Structural Comparison of a Composite and Steel Truss Bridge

by

Jeffrey Kinlan

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Approved:

Professor Ernesto Gutierrez-Miravete, Engineering Project Adviser

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Jeffrey Kinlan
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ABSTRACT

The main purpose of this project is to perform a structural analysis of a standard truss structure bridge made entirely out of composite materials. This analysis would attempt to show that composite materials make a much stronger, lighter, and more durable building material over the best steel material. Real world loading conditions of the bridge will be analyzed. The members that make up the truss bridge and the gusset plates that connect them will be optimized by customizing a layup to fit each member and gusset plates individual loading condition. The analysis will be performed using a hand analysis and then verified using a finite element model in ANSYS. Mesh studies will follow all ANSYS models. A similar analysis will be completed for a truss bridge made of steel in order to make a comparison. The steel truss bridge will contain the same number of members and gusset plates in the same geometric shape. The intent is to compare which material is more efficient when constructing a truss bridge.
1. Introduction/Background

A bridge is the solution to a puzzle. It solves the common problem of how to span an obstacle through the use of basic engineering principles. This solution comes in many forms and the best is the most efficient, elegant, and safest. One of the more basic types of bridge is a truss bridge. This is comprised of a collection of straight members organized such a way that a load can be transferred from the edges of the bridge into the surrounding structure. The members of a truss bridge are connected at gusset plates which transfer the load between members. Numerous different geometries are possible in a truss bridge but the one to be analyzed in this report is the Warren Truss, shown in Figure 1.1, which was created by James Warren and Willoughby Monzoni in 1848.

![Warren Truss](image)

**Figure 1.1 - Warren Truss**

This type of truss is characterized by alternating equilateral triangles.

Most truss bridges are constructed out of structural steel but wooden truss bridges are not uncommon if the forces are smaller. In bridges made of these materials the stresses in each member are checked against a material allowable. If the stress is too large a designer only has two choices. One is to increase cross sectional area and the other is to redesign the geometry of the truss to more evenly distribute load. Each of these choices has unfortunate tradeoffs. Increasing cross sectional area increases weight which adds more weight the truss has to carry and possibly causes other geometric problems which may violate the design parameters of the bridge. Redesigning the truss geometry adds to the number of connections needed in the truss and possible points of failure. The only option left is to change materials and the only kind of material that gives a designer full customization ability of individual members is composite materials.

Composite materials are known for their ability to be tailored to any situation. A composite layup can have most any strength and stiffness in any desired direction. In addition they often have better strength, stiffness, and corrosion properties as well as lower weight then standard metal materials. These properties make composite materials
ideal to use when designing truss bridge members and gusset plates. The layup of each member and gusset plate can be customized to meet the demands of each individual part without significantly increasing weight or cross sectional area.
1.1 Truss Geometry

As previously mentioned the truss bridge type that was analyzed in this report is the Warren truss. Dimensions of the truss were sized per the design standards of the United States Department of Transportation Federal Highway Administration. This puts a minimum on the clearance of the bridge at 16 feet. To meet this requirement and the requirement that the triangles in the bridge be equilateral the bridge members need to be 18.5 feet long. This provides for cross members of the bridge to be 16 feet above the road. The design standard also puts an absolute minimum on lane width at 11 feet but does strongly recommends this only be used for a temporary distance. As a result to be conservative and increase the safety of the bridge the lane width was set at 15 feet. The bridge design is for a two lane roadway which resulted in a total bridge width of 30 ft. To ensure that a bridge node coincided with the center of the span the number of triangles in the bridge was set to seven. This resulted in a bridge span of 74 feet. These dimensions are summarized in Table 1.1.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Length (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Span</td>
<td>74</td>
</tr>
<tr>
<td>Lane Width</td>
<td>15</td>
</tr>
<tr>
<td>Bridge Width</td>
<td>30</td>
</tr>
<tr>
<td>Member Length</td>
<td>18.5</td>
</tr>
<tr>
<td>Clearance Height</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 1.1 - Truss Dimensions

A wireframe schematic of these dimensions can be seen below in Figure 1.2.

![Truss Wireframe Schematic](image-url)
2. Theory/Methodology

2.1 Truss Loads

The three categories of loads on a bridge are the dead load, live load, and dynamic load. These three categories are treated individually in the following sections.

2.1.1 Dead Load

The dead load on a bridge is weight due to its structure. This is made up of the weight of the truss members, gusset plates, and road deck. These loads never change during the life of the bridge.

The weight of one truss member is calculated using Equation 2.1. There are 15 members per side and 9 cross members in the truss so the weight due to all members is 24 times this weight. For the time being a constant cross sectional area is being assumed for all members.

\[ W_{\text{member}} = \rho AL \]

Equation 2.1 - Member Weight

The weight of each gusset plate is calculated using Equation 2.2. There are 2 gusset plates per node connecting members which add up to a total of 36 gusset plates. For the time being a constant thickness and area are being assumed until they can be individually sized.

\[ W_{\text{gusset}} = \rho At \]

Equation 2.2 - Gusset Plate Weight

The weight of the road deck was calculated using the density of asphalt and the volume of the road as shown in Equation 2.3.

\[ W_{\text{road}} = \rho V \]

Equation 2.3 - Road Deck Weight
2.1.2 Live Load

The live load on a bridge is weight due to items traveling over the bridge or weights that may temporarily put load on the bridge. This is made up of the weight of vehicles and snow loads. These loads change and get redistributed over the life of the bridge.

The vehicle weight on the bridge is calculated by assuming the heaviest allowed vehicles are stacked over the entire span of the bridge on both lanes. According to the department of transportation the heaviest truck allowed on a highway weighs 80,000 lbs and measures 51 feet in length. The weight due to the bridge supporting these vehicles is shown in Equation 2.4.

\[
W_{\text{vehicle}} = 2 \left( \frac{L}{l_{\text{vehicle}}} W_{\text{truck}} \right)
\]

Equation 2.4 - Vehicle Load

A snow load must be accounted for in case the bridge is covered with snow. This is not an insignificant amount and should not be overlooked when calculating the bridge load. In the State of Connecticut building code specifies a snow load all structures must be designed to in terms of pound per area of potential snow coverage. In Connecticut the most stringent snow load is 40 lb/ft\(^2\). This means that the snow load on the bridge is calculated using Equation 2.5.

\[
W_{\text{snow}} = PA
\]

Equation 2.5 - Snow Load

2.1.3 Dynamic Load

The dynamic load on a bridge is due to temporary loads on a bridge that might perturb the structure momentarily. The most common type of dynamic load is wind load which acts in possibly any direction but most often as against the side faces of the truss. This load is braced against damaging the structure by the cross beam members. This load has not yet been calculated and will be presented at a later time.
2.2 Method of Joints

The forces in the truss members were analyzed using the method of joints. In this method a free body diagram is drawn at each joint or node to determine the forces in each of the members. The Warren truss in this report has a total of nine nodes and 15 members. Since the truss is simply supported this results in 15 unknown member forces, 3 reaction forces, and 18 equations. The members of the truss are numbered and the nodes were assigned letter designations as seen in Figure 2.1.

![Figure 2.1 - Member and Node Designation](image)

In the free body diagram of each node member forces are drawn such that they are positive in compression. In addition to the member forces nodes also support the forces on the bridge structure itself. There are three types of connection nodes in a Warren truss. They are the edge nodes, top side nodes, and internal nodes. Nodes A and I are edge nodes, nodes B and H are top side nodes, and nodes C, D, E, F, and G are internal nodes. Free body diagrams for these three node types can be seen in Figure 2.1.

![Figure 2.2 - Edge, Top Side, and Internal Node Free Body Diagrams](image)
After all the free body diagrams have been drawn the 18 equations can then be put into matrix form as seen in Equation 2.6 and then solved for the member forces.

\[
[C][F] = [P]
\]

**Equation 2.6 - Nodal Load to Force Relation**

In this equation \([C]\) is the coefficient matrix, \([F]\) is the vector of member forces and \([P]\) is the vector of nodal loads.
2.3 Stresses and Buckling

Once the forces have been found in each member the axial stress can be calculated using

$$\sigma = \frac{F}{A}$$

Equation 2.7 - Member Stress

These stresses can then be compared to the material allowable using a factor of safety.

Forces in members can also be used to calculate the stresses in the gusset plates. These values have not as of yet been calculated.

A potential failure mode of the truss members is buckling of those in compression. To check buckling the critical buckling load needs to be calculated and compared to the force in each member. The equation for the critical buckling load is shown in Equation 2.8.

$$P_{cr} = \frac{\pi^2 EI}{L^2}$$

Equation 2.8 - Critical Buckling Load

This is the buckling load for a pinned-pinned connection of an axially loaded compression member. If the force in any compression member exceeds this value the member will buckle.
2.4 ANSYS Model

An ANSYS model to verify the hand calculations computed via the method of joints will be created. The forces and stresses will be calculated using this method and presented at a later time.
2.5 Composite Laminate Theory

Composite laminate theory was used to compute the stiffness and stress in all composite truss members. The theory will be presented in this section at a later time.
3. Results

3.1 Bridge Loads

The loads on the bridge were calculated and are summarized in Table 3.1. These loads are the total for the entire bridge.

<table>
<thead>
<tr>
<th>Load</th>
<th>Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Members</td>
<td>88,208</td>
</tr>
<tr>
<td>Gusset Plates</td>
<td>122</td>
</tr>
<tr>
<td>Road Deck</td>
<td>99,900</td>
</tr>
<tr>
<td>Vehicle</td>
<td>232,157</td>
</tr>
<tr>
<td>Snow</td>
<td>88,800</td>
</tr>
</tbody>
</table>

Table 3.1 - Bridge Loads

Each side of the bridge is assumed to carry half of bridge loads. Therefore the magnitude used in the analysis is half of what is found in Table 3.1. The road deck, vehicle, and snow load were assumed to be reacted by the lower middle three nodes (load P). The weight of the gusset plates (load g) are reacted at each individual node while the weight of each member (load w) is spread of the two nodes it connects. The truss itself is assumed to be simply supported. The free body diagram of the bridge loads on the truss can be seen in Figure 3.1.

![Figure 3.1 - Truss Load FBD](image_url)
3.2 Member Forces

The fifteen member forces and three reaction forces were calculated and are presented in Table 3.2.

<table>
<thead>
<tr>
<th>Force</th>
<th>Magnitude (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F_1</td>
<td>143,051</td>
</tr>
<tr>
<td>F_2</td>
<td>-71,525</td>
</tr>
<tr>
<td>F_3</td>
<td>-137,823</td>
</tr>
<tr>
<td>F_4</td>
<td>140,437</td>
</tr>
<tr>
<td>F_5</td>
<td>50,296</td>
</tr>
<tr>
<td>F_6</td>
<td>-165,585</td>
</tr>
<tr>
<td>F_7</td>
<td>-43,763</td>
</tr>
<tr>
<td>F_8</td>
<td>187,467</td>
</tr>
<tr>
<td>F_9</td>
<td>-43,763</td>
</tr>
<tr>
<td>F_{10}</td>
<td>-165,585</td>
</tr>
<tr>
<td>F_{11}</td>
<td>50,296</td>
</tr>
<tr>
<td>F_{12}</td>
<td>140,437</td>
</tr>
<tr>
<td>F_{13}</td>
<td>-137,823</td>
</tr>
<tr>
<td>F_{14}</td>
<td>-71,525</td>
</tr>
<tr>
<td>F_{15}</td>
<td>143,051</td>
</tr>
<tr>
<td>R_y</td>
<td>127,281</td>
</tr>
<tr>
<td>R_x</td>
<td>0</td>
</tr>
<tr>
<td>R_i</td>
<td>127,281</td>
</tr>
</tbody>
</table>

Table 3.2 - Truss Forces

As can be seen seven of the members are in tension and eight are in compression. This is visualized in Figure 3.2 where red members are in tension and blue are in compression.
3.3 Member Stresses

The stresses in each of the members were calculated and presented in Table 3.3.

<table>
<thead>
<tr>
<th>Member</th>
<th>Stress (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3,974</td>
</tr>
<tr>
<td>2</td>
<td>-1,987</td>
</tr>
<tr>
<td>3</td>
<td>-3,828</td>
</tr>
<tr>
<td>4</td>
<td>3,901</td>
</tr>
<tr>
<td>5</td>
<td>1,397</td>
</tr>
<tr>
<td>6</td>
<td>-4,600</td>
</tr>
<tr>
<td>7</td>
<td>-1,216</td>
</tr>
<tr>
<td>8</td>
<td>5,207</td>
</tr>
<tr>
<td>9</td>
<td>-1,216</td>
</tr>
<tr>
<td>10</td>
<td>-4,600</td>
</tr>
<tr>
<td>11</td>
<td>1,397</td>
</tr>
<tr>
<td>12</td>
<td>3,901</td>
</tr>
<tr>
<td>13</td>
<td>-3,828</td>
</tr>
<tr>
<td>14</td>
<td>-1,987</td>
</tr>
<tr>
<td>15</td>
<td>3,974</td>
</tr>
</tbody>
</table>

Table 3.3 - Member Stresses

These stresses will be compared to a material allowable with a factor of safety in a later version.
3.4 Buckling Loads

The buckling load of each member is currently a constant 2.8 million pounds because each member has the same length, stiffness, and moment of inertia and the cross section area is currently very large. Since this is so substantial none of the members buckle. Later corrections on the cross sectional area and stiffness may change this result.
4. Conclusion

Since the composite truss bridge has not been analyzed as of yet no conclusions can be made. This will be included at a later date.
5. References


Ippolito, Dan. “Layered Fiberglass vs. Injection Molded Composite Surfboard Fin Finite Element Analysis” M.Eng Project. RPI Hartford, 2010