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Design, Technology and
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PENNSTATE

October 28, 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 local 100-year flood event has destroyed a structurally deficient bridge over Spring Creek along Puddintown Road in College Township, Centre County, PA. The loss of this bridge has created the need to reroute traffic nearly 10 moles, disrupting residential and commercial traffic.

Objective. A new vehicle bridge is to be designed to span Spring Creek, replacing the bridge destroyed by the recent flood event.

Design Criteria. The bridge design must include: standard abutments, no piers (the bridge must have only one span), medium strength concrete as a deck material (.23 meters thick), and no cable anchorages. It must support the load of AASHTO H20-44 trucks (225 kN), with one in each traffic lane. The deck elevation shall be 20 meters and the deck span shall be 40 meters. Both a Warren through truss bridge and a Howe through truss bridge shall be designed and analyzed.

Technical Approach.

Phase 1: Economic Efficiency. Economic efficiency, the cost-related efficiency of the designs, was determined using Engineering Encounters Bridge Design 2015 (EEBD 2015) software using the requirements, constraints, and performance criteria specified to create the two bridge designs. The optimal design was a stable replacement bridge with the lowest possible cost that can support the specified load and its own weight.

Phase 2: Structural Efficiency. To evaluate structural efficiency of the two designs, prototypes were built for both a Warren and Howe through truss bridge. These prototypes were load tested in a lab until they reached catastrophic failure. The truss with the greatest ability to dissipate live loads was determined to have the greatest structural efficiency. The exact magnitude of its structural efficiency was calculated by dividing the load that the bridge supported at the moment of failure by the weight of the bridge itself. To create the prototypes, white birch Popsicle sticks, Elmer's white glue and hot glue were used. Each bridge used a maximum of 60 sticks, with maximum dimensions of 13.5 inches in length, 4 inches in height, and 4.5 inches in width. The weight, or dead load, of the bridges were recorded and then a live load was added until catastrophic failure. The point of failure was also noted at the end of load testing.

Results.

Phase 1: Economic Efficiency. Attachment one details relevant results from the economic efficiency study. This contains output reports from EEBD 2015, including a tabulated cost calculations report for both bridges and a tabulated load test results report for each. Also in this document, the member details are provided for the structural member with the highest compressive force/strength ratio for each bridge.

Phase 2: Structural Efficiency. Attachment two details the results from the structural efficiency study. This contains all results from the lab load testing. Results obtained by all of the design teams are analyzed and compared. Comparisons were performed using Excel charts and are presented in tables. Class averages are also computed and discussed.

Best Solution. Load testing and and economic efficiency testing both provided insight as to which bridge designs were the "best solution" for the given problem. A Warren design was found to be the most economically efficient in that it was the cheapest, costing over $10,000 less than the Howe.

The Howe design was on average more structurally efficient. The average load strength was higher for Howe bridges than it was for Warren.

The objective of this project was to find the most economically efficient bridge that can still handle the required loads. Therefore, the Warren Bridge design has been selected as it has the lower total cost.

Conclusions and Recommendations. It is recommended that PennDot selects a Warren through truss bridge design to replace the bridge that was destroyed by the recent extreme flood event. The next step that should be taken by PennDot is to seek a contractor to plan the construction of the bridge design.

Respectfully,

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ATTACHMENT 1

Phase 1: Economic Efficiency

Howe Truss. First, a Howe through truss bridge was designed in the EEBD 2015 program that met all of the design criteria. This design was refined by continuing to use smaller and thinner structural members while also testing the bridge to make sure it could still support the required load. Using smaller members allowed for maximum economic efficiency, as smaller members cost less to manufacture.

It was found that hollow tube quenched and tempered steel members were the most economically efficient to use because they were the highest strength but also light-weight due to their hollowness. After using a combination of these members and carbon steel members, it was eventually determined to be best to use only QTS hollow tubes.

A final design was created that met the design constraints and came to a total of $227,579.90.

Attached for the Howe Truss design are a tabulated cost calculation report, Table 1, a tabulated load test report, Table 2, a tabulated member detail report, Table 3, and an image of the EEBD Howe Truss bridge design, Figure 1.

Warren Truss. Secondly, a Warren through truss bridge was designed also using EEBD 2015 software. The same process was used to produce the most economically efficient version of this design. Many of the same properties of the Howe design held true for the Warren design, including the fact that QTS hollow beams were the best combination of strength and cost, and that thinner beams generally cost less.

The final design that was created with the lowest cost that still met all of the design constraints costed $216,908.23.

Attached for the Warren Truss design are a tabulated cost calculation report, Table 4, a tabulated load test report, Table 5, a tabulated member detail report, Table 6, and an image of the EEBD Warren Truss bridge design, Figure 2.

ATTACHMENT 2

Phase 2: Structural Efficiency

Howe Truss. The statement of work called for a Howe truss bridge to be built using a maximum of 60 popsicle sticks and Elmer's glue. The following report shows the design process as well as the testing, results, and analysis of the bridge. The bridge was designed to hold the most weight possible.

Prototype Bridge. The materials used to build the prototype bridge were popsicle sticks, elmer's glue, binder clips to hold glue into place after gluing, sandpaper to sand to popsicle sticks so glue may hold better, and hot glue if necessary. The method to designing this bridge was to follow the traditional design of a howe truss which consists of vertical members and diagonals that connect to the center while attempting to utilize most of the popsicle sticks. In the end, 52 popsicle sticks were used to construct the bridge prototype. The final bridge dimensions were at the limit for each with the height being 4 in., the width being 4.5 in., and the length reaching 13.5 inches.

Load Testing. The Howe bridge that our design team built held a load of 34 lbs at failure. The actual weight of our bridge was 75.3 grams. Comparing these numbers to the loads of the other bridges, our bridge load was lower than the average load of 63.1 lbs. The minimum bridge load was our bridge at 34 lbs while the maximum load was 108.8 lbs. This gives a range of 74.8 lbs between the lowest and highest loads. Although our bridge held the lowest load, it was also the second lightest bridge at only 75.3 grams. The average bridge weight was 80.1 grams with a minimum of 74.7g and a maximum of 85.2g. This produced a structural efficiency of 204.8 when the mass of the load is converted to lbs. In comparison, the average efficiency of all the Howe bridges was 354.95. This means that for both the load at failure and structural efficiency our bridge was below the average.

Forensic Analysis. Through observing the bridge after its collapse, it was determined that the howe truss bridge failed because one of the center vertical members was inadequate and split in half when weight was applied. The split occurred directly in the center of the middle vertical member, approximately 6.75 inches down the length of the bridge.

Results. Table 7 shows the actual bridge weights, the loads at failure, and the structural efficiencies of all groups for the Howe truss bridges. The y axis shows the group numbers while the length of each bar corresponds to weight/strength of each bridge.

Warren Truss. The statement of work called for a Warren truss bridge to be built using a guideline of a maximum of 60 popsicle sticks, Elmer's glue, and hot glue for the struts. The following report details the design, results, and analysis of failure of the Warren truss bridge. The bridge was designed in order to maximize structural efficiency.

Prototype Bridge. The materials used to build the prototype bridge were popsicle sticks, elmer's glue, binder clips to hold glue into place after gluing, sandpaper to sand to popsicle sticks so glue may hold better, and hot glue if necessary. The method used in designing the warren bridge was by sticking to the traditional design of a warren truss which consists of angled members forming equiangular triangles while

also utilizing most of the popsicle sticks. Figure 5 shows the bridge that was constructed before load testing. The dimensions of the bridge was 4" high, 3.4" across, and 13" long.

Load Testing. The Warren truss bridge that our team built held 55.1 lbs. Comparing this number to the average load of 59.1 lbs, our bridge held slightly lower than average weight before it failed. The maximum load was 90.8 lbs while the minimum load was 32.7 lbs. This gave a load range of 58.1 lbs. The dead load of our bridge was measured to be 80.3 lbs. The average dead load was 81.1 grams meaning that our bridge was also slightly below the average dead load. The lightest bridge was 73.2 grams while the heaviest was 85.3 grams giving a range of 12.1 grams. The structural efficiency of our bridge was calculated to be 311.24. The average structural efficiency was 329.07 while the highest was 493.84 and the lowest was 202.63. This means that our structural efficiency was below the average.

Forensic Analysis. The failure of the Warren truss bridge occurred at the second bottom chord. This member was unable to hold the stress applied to it and eventually fractured. This caused the bridge to become disconnected at the top and bottom struts and fell apart. The fracture occurred in the middle of the stick where there was the most stress. Although difficult to see, figure 6 shows the crack in the bottom right of the bridge that is upright. The figure also shows that upon failure the two sides became disconnected after the struts failed. The Elmer's glue failed at one joint in the bridge, whereas the hot glue failed at multiple joints.

Results. Table 8 shows the dead loads, load at failure, and structural efficiency of all of the groups bridges. The group numbers are along the y axis and the weights are along the x axis in either grams or pounds depending on the measurement.

TABLES

Table 1: Howe Truss Bridge EEBD 2015 Cost Calculations Report

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Quenched & Tempered Steel Hollow Tube	(7803.9 kg) x ($7.70 per kg) x (2 Trusses) =	$120,179.90
Connection Cost (C)		(20 Joints) x (500.0 per joint) x (2 Trusses) =	$20,000.00
Product Cost (P)	4 - 110x110x5 mm	(%s per Product) =	$1,000.00
	3 - 120x120x6 mm	(%s per Product) =	$1,000.00
	2 - 130x130x6 mm	(%s per Product) =	$1,000.00
	4 - 140x140x7 mm	(%s per Product) =	$1,000.00
	3 - 160x160x8 mm	(%s per Product) =	$1,000.00
	1 - 170x170x8 mm	(%s per Product) =	$1,000.00
	4 - 180x180x9 mm	(%s per Product) =	$1,000.00
	7 - 200x200x10 mm	(%s per Product) =	$1,000.00
	6 - 220x220x11 mm	(%s per Product) =	$1,000.00
	3 - 240x240x12 mm	(%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	$120,179.90 + $20,000.00 + $10,000.00 + $77,400.00 =	$227,579.90

Table 2: Howe Truss Bridge EEBD 2015 Load Test Report

	Material Type	Size (mm)	Length (m)	Compression Force	Compression Strength	Compression Status	Tension Force	Tension Strength	Tension Status
1	QTS Hollow Tube	160x160x8	4	1389.61	1390.76	OK	0	2241.09	OK
2	QTS Hollow Tube	200x200x10	4	2469.47	2530.55	OK	0	3501.7	OK
3	QTS Hollow Tube	240x240x12	4	3238.51	3958.27	OK	0	5042.45	OK
4	QTS Hollow Tube	240x240x12	4	3695.64	3958.27	OK	0	5042.45	OK
5	QTS Hollow Tube	240x240x12	4	3674.34	3958.27	OK	0	5042.45	OK
6	QTS Hollow Tube	220x220x11	4	3196.28	3209.27	OK	0	4237.06	OK
7	QTS Hollow Tube	200x200x10	4	2406.94	2530.55	OK	0	3501.7	OK
8	QTS Hollow Tube	170x170x8	4	1356.74	1559.03	OK	0	2388.53	OK
9	QTS Hollow Tube	200x200x10	5.66	1918.72	1930.33	OK	0	3501.7	OK
10	QTS Hollow Tube	130x130x6	4	0	687.76	OK	1356.74	1371.19	OK
11	QTS Hollow Tube	180x180x9	4	0	1923.61	OK	2406.94	2836.38	OK
12	QTS Hollow Tube	200x200x10	4	0	2530.55	OK	3196.28	3501.7	OK
13	QTS Hollow Tube	220x220x11	4	0	3209.27	OK	3674.34	4237.06	OK
14	QTS Hollow Tube	220x220x11	4	0	3209.27	OK	3840.8	4237.06	OK
15	QTS Hollow Tube	220x220x11	4	0	3209.27	OK	3840.8	4237.06	OK
16	QTS Hollow Tube	220x220x11	4	0	3209.27	OK	3695.64	4237.06	OK
17	QTS Hollow Tube	200x200x10	4	0	2530.55	OK	3238.51	3501.7	OK
18	QTS Hollow Tube	180x180x9	4	0	1923.61	OK	2469.47	2836.38	OK
19	QTS Hollow Tube	140x140x7	4	0	935.47	OK	1389.61	1715.83	OK
20	QTS Hollow Tube	220x220x11	5.66	1965.2	2565.85	OK	0	4237.06	OK
21	QTS Hollow Tube	140x140x7	4	0	935.47	OK	1385.12	1715.83	OK
22	QTS Hollow Tube	200x200x10	5.66	1601.22	1930.33	OK	0	3501.7	OK
23	QTS Hollow Tube	120x120x6	4	0	562.96	OK	1126.84	1260.61	OK
24	QTS Hollow Tube	180x180x9	5.66	1235.71	1377.06	OK	0	2836.38	OK
25	QTS Hollow Tube	120x120x6	4	0	562.96	OK	867.55	1260.61	OK
26	QTS Hollow Tube	160x160x8	5.66	868.66	911.02	OK	0	2241.09	OK
27	QTS Hollow Tube	110x110x5	4	0	377.57	OK	607.82	967.57	OK
28	QTS Hollow Tube	140x140x7	5.66	501.54	537.86	OK	90.95	1715.83	OK
29	QTS Hollow Tube	110x110x5	4	0	377.57	OK	620.99	967.57	OK
30	QTS Hollow Tube	140x140x7	5.66	457.59	537.86	OK	134.89	1715.83	OK
31	QTS Hollow Tube	110x110x5	4	0	377.57	OK	576.75	967.57	OK
32	QTS Hollow Tube	160x160x8	5.66	824.2	911.02	OK	0	2241.09	OK
33	QTS Hollow Tube	110x110x5	4	0	377.57	OK	835.98	967.57	OK
34	QTS Hollow Tube	180x180x9	5.66	1190.37	1377.06	OK	0	2836.38	OK
35	QTS Hollow Tube	200x200x10	5.66	1555.97	1930.33	OK	0	3501.7	OK
36	QTS Hollow Tube	120x120x6	4	0	562.96	OK	1094.78	1260.61	OK
37	QTS Hollow Tube	130x130x6	4	0	687.76	OK	1352.81	1371.19	OK

Table 3: Howe Truss Bridge EEBD 2015 Member Detail Graph

Member 1

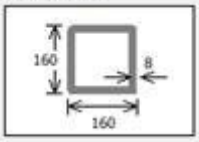
Material Properties:

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	160x160x8
Area	0.0049 sq. meters
Moment of Inertia	1.88E-05 meters^4
Member Length	4.00 meters

Section (mm):



Cost:

Unit Cost	$294.00 per meter
Member Cost	$1176.02

Strength vs. Length: Graph all tabs Member:

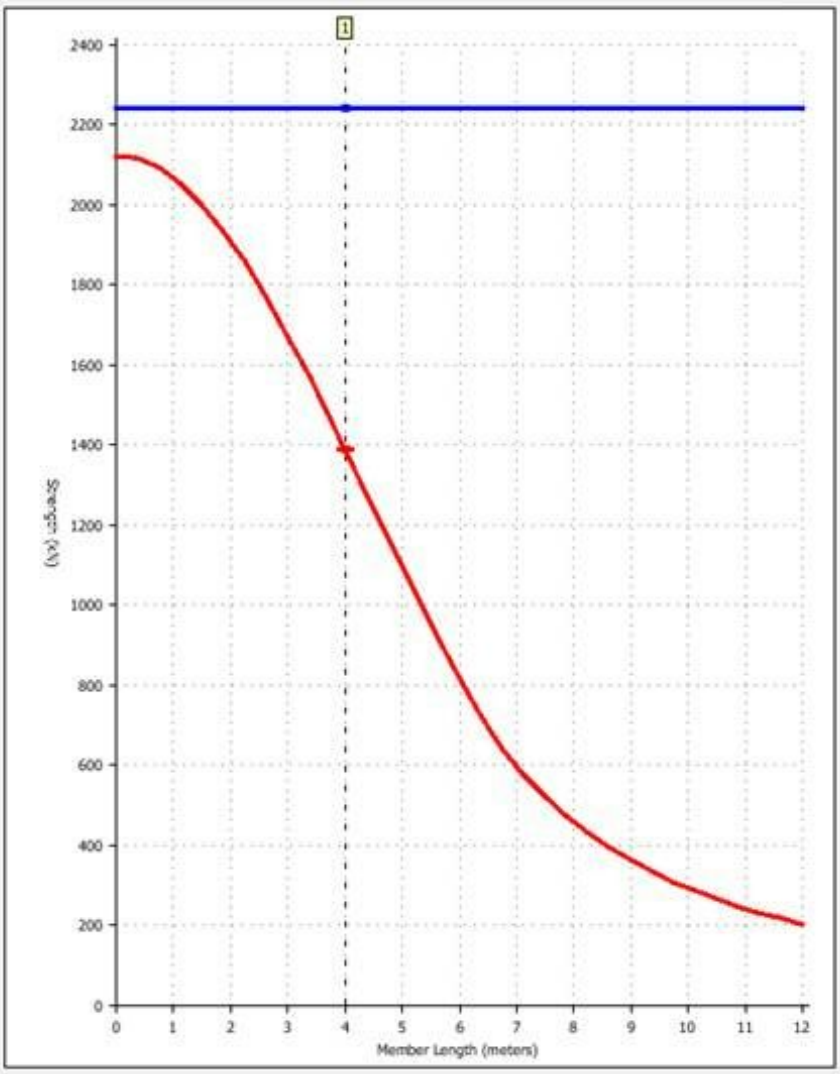


Table 4: Warren Truss Bridge EEBD 2015 Cost Calculations Report

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Quenched & Tempered Steel Hollow Tube	(6786.2 kg) x ($7.70 per kg) x (2 Trusses) =	$104,508.23
Connection Cost (C)		(21 Joints) x (500.0 per joint) x (2 Trusses) =	$21,000.00
Product Cost (P)	2 - 90x90x4 mm	(%s per Product) =	$1,000.00
	4 - 100x100x5 mm	(%s per Product) =	$1,000.00
	1 - 110x110x5 mm	(%s per Product) =	$1,000.00
	3 - 120x120x6 mm	(%s per Product) =	$1,000.00
	2 - 130x130x6 mm	(%s per Product) =	$1,000.00
	4 - 140x140x7 mm	(%s per Product) =	$1,000.00
	1 - 150x150x7 mm	(%s per Product) =	$1,000.00
	3 - 160x160x8 mm	(%s per Product) =	$1,000.00
	4 - 170x170x8 mm	(%s per Product) =	$1,000.00
	2 - 180x180x9 mm	(%s per Product) =	$1,000.00
	2 - 190x190x9 mm	(%s per Product) =	$1,000.00
	4 - 200x200x10 mm	(%s per Product) =	$1,000.00
	3 - 220x220x11 mm	(%s per Product) =	$1,000.00
	4 - 240x240x12 mm	(%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	$104,508.23 + $21,000.00 + $14,000.00 + $77,400.00 =	$216,908.23

Table 5: Warren Truss Bridge EEBD 2015 Load Test Report

	Material Type	Size (mm)	Length (m)	Compression Force	Compression Strength	Compression Status	Tension Force	Tension Strength	Tension Status
1	QTS Hollow Tube	180x180x9	4.47	1547.41	1769.4	OK	0	2836.38	OK
2	QTS Hollow Tube	140x140x7	4.47	0	814.77	OK	1543.63	1715.83	OK
3	QTS Hollow Tube	170x170x8	4.47	1262.67	1420.38	OK	0	2388.53	OK
4	QTS Hollow Tube	130x130x6	4.47	0	586.66	OK	1257.58	1371.19	OK
5	QTS Hollow Tube	160x160x8	4.47	975.83	1251.19	OK	0	2241.09	OK
6	QTS Hollow Tube	120x120x6	4.47	0	464.52	OK	969.54	1260.61	OK
7	QTS Hollow Tube	140x140x7	4.47	687.51	814.77	OK	0	1715.83	OK
8	QTS Hollow Tube	100x100x5	4.47	0	224.01	OK	680.96	875.43	OK
9	QTS Hollow Tube	120x120x6	4.47	398.78	464.52	OK	69.62	1260.61	OK
10	QTS Hollow Tube	90x90x4	4.47	75.78	132.87	OK	392.62	633.99	OK
11	QTS Hollow Tube	90x90x4	4.47	110.56	132.87	OK	357.84	633.99	OK
12	QTS Hollow Tube	120x120x6	4.47	364	464.52	OK	104.4	1260.61	OK
13	QTS Hollow Tube	100x100x5	4.47	0	224.01	OK	646.18	875.43	OK
14	QTS Hollow Tube	140x140x7	4.47	652.32	814.77	OK	0	1715.83	OK
15	QTS Hollow Tube	110x110x5	4.47	0	302.31	OK	934.19	967.57	OK
16	QTS Hollow Tube	150x150x7	4.47	939.68	961.41	OK	0	1844.84	OK
17	QTS Hollow Tube	130x130x6	4.47	0	586.66	OK	1221.21	1371.19	OK
18	QTS Hollow Tube	170x170x8	4.47	1226.3	1420.38	OK	0	2388.53	OK
19	QTS Hollow Tube	140x140x7	4.47	0	814.77	OK	1507.26	1715.83	OK
20	QTS Hollow Tube	180x180x9	4.47	1511.04	1769.4	OK	0	2836.38	OK
21	QTS Hollow Tube	170x170x8	4	1382.35	1559.03	OK	0	2388.53	OK
22	QTS Hollow Tube	200x200x1	4	2457.08	2530.55	OK	0	3501.7	OK
23	QTS Hollow Tube	240x240x1	4	3222.34	3958.27	OK	0	5042.45	OK
24	QTS Hollow Tube	240x240x1	4	3677.23	3958.27	OK	0	5042.45	OK
25	QTS Hollow Tube	240x240x1	4	3821.68	3958.27	OK	0	5042.45	OK
26	QTS Hollow Tube	240x240x1	4	3655.97	3958.27	OK	0	5042.45	OK
27	QTS Hollow Tube	220x220x1	4	3180	3209.27	OK	0	4237.06	OK
28	QTS Hollow Tube	200x200x1	4	2394.35	2530.55	OK	0	3501.7	OK
29	QTS Hollow Tube	170x170x8	4	1349.82	1559.03	OK	0	2388.53	OK
30	QTS Hollow Tube	100x100x5	4	0	280.02	OK	675.76	875.43	OK
31	QTS Hollow Tube	160x160x8	4	0	1390.76	OK	1873.22	2241.09	OK
32	QTS Hollow Tube	190x190x9	4	0	2110.37	OK	2787.23	3002.25	OK
33	QTS Hollow Tube	200x200x1	4	0	2530.55	OK	3392.01	3501.7	OK
34	QTS Hollow Tube	220x220x1	4	0	3209.27	OK	3686.66	4237.06	OK
35	QTS Hollow Tube	220x220x1	4	0	3209.27	OK	3671.11	4237.06	OK
36	QTS Hollow Tube	200x200x1	4	0	2530.55	OK	3372.69	3501.7	OK
37	QTS Hollow Tube	190x190x9	4	0	2110.37	OK	2788.74	3002.25	OK
38	QTS Hollow Tube	160x160x8	4	0	1390.76	OK	1894.67	2241.09	OK
39	QTS Hollow Tube	100x100x5	4	0	280.02	OK	692.02	875.43	OK

Table 6: Warren Truss Bridge EEBD 2015 Member Detail Graph

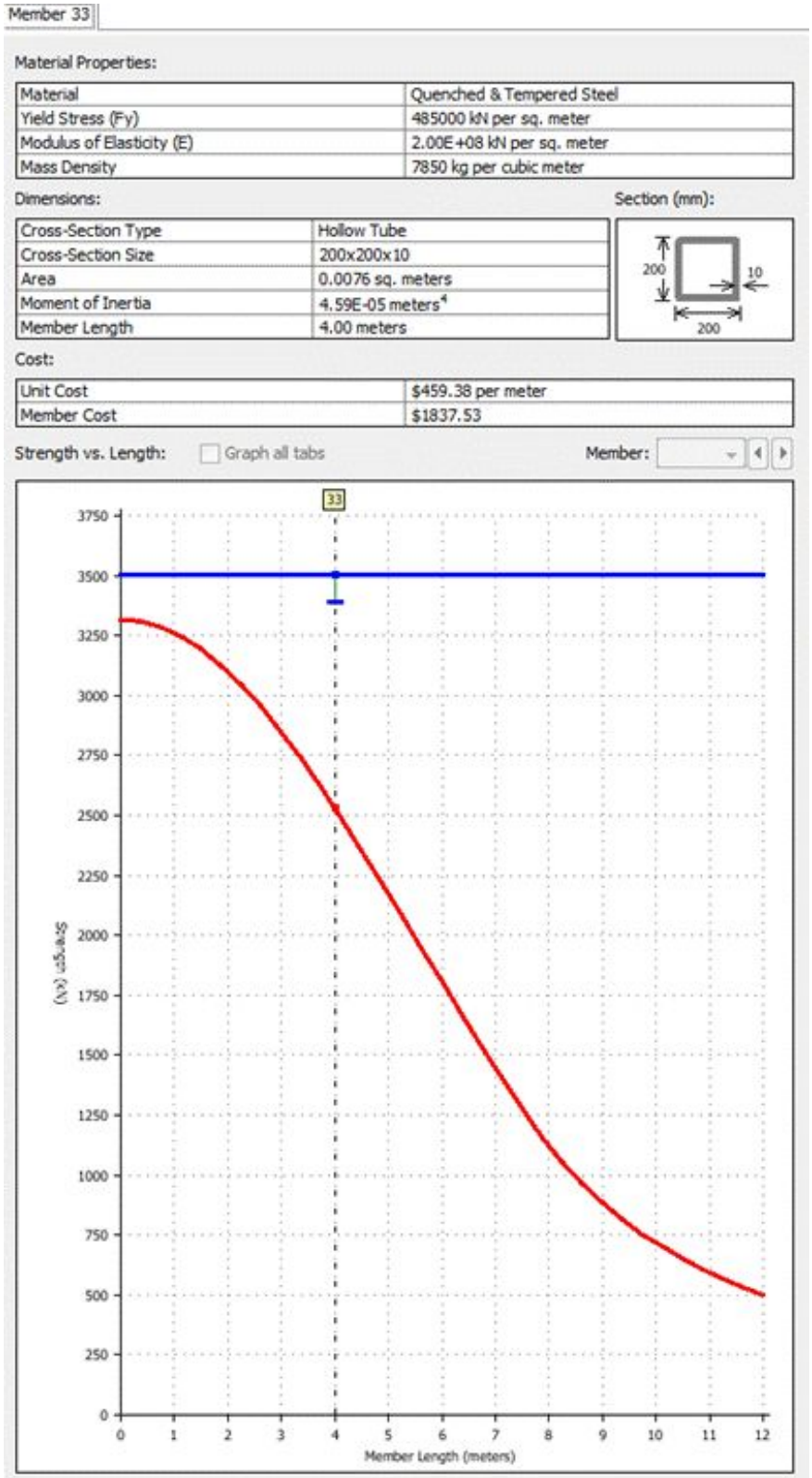


Table 7: Graph of Howe Truss Bridge Structural Efficiency for all Teams

	Actual Bridge Weight (grams)	Actual Bridge Weight (lbs) (grams* 0.00220462)	Load at Failure (lbs)	Structural Efficiency (strength: weight) (load at failure / actual bridge weight in grams)
Group 8	80	0.1763696	70	396.8937958
Group 7	79.7	0.175708214	34.3	195.2099974
Group 6	85.2	0.187833624	72.1	383.8503377
Group 5	81.4	0.179456068	58.3	324.8705973
Group 4	78.1	0.172180822	77.9	452.4313399
Group 3	81.8	0.180337916	108.8	603.3118404
Group 2	75.3	0.166007886	34	204.8095474
Group 1	84.5	0.18629039	49.4	265.1773932

Table 8: Graph of Warren Truss Bridge Structural Efficiency for all Teams

	Actual Bridge Weight (grams)	Actual Bridge Weight (lbs) (grams* 0.00220462)	Load at Failure (lbs)	Structural Efficiency (strength: weight) (load at failure / actual bridge weight in grams)
Group 8	81.9	0.180558378	68.4	378.8248474
Group 7	75.5	0.16644881	55.6	334.0366326
Group 6	83.8	0.184747156	70.4	381.0613464
Group 5	85.3	0.188054086	60.8	323.3112414
Group 4	73.2	0.161378184	32.7	202.6296194
Group 3	83.4	0.183865308	90.8	493.8397623
Group 2	80.3	0.177030986	55.1	311.2449478
Group 1	85.2	0.187833624	39	207.6305571

FIGURES

Figure 1: Howe Truss Bridge

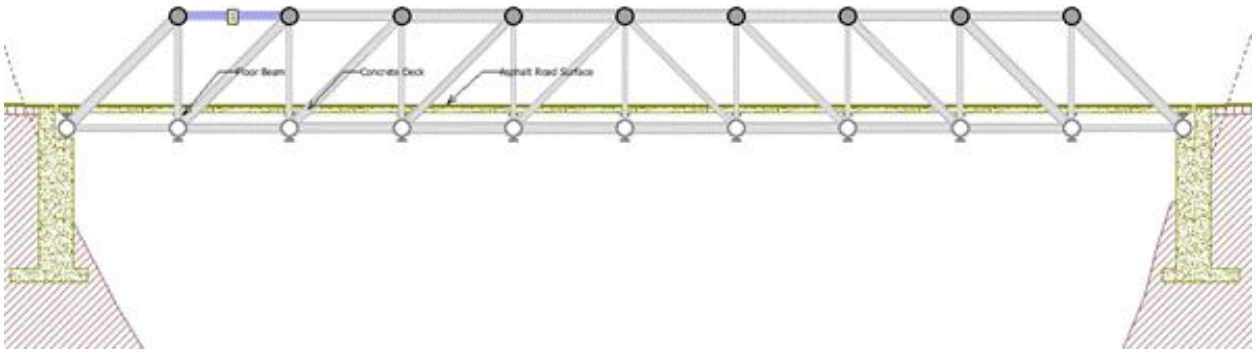


Figure 2: Warren Truss Bridge

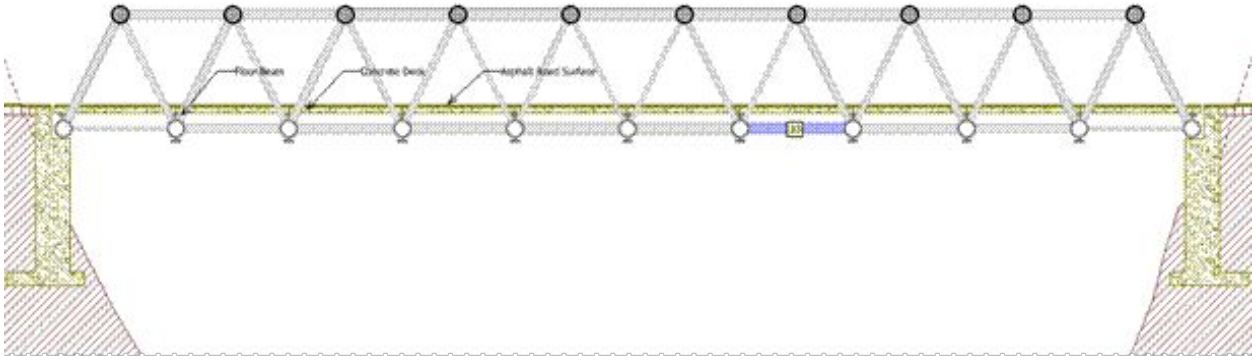


Figure 3: Howe Truss Bridge

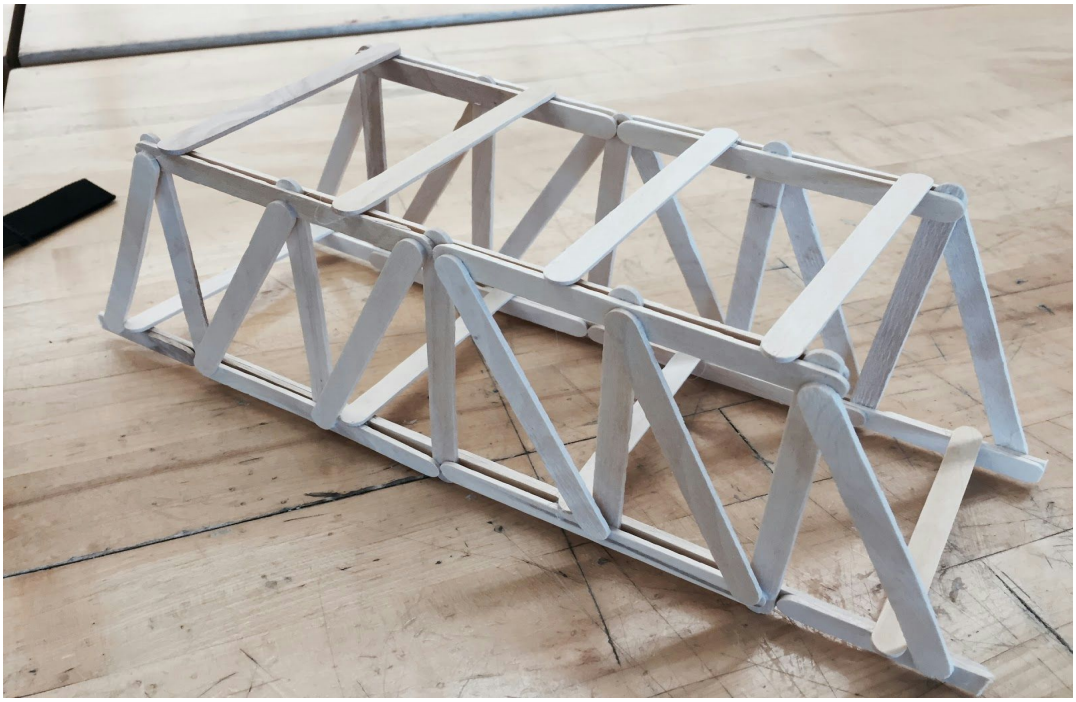


Figure 4: Howe Truss Bridge After Testing

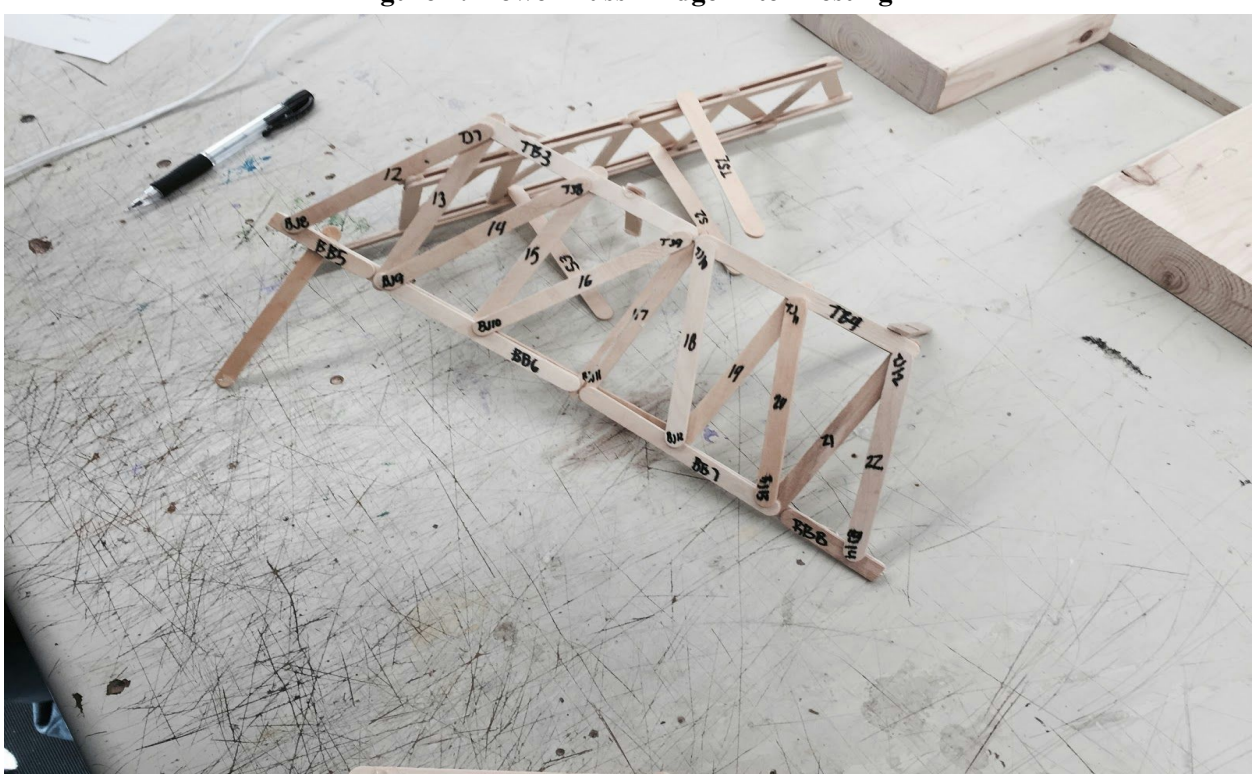


Figure 5: Warren Truss Bridge

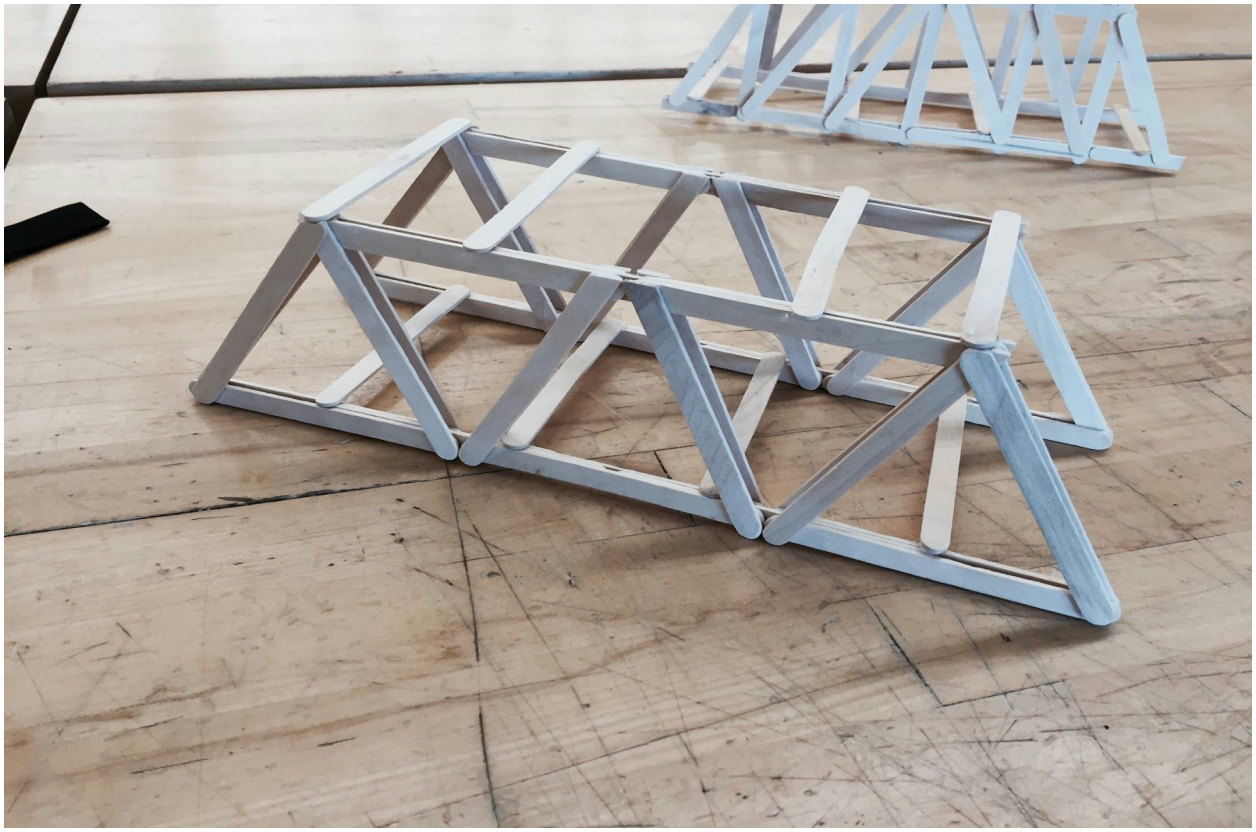


Figure 6: Warren Truss Bridge After Testing

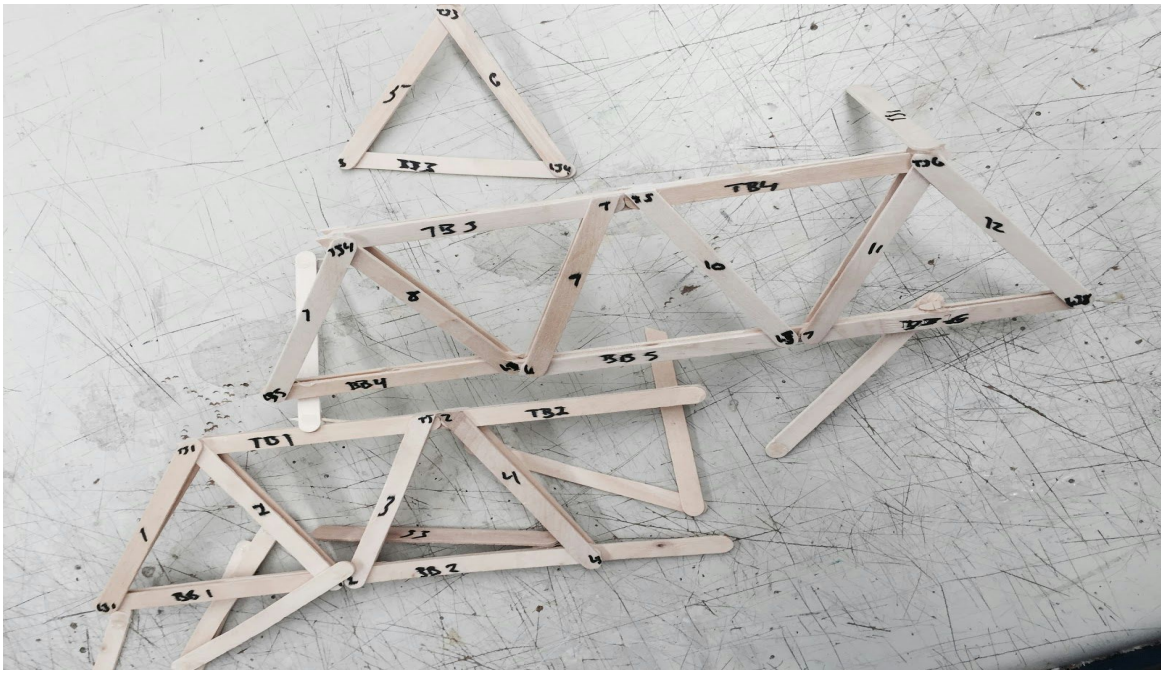


Figure 7: Graph of Howe Truss Bridge Structural Efficiency for all Teams

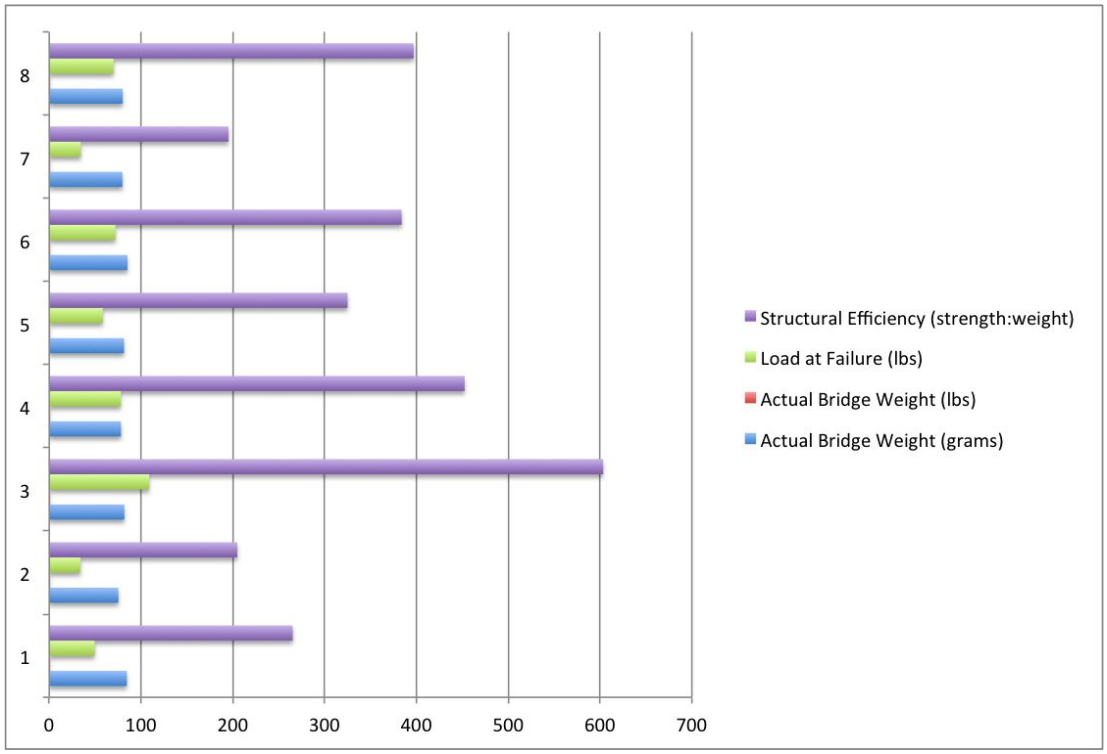
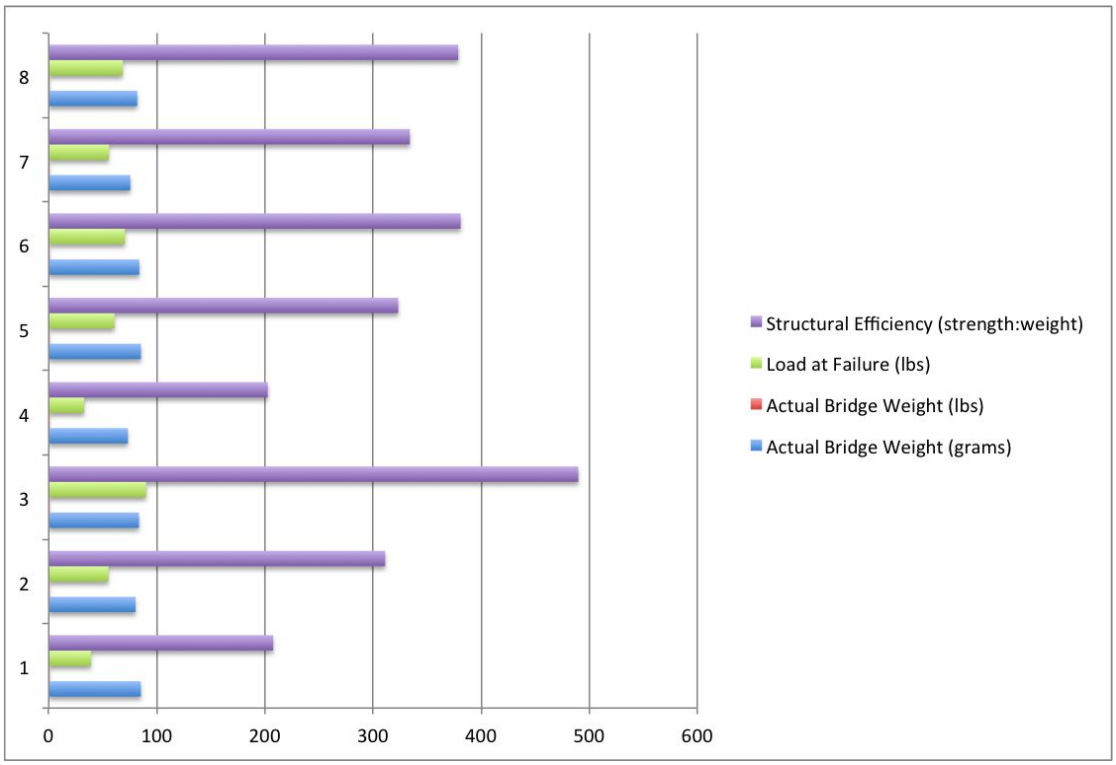



Figure 8: Chart of Warren Truss Bridge Structural Efficiency for all Teams