PENNSTATE

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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 local flooding from a recent 100-year flood event, a structurally deficient vehicle bridge has been completely destroyed in Spring Creek along Puddintown Road in College Township, Centre County, PA. This destroyed bridge is along a very populated and heavily travelled road and is supposed to be a designated vital lifeline for vehicle access to Mount Nittany Medical Center located in State College, PA. This heavy traffic now has to be re-routed more than 10 miles around the destroyed bridge, disrupting residential traffic flow, local commerce, and exposing State College residents to considerable risk since police and other emergency vehicles do not have easy access to that area of College Township because of this dilemma. The damaged bridge also severely restricts general regional vehicle access to the Mount Nittany Medical Center.

Objective. After an engineering investigation of the bridge was conducted, it was concluded that the bridge failure was a result of the collapse of the main pier by scour of its foundation from fast moving flood water. Pennsylvania Department of Transportation of (PennDOT) Engineering District 2-0 has initiated an emergency, fast track project to expedite a new design for a vehicle bridge to replace the destroyed bridge over Spring Creek.

Design Criteria. PennDOT District 2-0 has recommended that a new steel through-truss bridge should be the replacement for the destroyed bridge because truss bridges are very economical to construct and they can span large distances without needing an intermediate pier. They also concluded that the Warren and Howe truss bridges would be the best options because they span the longest distances out of all through-truss bridges. The Warren and Howe do not require a pier to support the span, which would eliminate the option of failing if flooding occurs again. The design for the replacement bridge will have standard abutments, no piers (one span), a deck material of medium strength concrete (0.23 meter thick), no cable anchorages, and designed for the load of two AASHTO H20-44 trucks (225kN) with one in each

traffic lane. The bridge deck elevation will be set at 20 meters and the span of the bridge will be 40 meters. Both a Warren and Howe bridged will be analyzed.

Technical Approach.

There will be a two phase engineering analysis to determine the best solution to replace the destroyed bridge over Spring Creek due to extreme flooding. They are as follows:

Phase 1: Economic Efficiency. The economic efficiency (cost) will be determined using the Engineering Encounters Bridge Design 2015 software based on the requirements, constraints, and performance criteria that have been previously specified. The design objective is to use this bridge software to design a stable Warren and Howe bridge; keeping the bridge cost as low as possible and ensuring that the bridge can support its own weight plus the weight of a standard truck loading.

Phase 2: Structural Efficiency. A prototype will be designed and built of a standard Warren through truss and Howe through truss bridge. Each prototype will be load test to failure, and the best truss bridge type will be determined from these results. Structural Efficiency (SE) is calculated by dividing the load the bridge supports at catastrophic failure by the weight of the prototype bridge. The bridge type with the best structural efficiency will be reported.

The prototypes will be built with standard (4-1/2 x 3/8 x 1/12 inch) wooden (white birch) Popsicle (craft) sticks and Elmer's white glue only. Hot glue will be used to secure the floor beams on the day of testing. Each prototype bridge shall have a maximum of sixty (60) Popsicle sticks, with approximate final bridge dimensions of 13.5 inches in length, 4 inches in height and 4.5 inches in width.

The testing will be done by test loading the top cord of the truss with a loading block attached to a dead load suspended from the block. The prototypes will be accurately weighed, measured, and recorded prior to testing. The load at failure will also be weighed and recorded.

After failure, an engineering investigation will be conducted to see why the bridge failed and will include: why it failed, where it failed, and how it failed. It will be documented will pictures, sketches, and measurements. All structural members and joints of each bridge shall be uniquely identified and marked prior to loading and failure. Both trusses will be uniquely marked, which will be used to identify the type of failure and where it failed.

Results.

Phase 1: Economic Efficiency. Attachment 1 breaks down the cost for each part of both the Howe and Warren Bridge. After comparing these bridges cost by looking at each individual element, Attachment 1 reveals that the most economic efficient bridge is the Warren Bridge.

Phase 2: Structural Efficiency. Attachment 2 discusses the structural efficiency results of both bridges. In Attachment 2, the weight of each the Warren and the Howe Bridge is compared to the load at failure. The information in this Attachment reveals that the Warren Bridge had a higher structural efficiency of 405 compared the Howe Bridge, which had a structural efficiency of only 201.

Best Solution.

(i) Economic Efficiency: In Tables 1 and 4, the total cost for the Howe and Warren truss bridge, respectively, is divided into four sections, material, connection, product, and site cost. These four sections are then added up to give the total cost. The total cost of the Howe Bridge, displayed in Table 1, is $256,465.20. The total cost of the Warren Bridge is $251,890.30. Looking strictly at cost, the Warren Bridge, which is around $4,500 less than the Howe Bridge, is the more economically efficient bridge.

(ii) Structural Efficiency: In Table 7, the structural efficiency of the Howe Bridge for each of the EDSGN 100 teams was calculated. The mean of the data was 335, while the geomean was calculated to be 318. The values of structural efficiencies has a large range of 358, between the minimum of 201 to the maximum of 509. For Design Team 8, the structural efficiency of the Howe Bridge was the minimum of the set of data; the number was only 201, which was lower than all of the other EDSGN 100 teams.

In Table 8, the structural efficiency of the Warren Bridge for every EDSGN 100 team was calculated. The mean of this data was found to 411, while the geomean was 388. The range was much larger for this set of data compared to the Howe Bridge; the range was equal to 494, while the minimum was 238 and the maximum was 732. For Design Team 8, the structural efficiency was calculated to be 405. Although this number was below the mean, it was the median (the middle point) for the set of data; this information reveals that the average must have been skewed by Design Team 6's structural efficiency, raising the mean. The geomean does a better job of reporting the mean by minimizing the effect of the outlier; the structural efficiency of 405 was above the geomean value of 388.

When comparing structural efficiency, the Warren Bridge performed much higher than the Howe Bridge; the structural efficiency of the Warren Bridge was 405 compared to the Howe bridge structural efficiency of 201. Therefore, the more structurally efficient bridge is the Warren Bridge.

(iii) The Design Efficiency: The design efficiency, which is the total cost of each bridge divided by their respective structural efficiency reveals the total cost per one unit of structural efficiency. For the Howe Bridge, the total cost, $256,465.20, divided by the structural efficiency, 201, gives a value of $1276 per one unit of structural efficiency. The Warren bridge total cost, $251,890.30, divided by the structural efficiency, 405, gives a value of $622 per one unit of structural efficiency. The Howe Bridge costs over twice as much as the Warren Bridge for one unit of structural efficiency. The Warren Bridge is more cost efficient than the Howe Bridge when comparing the bridge cost per unit of structural efficiency.

(iv) The Constructability: The constructability of each bridge compares the the material, connection, product, and site cost. For the Howe Bridge, the breakdown of the cost is displayed in Table 1, while the Warren bridge cost breakdown is displayed in Table 4.

For the Howe Bridge, the total cost of materials came from a combination of carbon steel solid bars and carbon steel hollow tubes. The total cost of materials was $148,065.20. Comparatively, the total cost of the Warren Bridge, which also consisted of carbon steel solid bars and hollow tubes, cost $142,690.30.

For the connection cost the, the Howe Bridge had 20 joints on two trusses, each costing $400 per joint, totaling up to $16,000. The Warren Bridge had 21 joints on each of the two trusses and since the price of each joint was the same, the total came up to $16,800; slightly higher than the Howe Bridge.

For the product cost, each bridge used 15 different varieties of carbon steel solid bar or hollow tube. Since this was the case, for both the Warren and the Howe Bridge, the product cost was the same at $15,000.

Finally, for the site cost, both bridges also had the same deck, excavation, abutment, pier, and cable anchorage cost. Thus, both bridges had the same site cost of $77,400.

When the these numbers for each bridge are added together, the cost of each bridge is determined, and, despite having one more joint per truss, the Warren bridge less carbon steel and therefore is less expensive than the Howe bridge.

After considering all of the above information, the best solution will be to create a Warren truss bridge. Not only is the bridge less expensive, it is also has a much higher structural efficiency.

Conclusions and Recommendations. The best option to replace the truss bridge destroyed by the flood will be to create a Warren Truss bridge. Not only would this bridge be less expensive to build, costing $4,500 less than the Howe Bridge, the structural efficiency, which is the load at failure divided by the weight of the bridge, for the Warren Bridge is 405, compared the Howe bridge, which has a structural efficiency of only 201. To move this project into the next step, engineers will need to examine what exactly lead to the collapse of the Prototype Bridge and figure out ways to fix the problem. Once these problems are figured out, a new bridge will be designed and tested that will hopefully fix the fatal flaws from the first bridge and the cost will be reevaluated.

Respectfully,

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ATTACHMENT 1

Phase 1: Economic Efficiency

Howe Truss. The team 8's Howe Truss Bridge was made of various kinds of carbon steel bars and tubes. Overall, 21 carbon steel bar and 16 carbon steel tube was used and the total cost was $256,465.20. Details are as follows; 80x80mm carbon steel bar was $216.03 per meter (4m, $864.13 per each member), 110x110mm carbon steel bar was $408.44 per meter (4m, $1633.74 per each member), 120x120mm carbon steel bar was $486.07 per meter (each member was 4m, $1944.29), 130x130mm carbon steel bar was $570.46 per meter (each member was 4m, $2281.84), 140x140mm carbon steel bar was $661.60 per meter (each member was 4m, $2649.39), and 150x150mm carbon steel bar was $759.49 per meter (each member was 5.66m, $4296.31). 160x160mm carbon steel bar was $864.13 per meter (each member was 4m, $3456.51), Additionally, 120x120x6mm carbon steel tube was $135.31 per meter (each member was 4m, $541.24), 130x130x6mm carbon steel tube was $147.18 per meter (each member was 4m, $588.71), 140x140x7mm carbon steel tube was $184.17 per meter (each member was 5.66m, $1041.83), 150x150x7mm carbon steel tube was $198.02 per meter (members were 4m, 792.07m, and 5.66m, $1120.16), 170x170x8mm carbon steel tube was $256.37 per meter (each member was 4m, $1025.5), 180x180x9mm carbon steel tube was $304.44 per meter (each member was 5.66m, $1722.20), 200x200x10mm carbon steel tube was $375.86 per meter (each member was 5.66m, $2126.17), 240x240x12mm carbon steel tube was $541.24 per meter (each member was 5.66m, $3061.69).

The bridge was built in the way that has the highest efficiency with the value for compression force/strength and tension force/strength as close to 1 as possible. The highest value for compression force/strength was 0.99 (member 11) and the lowest value for compression force/strength was 0.79 (member 22). Also, the highest value for tension force/strength was 0.95 (member 4, 7, 31) and the lowest value for tension force/strength was 0.14 (member28).

Warren Truss. The team 8's Warren Truss bridge was made of various kinds of carbon steel bars and tubes. Overall, 34 carbon steel bar and 5 carbon steel tube was used and the total cost was $251,890.30. Details are as follows; 55x55mm carbon steel bar was $102.11 per meter (4m, $408.44 per each member), 65x65mm carbon steel bar was $142.61 per meter (4.47m, $637.79 per each member), 70x70mm carbon steel bar was $165.40 per meter (each member was 4.47m, $739.69), 75x75mm carbon steel bar was $189.87 per meter (each member was 4.47m, $849.13), 90x90mm carbon steel bar was $273.42 per meter (each member was 4.47m, $1222.75), and 100x100mm carbon steel bar was $ 337.55 per meter (each member was 4m, $1350.2). 110x110mm carbon steel bar was $ 408.44 per meter (each member was 4.47m, $1826.58), 120x120mm carbon steel bar was $ 486.07 per meter (each member was 4.47m, $2173.78), 130x130mm carbon steel bar was $ 570.46 per meter (each member was 4m, $2281.84 and 4.47m, $ 2551.17), 140x140mm carbon steel bar was $ 661.6 per meter (each member was 4m, $ 2646.39), 160x160mm carbon steel bar was $ 864.13per meter (each member was 4m, $ 3456.51), 170x170mm carbon steel bar was $975.52 per meter (each member was 4m, $3902.08). Additionally, 100x100x5 mm carbon steel tube was $93.96 per meter (each member was 4.47m, $ 420.22), 130x130x6mm carbon steel tube was $147.18 per meter (each member was 4.47m, $658.2), 140x140x7mm carbon steel tube was $184.17 per meter (each member was 4m, $736.68)

The bridge was built in the way that has the highest efficiency with the value for compression force/strength and tension force/strength as close to 1 as possible. The highest value for compression force/strength was 0.99 (member 20) and the lowest value for compression force/strength was 0.51 (member 26). Also, the highest value for tension force/strength was 0.99 (member 23) and the lowest value for tension force/strength was 0.80 (member 26)

ATTACHMENT 2

Phase 2: Structural Efficiency

Howe Truss. The load testing on Howe Truss Bridge was done and the structural efficiency was calculated from measured bridge weight (lbs.) and load failure (lbs.). The weight of bridge made by team 8 was 0.162lbs and load at failure was 32.6lbs. The structural efficiency was 201 (= bridge weight / load at failure). The geometric mean from the class was 318 which was higher than the one by team 8.

Prototype Bridge. The prototype Howe Truss Bridge was built by using 60 Popsicle sticks. Eight Popsicle sticks were saved to make the struts and the floor beam. The bridge is designed to have four diagonals and four verticals on each side as shown in Figure 3. Based on the design, an extra Popsicle stick is glued on V1 and also V2 on the other side. D7 and D6 also has an extra Popsicle stick. As on the other half of the prototype bridge, D2 and D3 both has an extra Popsicle stick. This is because according to the JHU Virtual Bridge Designer, the forces when weight is put on the bridge is greatest at those verticals and diagonals. The force is also great at BC2 and BC5, so extra Popsicle stick is added to withstand the great force acting on it when weight is put. TC3 also has to withstand a great force thus another Popsicle stick is added right at the middle of the intersection of the TC1 and TC2. This process is also done to the other half of the bridge on the intersection of TC4 and TC5 making a stronger and more durable TC6. Any extras of the diagonals that are protruding out from the bridge is cut using the saw. Each Popsicle stick that is glued is sanded to make the surface rough so that the glue can penetrate deeply to ensure attachment of each sticks. The struts and floor beams however is put with a hot glue gun and left for a 10-15 minutes before load testing.

Load Testing. For Team 8's Howe Bridge, the structural efficiency compared to the other groups was very poor. The bridge weighed 73.3 grams, or .162 pounds; it failed at only 32.6 pounds. The calculated efficiency is 201. This number is the minimum structural efficiency for all 7 groups. This bridge set the bottom value for the range of all design teams. The highest structural efficiency set by design team 6 was 559. As the range for all groups is 358, this Howe design was not very successful in comparison with the other groups. This failure is recognized and would be taken into consideration for any future bridge designs for this group.

Forensic Analysis. As stated previously, Team 8's Howe Bridge failed at a load of 32.6 pounds. After examining the remains of the broken bridge, it was concluded that the Howe Bridge failed in one of the trusses and almost all of the connecting beams. For a visual depiction of the failed bridge and the location of the following beams and joins referenced, please see Figure 4. TC1, a top chord on one of the two trusses, completely snapped. The probable cause was too much overall tor on the fairly weak Popsicle stick member. BC5, another member of the same truss, was a bottom chord that broke from the truss at the joint. This is most likely due to a failure to allow the glue to fully set before testing. S4, FB1, FB3, along with other missing struts and beams, all came apart at their glued joints. Again, this is due to the torsion on the structure which ripped the members from their glued joints. Overall, the biggest issue was the twisting motion and should have been stabilized better. Obviously, a stronger material for construction would have been more successful and would be considered in any further remakes of this type of bridge design.

Results. The results in comparing the structural efficiency is represented in both Figure 7 and Table 7. Compared to the other groups, is one of the lightest (.162 pounds), and could only withstand 32.6 pounds. The Howe truss bridge could not withstand the force exerted as the glue was not as dry as expected when load testing was done. But overall, based on the design and on aesthetic value, the Howe truss bridge was a representable bridge design. The efficiency of the bridge is 201.

Warren Truss. The load testing on Warren Truss Bridge was done and the structural efficiency was calculated from measured bridge weight (lbs.) and load failure (lbs.). The weight of bridge made by team 8 was 0.159lbs and load at failure was 64.4lbs. The structural efficiency was 388 (= bridge weight / load at failure). The geometric mean from the class was 388 which was lower than the one by team 8.

Prototype Bridge. The prototype Warren Truss Bridge was built by using 60 Popsicle sticks. Eight Popsicle sticks were saved to make the struts and the floor beam. The bridge is designed to have four diagonals on each side as shown in Figure 5. Based on the design, each diagonal has an extra Popsicle stick to withstand the great force exerted during load testing. This is because according to the JHU Virtual Bridge Designer, the forces when weight is put on the bridge is distributed almost similarly among the diagonals. The forces are also great at the top cords and also the bottom cords, thus extra Popsicle sticks are added. Any extras of the diagonals that are protruding out from the bridge is cut using the saw. Each Popsicle stick that is glued is sanded to make the surface rough so that the glue can penetrate deeply to ensure attachment of each sticks. The struts and floor beams however are put with a hot glue gun and left for a 10-15 minutes before load testing.

Load Testing. The Team 8 Warren Bridge was much more successful than the Howe and placed towards the middle of the range out of the design groups, instead of last like the Howe. With a weight of 72.6 grams, or .159 pounds, this Warren held a 64.4 lbs. load before failing, giving it a 405 for structural efficiency. The range for structural efficiency is 494, with a minimum of 238 and a maximum of 732. Interestingly, the structural efficiency for the Warren is much better overall than the Howe since every design group (besides Group 1) had a higher efficiency with this classic Warren design.

Forensic Analysis. Again, Team 8's Warren Bridge failed at a max load of 64.4 pounds. Figure 6 provides a detailed look at which members were the cause of this failure. S1, S2, S3, and S4 (all top struts), along with FB1, FB2, FB3, and FB4 (all bottom beams), were damaged by the load bearing on the bridge during testing. Each member dislocated from either its right or left truss at the glued joint. It can be inferred that the trusses of this Warren were much stronger than the trusses of the Howe, since these sustained no damage at a higher load. All of these failures were due to the torsion affecting the bridge, which was witnessed during testing. If redesigned, Team 8 would propose a design that accounts for these forces on the joints and works to combat it better and more effectively.

Results. The results in comparing the structural efficiency is represented in both Figure 8 and Table 8. Compared to the other groups, Warren Truss Bridge is a good bridge as it has

quite a high structural efficiency which is 405 as it can withstand 64.4 lbs. of load. Warren truss bridge was a good design and can withstand the force exerted.

TABLES

TABLE 1
Cost Calculation Report from Bridge Designer 2016 for the Howe Truss Bridge

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Carbon Steel Solid Bar	(12266.1 kg) x ($4.30 per kg) x (2 Trusses)	$105,488.32
	Carbon Steel Hollow Tube	(3379.1 kg) x ($6.30 per kg) x (2 Trusses)	$42,576.87
Connection Cost (C)		(20 joints) x ($400 per joint) x (2 Trusses)	$16,000.00
Product Cost (P)	4 - 80x80 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	2 - 110x110 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	2 - 120x120 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	2 - 120x120x6 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	4 - 130x130 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	1 - 130x130x6 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	4 - 140x140 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	1 - 140x140x7 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	2 - 150x150 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	3 - 150x150x7 mm	(%s per Product)	$1,000.00

	Carbon Steel Tube		
	4 - 160x160 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	2 - 170x170x8 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	2 - 180x180x9 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	2 - 200x200x10 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	2 - 240x240x12 mm Carbon Steel Tube	(%s per Product)	$1,000.00
Site Cost(C)	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 Cost	(2 standard abutment x $5,500 per abutment)	$11,000.00
	Pier Cost	No Pier	$0
	Cable Anchorage Cost	No Anchorage	$0
Total Cost	**M+C+P+S**	**$148,065.20 + $16,000.00 + $15,000.00 + $77,400.00**	**$256,465.20**

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	CS	Solid Bar	80x80	4	0	333.51	OK	1436.25	1520	OK
2	CS	Solid Bar	110x110	4	0	1181.16	OK	2552.98	2873.75	OK
3	CS	Solid Bar	130x130	4	0	2091.29	OK	3348.82	4013.75	OK
4	CS	Solid Bar	130x130	4	0	2091.29	OK	3822.33	4013.75	OK
5	CS	Solid Bar	140x140	4	0	2633.62	OK	3973.3	4655	OK
6	CS	Solid Bar	140x140	4	0	2633.62	OK	3973.3	4655	OK
7	CS	Solid Bar	130x130	4	0	2091.29	OK	3801.79	4013.75	OK
8	CS	Solid Bar	130x130	4	0	2091.29	OK	3307.8	4013.75	OK
9	CS	Solid Bar	110x110	4	0	1181.16	OK	2491.5	2873.75	OK
10	CS	Solid Bar	80x80	4	0	333.51	OK	1404.35	1520	OK
11	CS	Solid Bar	150x150	5.66	2031.17	2062.08	OK	0	5343.75	OK
12	CS	Solid Bar	120x120	4	1436.25	1606.24	OK	0	3420	OK
13	CS	Solid Bar	140x140	4	2552.98	2633.62	OK	0	4655	OK
14	CS	Solid Bar	160x160	4	3348.82	3881.59	OK	0	6080	OK
15	CS	Solid Bar	160x160	4	3822.33	3881.59	OK	0	6080	OK
16	CS	Solid Bar	160x160	4	3801.79	3881.59	OK	0	6080	OK
17	CS	Solid Bar	160x160	4	3307.8	3881.59	OK	0	6080	OK
18	CS	Solid Bar	140x140	4	2491.5	2633.62	OK	0	4655	OK
19	CS	Solid Bar	120x120	4	1404.35	1606.24	OK	0	3420	OK
20	CS	Solid Bar	150x150	5.66	1986.05	2062.08	OK	0	5343.75	OK

21	CS	Solid Bar	80x80	4	0	333.51	OK	1393.41	1520	OK
22	CS	Hollow Tube	240x240 x12	5.66	1608.24	2028.51	OK	0	2599.2	OK
23	CS	Hollow Tube	170x170 x8	4	0	962.6	OK	1125.83	1231.2	OK
24	CS	Hollow Tube	200x200 x10	5.66	1228.49	1293.53	OK	0	1805	OK
25	CS	Hollow Tube	150x150 x7	4	0	704.11	OK	856.21	950.95	OK
26	CS	Hollow Tube	180x180 x9	5.66	846.72	981.36	OK	0	1462.05	OK
27	CS	Hollow Tube	120x120 x6	4	0	417.77	OK	585.7	649.8	OK
28	CS	Hollow Tube	140x140 x7	5.66	464.75	474.03	OK	127.74	884.45	OK
29	CS	Hollow Tube	130x130 x6	4	0	482.45	OK	625.5	706.8	OK
30	CS	Hollow Tube	150x150 x7	5.66	509.75	550.3	OK	82.74	950.95	OK
31	CS	Hollow Tube	120x120 x6	4	0	417.77	OK	617.6	649.8	OK
32	CS	Hollow Tube	180x180 x9	5.66	891.83	981.36	OK	0	1462.05	OK
33	CS	Hollow Tube	150x150 x7	4	0	704.11	OK	888.11	950.95	OK
34	CS	Hollow Tube	200x200 x10	5.66	1273.6	1293.53	OK	0	1805	OK
35	CS	Hollow Tube	170x170 x8	4	0	962.6	OK	1157.74	1231.2	OK
36	CS	Hollow Tube	240x240 x12	5.66	1653.35	2028.51	OK	0	2599.2	OK
37	CS	Solid Bar	80x80	4	0	333.51	OK	1425.31	1520	OK

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

[Member 11, Compression Force/Strength = 0.99]

Member List | Member Details

Member 11

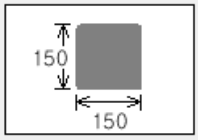
Material Properties:

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	Solid Bar
Cross-Section Size	150x150
Area	0.0225 sq. meters
Moment of Inertia	4.22E-05 meters^4
Member Length	5.66 meters

Section (mm):



Cost:

Unit Cost	$759.49 per meter
Member Cost	$4296.31

Strength vs. Length: Graph all tabs Member:

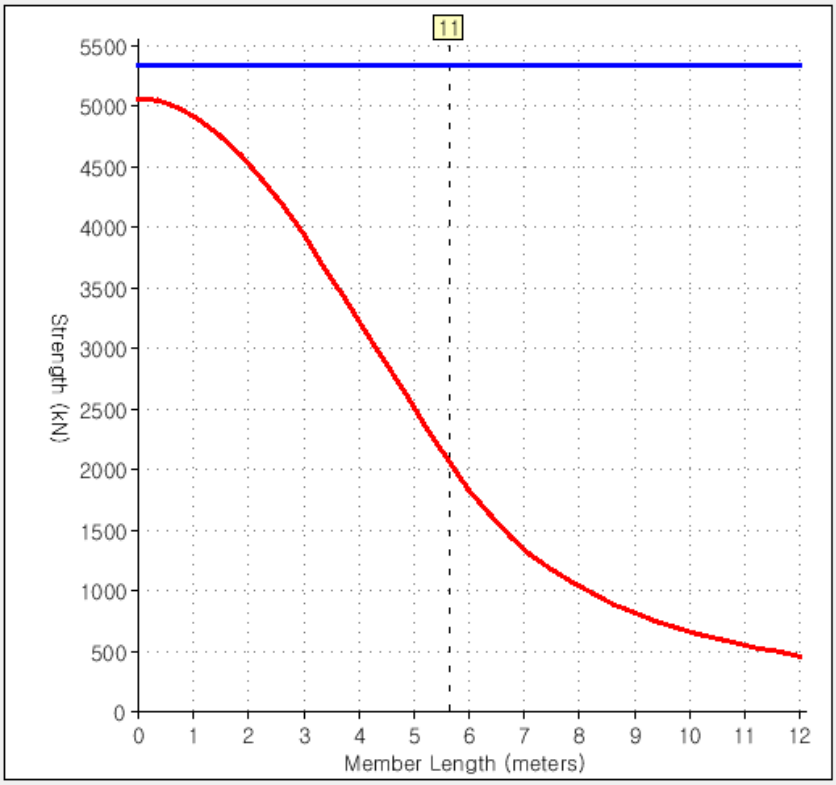


TABLE 4
Cost Calculation Report from Bridge Designer 2016 for the Warren Truss Bridge

Type of Cost	Item	Cost Calculation	Cost
Material Cost (M)	Carbon Steel Solid Bar	(15919.0 kg) x ($4.30 per kg) x (2 Trusses)	$136,903.25
	Carbon Steel Hollow Tube	(459.3 kg) x ($6.30 per kg) x (2 Trusses)	$5,787.05
Connection Cost (C)		(21 joints) x ($400 per joint) x (2 Trusses)	$16,800.00
Product Cost (P)	1 - 55x55 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	1 - 65x65 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	1 - 70x70 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	2 - 75x75 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	4 - 90x90 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	2 - 100x100 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	2 - 100x100x5 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	2 - 110x110 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	8 - 120x120 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	6 - 130x130 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	2 - 130x130x6 mm	(%s per Product)	$1,000.00

	Carbon Steel Tube		
	2 - 140x140 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	1 - 140x140x7 mm Carbon Steel Tube	(%s per Product)	$1,000.00
	4 - 160x160 mm Carbon Steel Bar	(%s per Product)	$1,000.00
	1 - 170x170 mm Carbon Steel Bar	(%s per Product)	$1,000.00
Site Cost(C)	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 Cost	(2 standard abutment x $5,500 per abutment)	$11,000.00
	Pier Cost	No Pier	$0
	Cable Anchorage Cost	No Anchorage	$0
Total Cost	**M+C+P+S**	**$142,690.30 + $16,800.00 + $15,000.00 + $77,400.00**	**$251,890.30**

TABLE 5
Warren Truss Bridge
Load Test Results Report 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	140x140x7	4	0	630.23	OK	722.27	884.45	OK
2	CS	Solid Bar	100x100	4	0	814.24	OK	1977.69	2375	OK
3	CS	Solid Bar	120x120	4	0	1606.24	OK	2912.29	3420	OK
4	CS	Solid Bar	130x130	4	0	2091.29	OK	3522.72	4013.75	OK
5	CS	Solid Bar	130x130	4	0	2091.29	OK	3833.81	4013.75	OK
6	CS	Solid Bar	130x130	4	0	2091.29	OK	3849.66	4013.75	OK
7	CS	Solid Bar	130x130	4	0	2091.29	OK	3542.9	4013.75	OK
8	CS	Solid Bar	120x120	4	0	1606.24	OK	2911.86	3420	OK
9	CS	Solid Bar	100x100	4	0	814.24	OK	1956.89	2375	OK
10	CS	Solid Bar	55x55	4	0	74.51	OK	706.2	718.44	OK
11	CS	Solid Bar	130x130	4.47	1615.04	1800.95	OK	0	4013.75	OK
12	CS	Solid Bar	90x90	4.47	0	427.38	OK	1605.2	1923.75	OK
13	CS	Solid Bar	120x120	4	1440.14	1606.24	OK	0	3420	OK
14	CS	Solid Bar	140x140	4	2561.74	2633.62	OK	0	4655	OK
15	CS	Solid	120x120	4.47	1319.09	1347.81	OK	0	3420	OK

		Bar								
16	CS	Solid Bar	75x75	4.47	0	206.11	OK	1305.99	1335.94	OK
17	CS	Solid Bar	120x120	4.47	1018.04	1347.81	OK	0	3420	OK
18	CS	Solid Bar	70x70	4.47	0	156.4	OK	1002.52	1163.75	OK
19	CS	Solid Bar	160x160	4	3360.63	3881.59	OK	0	6080	OK
20	CS	Solid Bar	160x160	4	3834.85	3881.59	OK	0	6080	OK
21	CS	Solid Bar	170x170	4	3985.39	4583.96	OK	0	6863.75	OK
22	CS	Solid Bar	110x110	4.47	713.76	953.71	OK	0	2873.75	OK
23	CS	Hollow Tube	130x130x6	4.47	0	444.49	OK	697.94	706.8	OK
24	CS	Solid Bar	90x90	4.47	410.13	427.38	OK	58.27	1923.75	OK
25	CS	Hollow Tube	100x100x5	4.47	73.53	212.76	OK	394.87	451.25	OK
26	CS	Hollow Tube	100x100x5	4.47	108.95	212.76	OK	359.45	451.25	OK
27	CS	Solid Bar	90x90	4.47	374.71	427.38	OK	93.69	1923.75	OK
28	CS	Solid Bar	160x160	4	3814.17	3881.59	OK	0	6080	OK
29	CS	Solid Bar	160x160	4	3319.26	3881.59	OK	0	6080	OK
30	CS	Solid Bar	140x140	4	2499.93	2633.62	OK	0	4655	OK

31	**CS**	**Solid Bar**	**120x120**	**4**	**1407.99**	**1606.24**	**OK**	**0**	**3420**	**OK**
32	**CS**	**Solid Bar**	**130x130**	**4.47**	**1579.11**	**1800.95**	**OK**	**0**	**4013.75**	**OK**
33	**CS**	**Solid Bar**	**90x90**	**4.47**	**0**	**427.38**	**OK**	**1569.26**	**1923.75**	**OK**
34	**CS**	**Solid Bar**	**120x120**	**4.47**	**1283.32**	**1347.81**	**OK**	**0**	**3420**	**OK**
35	**CS**	**Solid Bar**	**75x75**	**4.47**	**0**	**206.11**	**OK**	**1270.21**	**1335.94**	**OK**
36	**CS**	**Solid Bar**	**120x120**	**4.47**	**982.26**	**1347.81**	**OK**	**0**	**3420**	**OK**
37	**CS**	**Solid Bar**	**65x65**	**4.47**	**0**	**116.28**	**OK**	**966.92**	**1003.44**	**OK**
38	**CS**	**Solid Bar**	**110x110**	**4.47**	**678.33**	**953.71**	**OK**	**0**	**2873.75**	**OK**
39	**CS**	**Hollow Tube**	**130x130x6**	**4.47**	**0**	**444.49**	**OK**	**662.52**	**706.8**	**OK**

TABLE 6
Warren Truss Bridge
Member Details Report from Bridge Designer 2015
Member with the Highest Tension Force/Strength Ratio

[Member 23, Tension Force/Strength = 0.98]

Member List | Member Details

Member 23

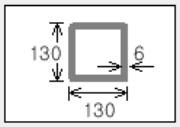
Material Properties:

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	4.47 meters

Section (mm):



Cost:

Unit Cost	$147.18 per meter
Member Cost	$658.20

Strength vs. Length: Graph all tabs Member:

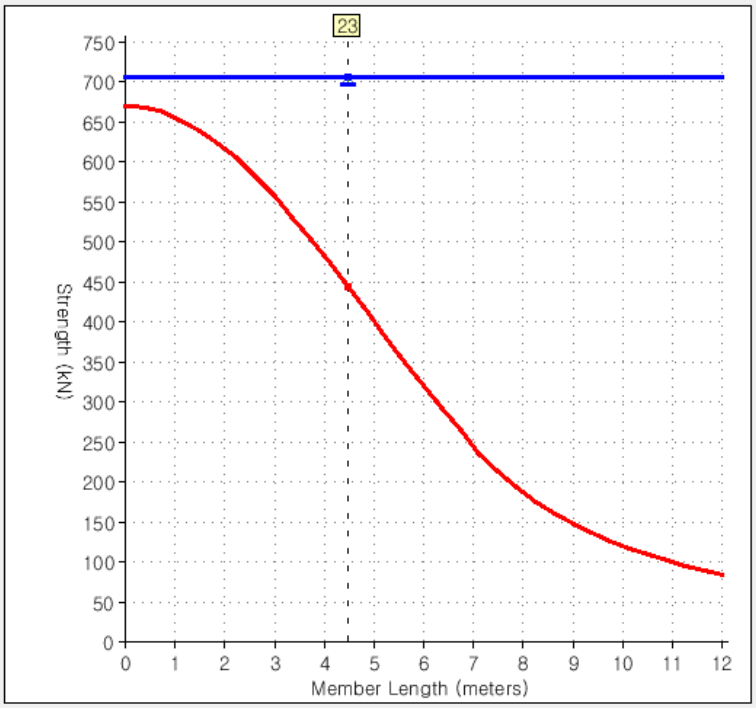


TABLE 7
Load Testing Results for Howe Truss Bridge

Design Team #	Howe Truss Bridge Weight (grams)	Bridge Weight (lbs.)	Load at Failure (lbs.)	Structural Efficiency
1	83.8	.185	65.3	353
2	80.8	.178	57.4	322
3	66.6	.147	32.6	222
4	80.8	.178	66.7	375
5	76.4	.168	52.3	311
6	82.0	.181	101.1	559
8	73.7	.162	32.6	201

Minimum: 201
Maximum: 559
Range: 358
Average: 335
Geomean: 318

TABLE 8
Load Testing Results for Warren Truss Bridge

Design Team #	Warren Truss Bridge Weight (grams)	Bridge Weight (lbs.)	Load at Failure (lbs.)	Structural Efficiency
1	80.1	.177	59.7	337
2	78.6	.173	41.1	238
3	73.0	.161	48.2	299
4	57.6	.127	54.1	426
5	73.9	.163	71.8	440
6	82.5	.182	133.3	732
8	72.0	.159	64.4	405

Minimum: 238
Maximum: 732
Range: 494
Average: 411
Geomean: 388

FIGURES

Figure 1. Howe Truss Bridge Model from Bridge Designer 2015

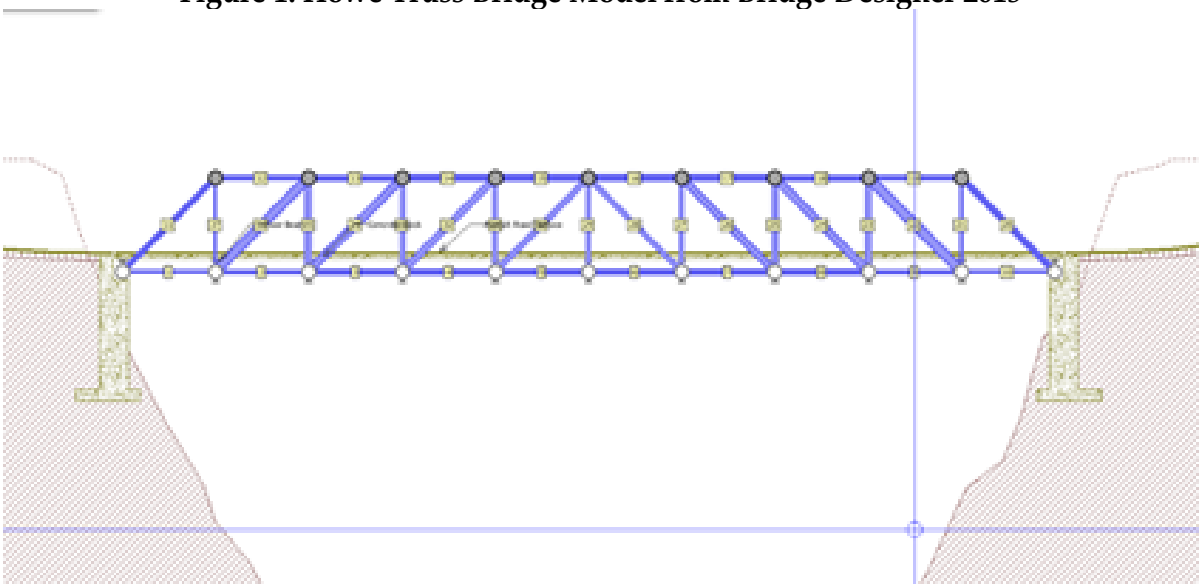


Figure 2. Warren Truss Bridge Model from Bridge Designer 2015

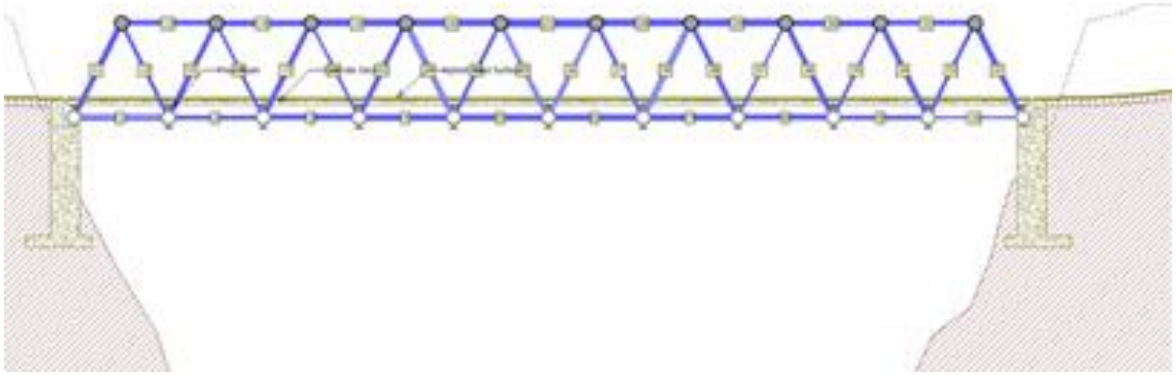


Figure 3. Howe Truss Bridge Prototype before Load Testing

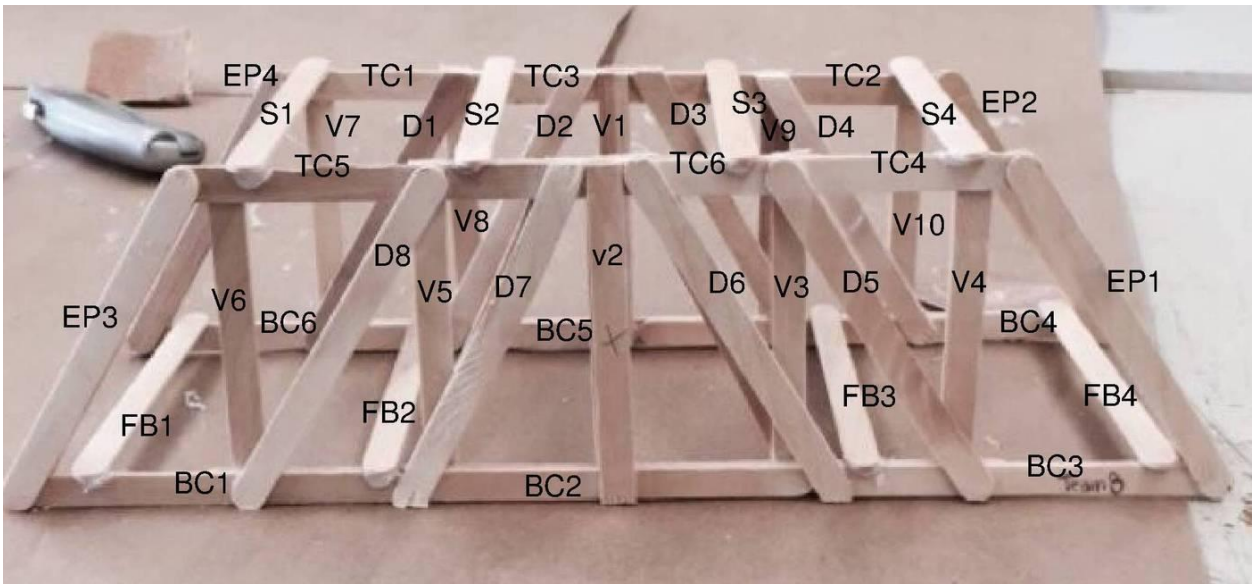


Figure 4. Howe Truss Bridge Prototype Failure after Load Testing

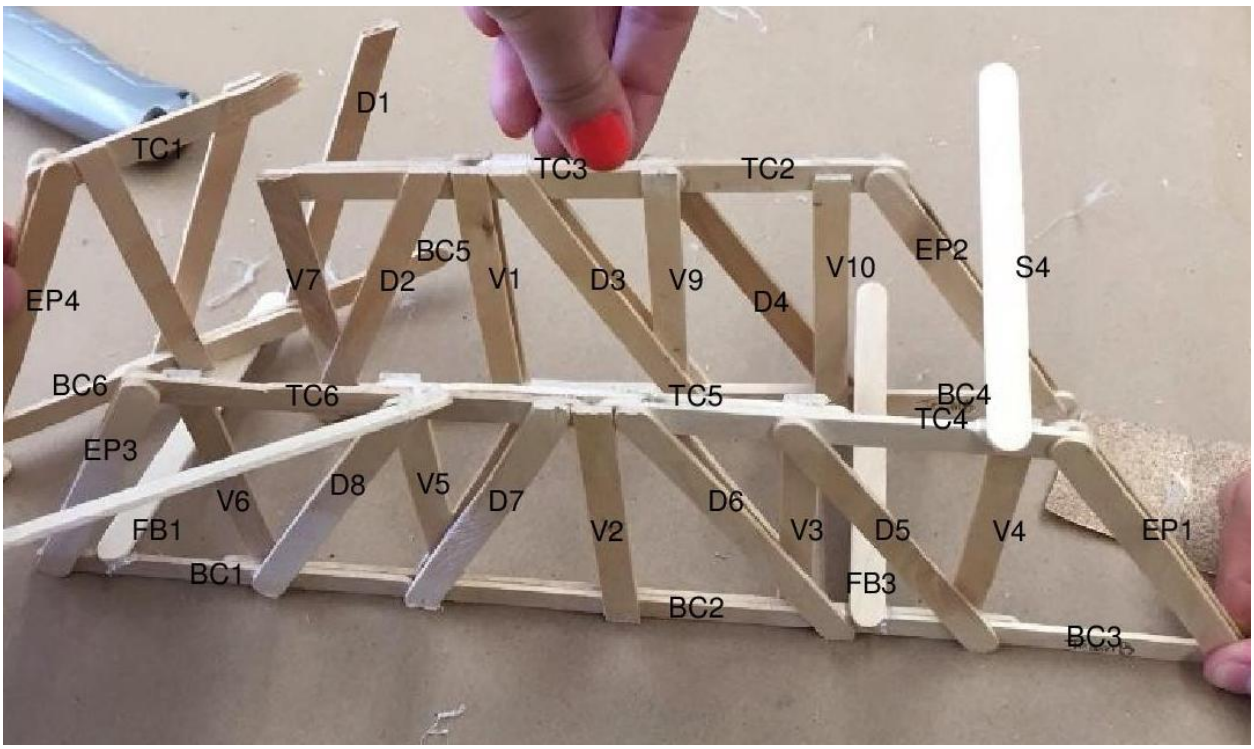


Figure 5. Warren Truss Bridge Prototype before Load Testing

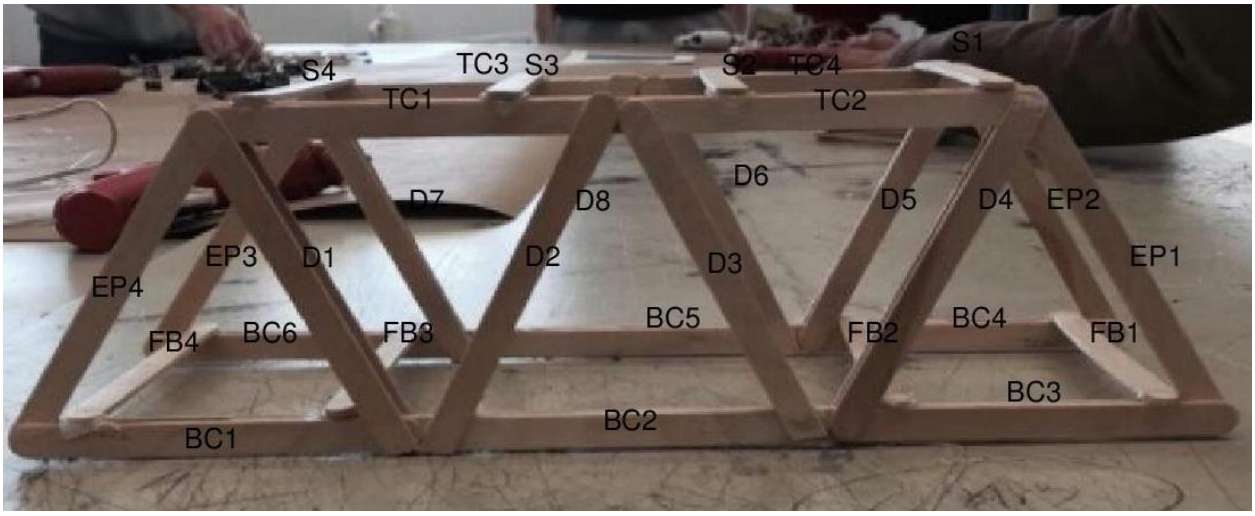


Figure 6. Warren Truss Bridge Prototype Failure after Load Testing

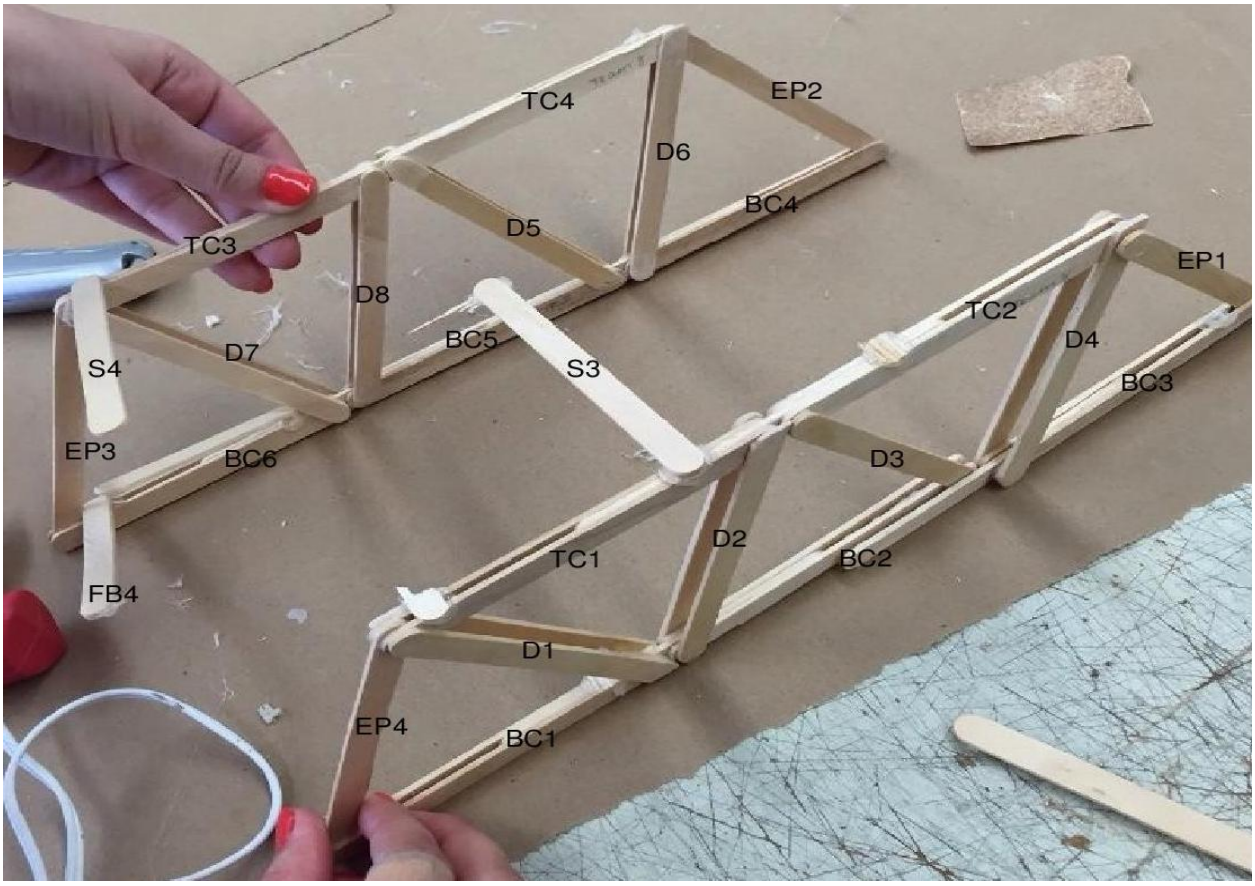


Figure 7. Howe Truss Bridge Structural Efficiencies

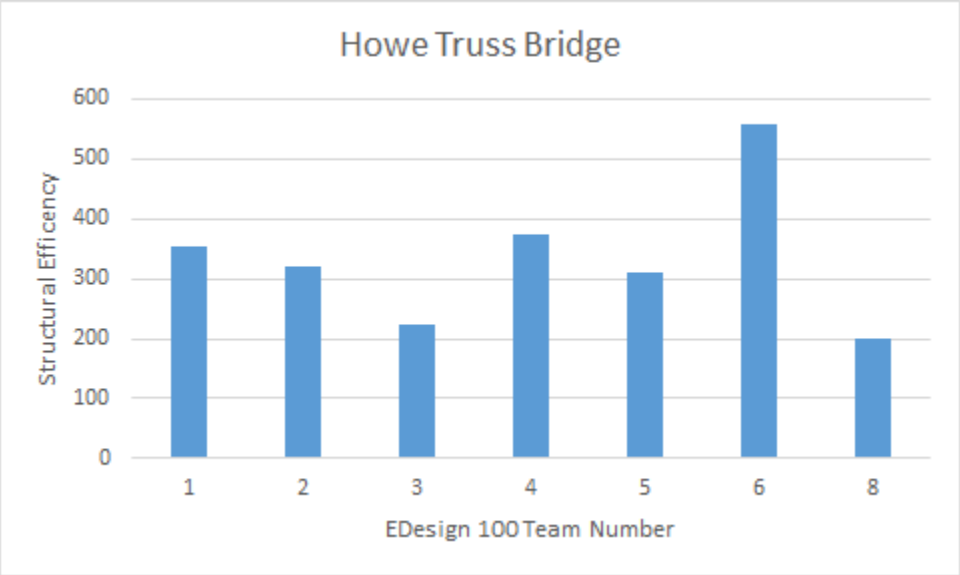
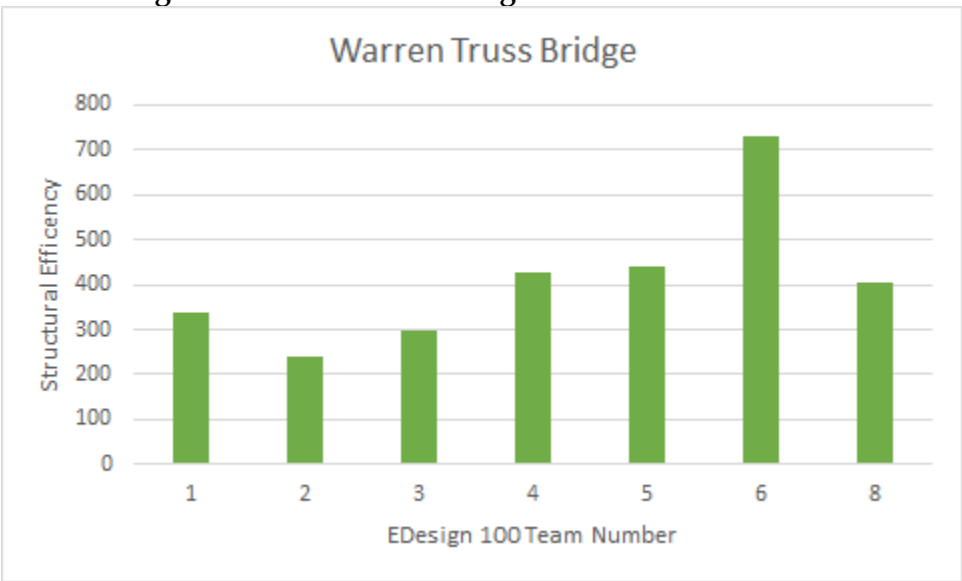



Figure 8. Warren Truss Bridge Structural Efficiencies