	Solid Bar	160x160	4.00	3274.73	3881.59	OK	0.00	6080.00	OK
18	CS	Solid Bar	140x140	4.00	2465.85	2633.62	OK	0.00	4655.00	OK
19	CS	Solid Bar	120x120	4.00	1388.94	1606.24	OK	0.00	3420.00	OK
20	CS	Tube	240x240	5.66	1964.26	2028.51	OK	0.00	2599.20	OK
21	CS	Tube	240x240	5.66	1593.75	2028.51	OK	0.00	2599.20	OK
22	CS	Tube	150x150	5.66	462.30	550.30	OK	130.18	950.95	OK
23	CS	Tube	190x190	5.66	840.56	1077.83	OK	0.00	1547.55	OK
24	CS	Tube	200x200	5.66	1218.00	1293.53	OK	0.00	1805.00	OK
25	CS	Tube	240x240	5.66	1638.84	2028.51	OK	0.00	2599.20	OK
26	CS	Tube	200x200	5.66	1263.09	1293.53	OK	0.00	1805.00	OK
27	CS	Tube	190x190	5.66	885.66	1077.83	OK	0.00	1547.55	OK

28	CS	Tube	150x150	5.66	507.40	550.30	OK	85.09	950.95	OK
29	CS	Solid Bar	80x80	4.00	0.00	333.51	OK	1413.28	1520.00	OK
30	CS	Solid Bar	75x75	4.00	0.00	257.63	OK	1147.38	1335.94	OK
31	CS	Solid Bar	65x65	4.00	0.00	145.35	OK	880.63	1003.44	OK
32	CS	Solid Bar	65x65	4.00	0.00	145.35	OK	612.82	1003.44	OK
33	CS	Solid Bar	65x65	4.00	0.00	145.35	OK	621.77	1003.44	OK
34	CS	Solid Bar	65x65	4.00	0.00	145.35	OK	580.93	1003.44	OK
35	CS	Solid Bar	65x65	4.00	0.00	145.35	OK	848.75	1003.44	OK
36	CS	Solid Bar	75x75	4.00	0.00	257.63	OK	1115.50	1335.94	OK
37	CS	Solid Bar	80x80	4.00	0.00	333.51	OK	1381.40	1520.00	OK

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

Member List | Member Details

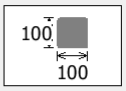
Current Material

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: Section (mm):

Cross-Section Type	Solid Bar
Cross-Section Size	100x100
Area	0.0100 sq. meters
Moment of Inertia	8.33E-06 meters⁴
Member Length	--



Cost:

Unit Cost	$471.00 per meter
Member Cost	--

Strength vs. Length: Graph all tabs Member:

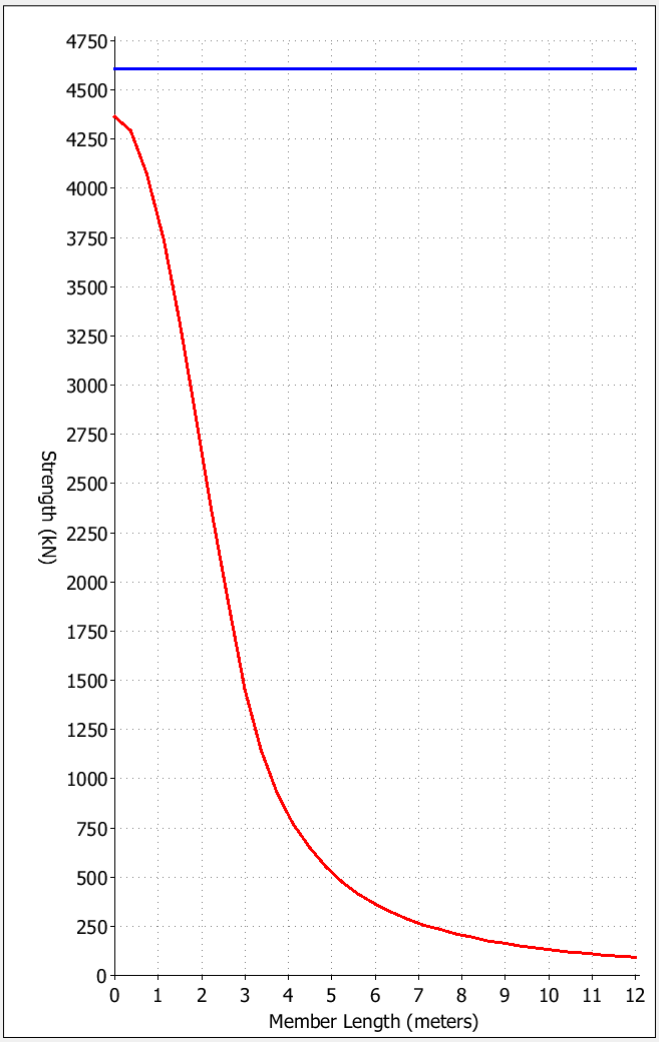


Table 4
Cost Calculation Report from Bridge Designer 2015 for the Warren Truss Bridge

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Carbon Steel Solid Bar	(11635.6 kg) x ($4.30 per kg) x (2 Trusses) =	$100,065.89
	Carbon Steel Hollow Tube	(2280.9 kg) x ($6.30 per kg) x (2 Trusses) =	$28,739.75
	Quenched & Tempered Steel Solid Bar	(508.7 kg) x ($6.00 per kg) x (2 Trusses) =	$6,104.16
	Quenched & Tempered Steel Hollow Tube	(314.9 kg) x ($7.70 per kg) x (2 Trusses) =	$4,848.74
Connection Cost (C)		(21 Joints) x (400.0 per joint) x (2 Trusses) =	$16,800.00
Product Cost (P)	2 – 90x90 mm Carbon Steel Bar	($1,000.00 per Product) =	$1,000.00
	2 – 90x90 mm Quenched & Tempered Steel Bar	($1,000.00 per Product) =	$1,000.00
	6 – 110x110 mm Carbon Steel Bar	($1,000.00 per Product) =	$1,000.00
	2 – 120x120 mm Carbon Steel Bar	($1,000.00 per Product) =	$1,000.00
	4 – 120x120x6 mm Carbon Steel Tube	($1,000.00 per Product) =	$1,000.00
	4 – 130x130 mm Carbon Steel Bar	($1,000.00 per Product) =	$1,000.00
	3 – 130x130x6 mm Carbon Steel Tube	($1,000.00 per Product) =	$1,000.00
	2 – 140x140 mm Carbon Steel Bar	($1,000.00 per Product) =	$1,000.00
	1 – 140x140x7 mm Carbon Steel Tube	($1,000.00 per Product) =	$1,000.00
	2 – 140x140x7 mm Quenched & Tempered Steel Tube	($1,000.00 per Product) =	$1,000.00
	5 – 150x150 mm Carbon Steel Bar	($1,000.00 per Product) =	$1,000.00
	4 – 160x160x8 mm Carbon Steel Tube	($1,000.00 per Product) =	$1,000.00
	2 – 180x180x9 mm Carbon Steel Tube	($1,000.00 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**	**$139,758.54 + $16,800.00 + $13,000.00 + $77,400.00 =**	**$246,958.54**

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	CS	Tube	120x120	4.00	0.00	417.77	OK	572.87	649.80	OK
2	CS	Solid Bar	90x90	4.00	0.00	534.22	OK	1564.33	1923.75	OK
3	CS	Solid Bar	110x110	4.00	0.00	1181.16	OK	2299.26	2873.75	OK
4	CS	Solid Bar	120x120	4.00	0.00	1606.24	OK	2778.95	3420.00	OK
5	QTS	Solid Bar	90x90	4.00	0.00	534.22	OK	3023.34	3732.08	OK
6	QTS	Solid Bar	90x90	4.00	0.00	534.22	OK	3035.95	3732.08	OK
7	CS	Solid Bar	120x120	4.00	0.00	1606.24	OK	2795.16	3420.00	OK
8	CS	Solid Bar	110x110	4.00	0.00	1181.160	OK	2299.14	2873.75	OK
9	CS	Solid Bar	90x90	4.00	0.00	2091.29	OK	1547.87	1923.75	OK
10	CS	Tube	120x120	4.00	0.00	3230.99	OK	560.09	649.80	OK
11	CS	Solid Bar	110x110	4.00	1141.18	3230.99	OK	0.00	2873.75	OK
12	CS	Solid Bar	130x130	4.00	2024.65	3230.99	OK	0.00	4013.75	OK
13	CS	Solid Bar	150x150	4.00	2653.16	3230.99	OK	0.00	5343.75	OK
14	CS	Solid Bar	150x150	4.00	3025.80	3230.99	OK	0.00	5343.75	OK
15	CS	Solid Bar	150x150	4.00	3143.97	3230.99	OK	0.00	5343.75	OK
16	CS	Solid Bar	150x150	4.00	3009.21	3230.99	OK	0.00	5343.75	OK
17	CS	Solid Bar	150x150	4.00	2620.24	3230.99	OK	0.00	5343.75	OK
18	CS	Solid Bar	130x130	4.00	1975.39	2091.29	OK	0.00	4013.75	OK
19	CS	Solid Bar	110x110	4.00	1115.62	1181.16	OK	0.00	2873.75	OK
20	CS	Solid Bar	140x140	5.39	1542.50	1732.39	OK	0.00	4655.00	OK
21	CS	Solid Bar	140x140	5.39	1508.09	1732.39	OK	0.00	4655.00	OK
22	CS	Solid Bar	110x110	5.39	0.00	657.73	OK	1495.82	2873.75	OK
23	CS	Solid Bar	110x110	5.39	0.00	657.73	OK	1530.24	2873.75	OK
24	CS	Solid	130x130	5.39	1252.16	1283.07	OK	0.00	4013.84	OK

		Bar								
25	QTS	Tube	140x140	5.39	0.00	593.50	OK	1239.45	1715.83	OK
26	CS	Tube	180x180	5.39	965.03	1013.58	OK	0.00	1462.05	OK
27	CS	Tube	160x160	5.39	0.00	737.10	OK	952.89	1155.20	OK
28	CS	Tube	160x160	5.39	677.11	737.10	OK	0.00	1155.20	OK
29	CS	Tube	130x130	5.39	0.00	369.64	OK	664.68	706.80	OK
30	CS	Tube	140x140	5.39	390.71	500.03	OK	60.52	884.45	OK
31	CS	Tube	120x120	5.39	72.54	304.89	OK	378.68	649.80	OK
32	CS	Tube	120x120	5.39	106.50	304.89	OK	344.73	649.80	OK
33	CS	Tube	130x130	5.39	356.52	369.64	OK	94.70	706.80	OK
34	CS	Tube	130x130	5.39	0.00	369.64	OK	630.27	706.80	OK
35	CS	Tube	160x160	5.39	642.70	737.10	OK	0.00	1155.20	OK
36	CS	Tube	160x160	5.39	0.00	737.10	OK	918.48	1155.20	OK
37	CS	Tube	180x180	5.39	930.62	1013.58	OK	0.00	1462.05	OK
38	QTS	Tube	140x140	5.39	0.00	593.50	OK	1205.04	1715.83	OK
39	CS	Solid Bar	130x130	5.39	1217.74	1283.07	OK	0.00	4013.75	OK

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

Member List | Member Details

Member 29

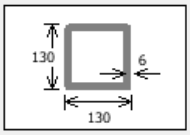
Material Properties:

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	130x130x6
Area	0.0030 sq. meters
Moment of Inertia	7.64E-06 meters^4
Member Length	5.39 meters

Section (mm):



Cost:

Unit Cost	$147.18 per meter
Member Cost	$792.58

Strength vs. Length: Graph all tabs Member:

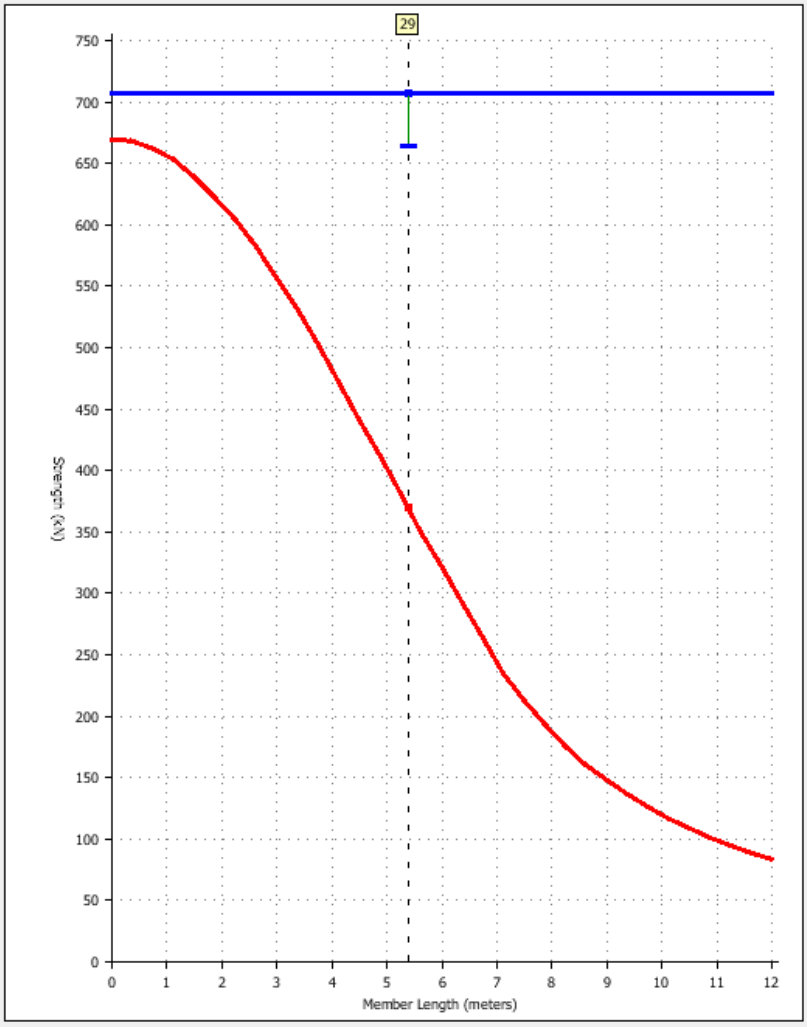


Table 7
Load Testing Results for the Howe Truss Bridge

EDSGN100 Design Team#	Howe Truss Bridge Weight (grams)	Bridge Weight (lbs.)	Load at Failure (lbs.)	Structural Efficiency
1	83.8	0.1847	65.3	354
2	80.8	0.1781	57.4	322
3	66.6	0.1468	32.6	222
4	80.8	0.1781	66.7	375
5	76.4	0.1684	52.3	311
6	82.6	0.1821	101.1	555
8	73.7	0.1624	32.6	201

minimum	**201**
maximum	**555**
range	**354**
average	**334**
geomean	**318**

Table 8
Load Testing Results for the Warren Truss Bridge

EDSGN100 Design Team#	Warren Truss Bridge Weight (grams)	Bridge Weight (lbs.)	Load at Failure (lbs.)	Structural Efficiency
1	80.1	0.1766	59.7	338
2	78.6	0.1733	41.1	237
3	73.0	0.1609	48.2	300
4	57.6	0.1270	54.1	426
5	73.9	0.1629	76.8	471
6	82.5	0.1819	133.3	733
8	72.6	0.1601	64.4	402

minimum	**237**
maximum	**733**
range	**496**
average	**415**
geomean	**392**

FIGURES

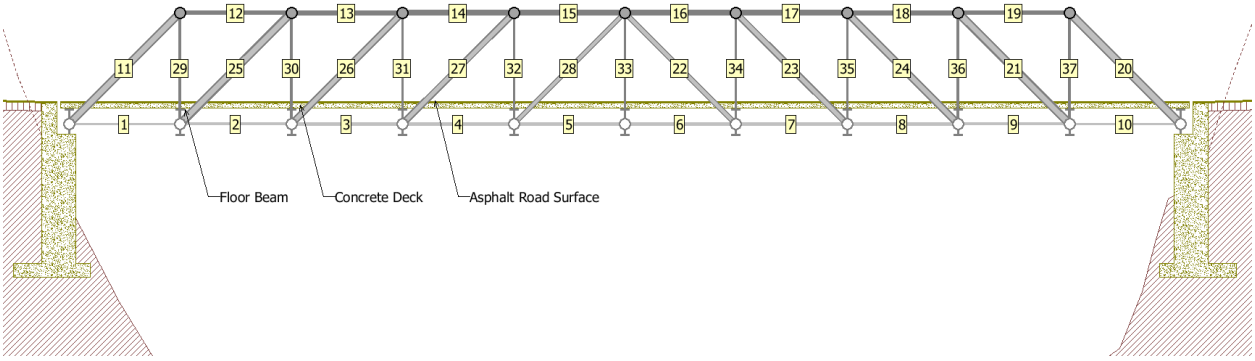


Figure 1. Howe Truss Bridge Model from Bridge Designer 2015

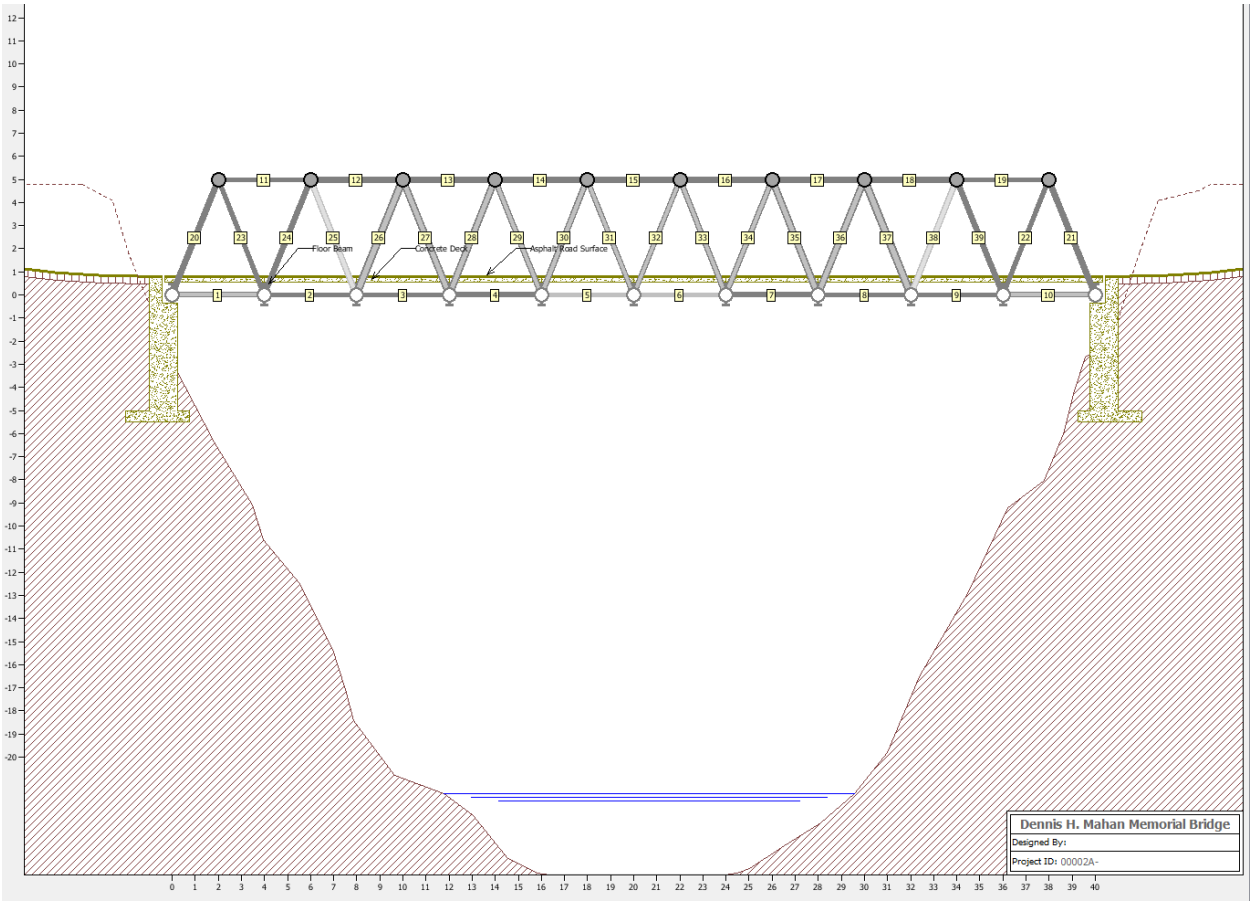


Figure 2. Warren Truss Bridge Model from Bridge Designer 2015

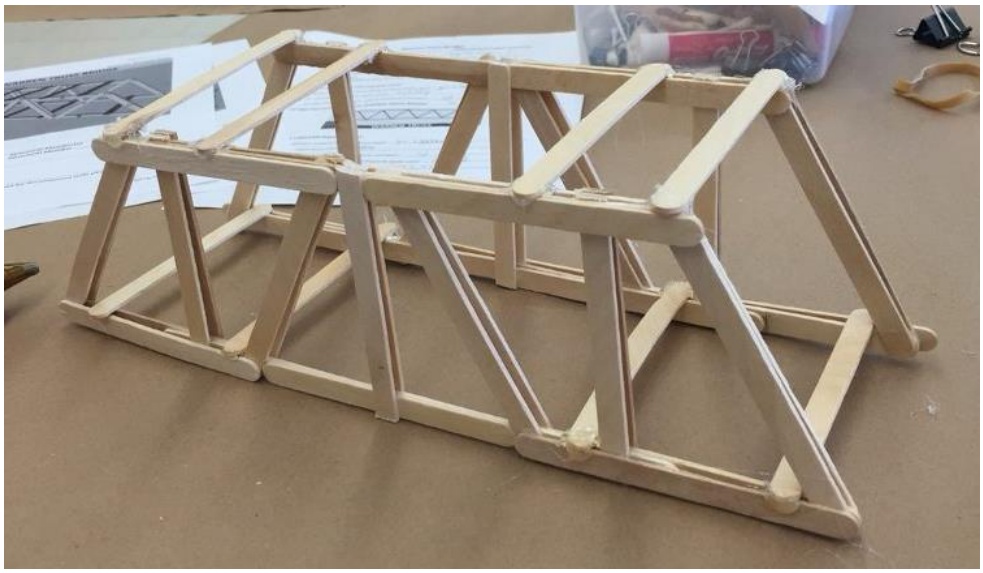


Figure 3. Howe Truss Bridge Prototype before Load Testing

Figure 4. Howe Truss Bridge Prototype Failure after Load Testing

Figure 5. Warren Truss Bridge Prototype before Load Testing

Figure 6. Warren Truss Prototype Bridge Failure after Load Testing

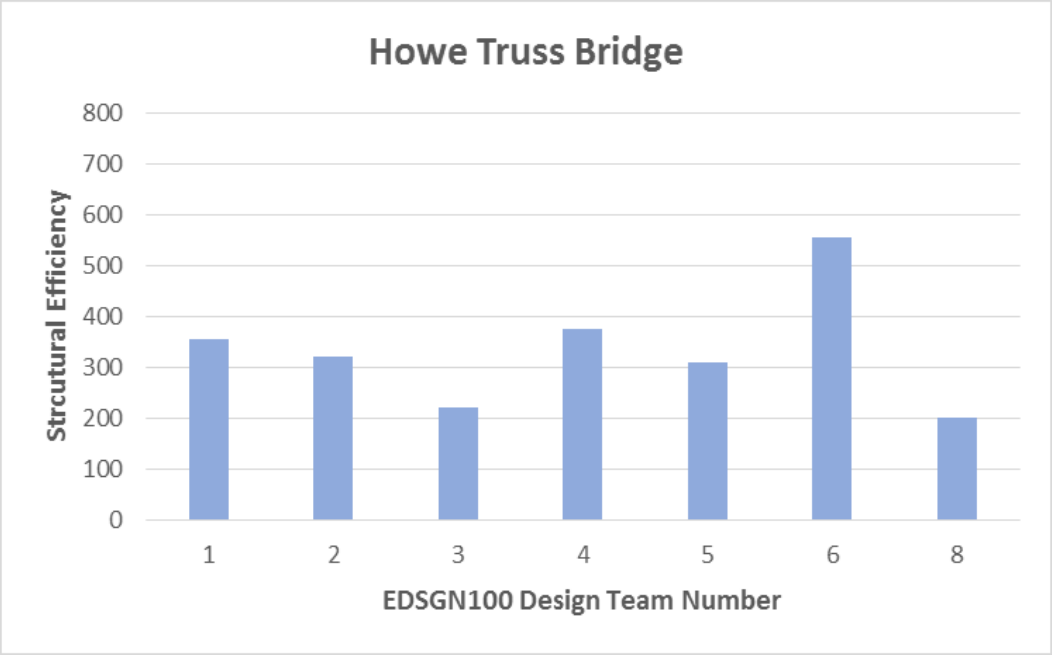


Figure 7. Howe Truss Bridge Structural Efficiencies

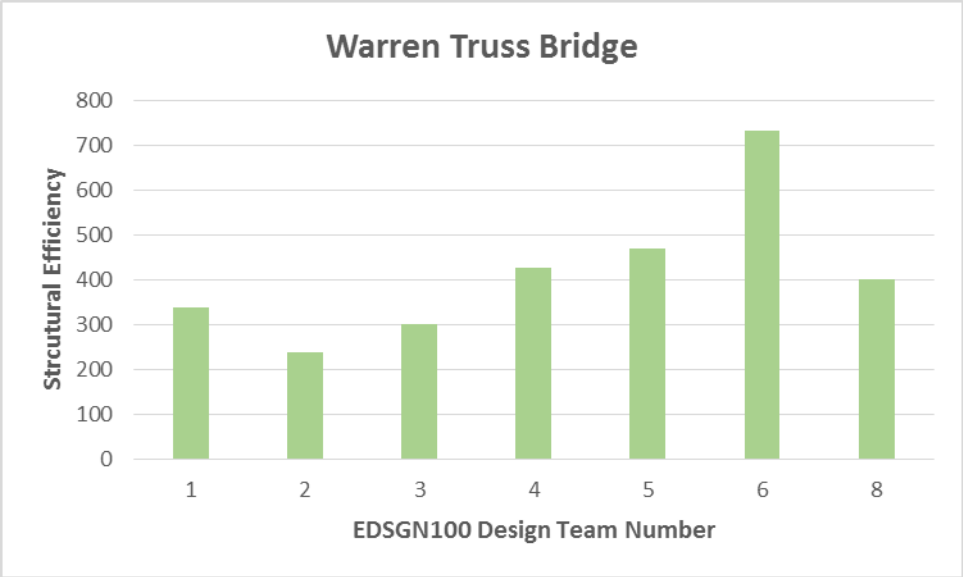


Figure 8. Warren Truss Bridge Structural Efficiencies