5-20-2015

Measuring Strain in Trusses

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Measuring Strain in Trusses

Spencer Metzsch

A Thesis
Presented to the Department of Physics
LINFIELD COLLEGE
McMinnville, Oregon

In partial fulfillment of the requirements
For the Degree of
BACHELOR OF SCIENCE
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Updated April 2, 2012
Thesis Acceptance

Linfield College

Thesis Title: Measuring Strain in Trusses

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Date Submitted: May 2015

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Abstract

Strain is an important quantity in engineering design and materials science that relates the deformation of a material to its original length, through a percentage. Different materials exhibit particular qualities under loading, for example the amount of strain due to a certain magnitude of force, or the amount of strain that can be borne before failure. This experiment aims to compare the relative strengths of three common truss configurations by measuring the strain in their members under loading. The Queen’s Post truss was found to be the best at minimizing strain under similar loading conditions.
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I. Introduction

Strain is an important concept in scientific disciplines that deal with designing and maintaining structures. It is defined as the ratio of the change in a sample material relative to its original length. Being able to easily calculate and measure strain is very important, in order to build and maintain structures that are sturdy enough for safe use, while not wasting excess material. Different materials have their own particular response under loading that are experimentally found with a sample of the material. Basically stresses produce strain, and if continually increased that deformation will eventually lead to failure. (1)

Figure 1. Beam (top) vs a simple truss

A beam is the most basic structure used in engineering. It is simply a straight piece of material that carries a load, as shown in Figure 1. A series of smaller beams can be combined into a truss shape. Trusses have the benefit of being stronger than a similarly dimensioned solid beam, but with much less material used and therefore less dead weight on the structure (2). Trusses also resist forces better than beams in skewed dimensions relative to their plane. For example, a beam might twist or bend unevenly, while a truss will direct the forces along its members and flex
evenly throughout its structure. Many different truss designs exist and are commonly used in various applications, taking into account the dimensions, load, and aesthetics. The case I will be looking at is a truss that has to carry a load over a horizontal span, most commonly seen in bridges and buildings.

The goal of this experiment is to measure strain to determine the overall strength and stability of a truss structure. A Warren truss should outperform a King’s post truss and Queen’s post truss in terms of minimizing strain under the same loading due to its uniform design and also because it has the shortest individual member lengths.
II. Theory

The core of this experiment is measuring the strain in a material. Stresses will be introduced to a truss structure, and the resulting strain will be measured and calculated.

2.1 Strain

Strain is measured with a sensor called a strain gauge, which is in essence a precision resistor. It is affixed to the surface of a beam to be measured, and works due to a simple property of resistance of a material. Equation one shows the definition of electrical resistance.

\[ R = \rho \frac{l}{A} \]  

(1)

Where \( R \) is electrical resistance, \( \rho \) is the resistivity, \( l \) is the length of material, and \( A \) is the cross sectional area of the material. (3)

When the wire in the gauge is strained, it grows in length while shrinking in cross-sectional area, both of which lead to an increase in resistance. The converse of that is true: if the wire is compressed, the length decreases and area increases, decreasing the resistance. So, under stress the strain gauge’s resistance changes, and this change is proportional to the strain in the material it is attached to, as they both experience the same percent elongation. (1)

Figure 2 shows a diagram of a strain gauge. The wire snakes back and forth on one axis, so that its effective length along that axis is increased without increasing the gauge size so as to become impractical. Figure 3 shows an actual strain gauge that this experiment used in testing, attached to a truss. In a measuring application outside of academia the gauge would be completely covered with an insulator, for example a silicone adhesive, in order to help hold everything in place and prevent contamination of readings (4).
Figure 2. Enlarged diagram of a strain gauge. The large squares are solder pads for connecting to the circuit, and the lines are the resistance wire. Everything in blue is conducting, except for the radial alignment marks around the outside. (5)

Figure 3. Photo of actual strain gauge on aluminum member. Note: the aluminum is 0.75 inches wide (gauge is approx. 0.16” by 0.2”)

In Figure 4 the relationship between strain in the gauge and strain in the member is related. Since they are connected, they both have the same percent elongation relative to their original lengths.

The resistance change in a strain gauge can be measured indirectly with an electric circuit, and the strain in the material can be calculated from there. Figure 5 shows the circuit necessary for measuring this resistance known as a Wheatstone bridge. When a voltage $V_{in}$ is applied to this circuit, there will be a output voltage $V_O$, unless the ratio of resistances fits the condition of Equation 2. This bridge is highly sensitive to minute resistance changes. This makes it useful for measuring the very small changes in gauge resistance, which otherwise could not be measured in a significant way, for example with a multimeter (6). The relationship for the resistances of these gauges can be seen in equation two. When these resistances are “balanced” and all are equivalent, there will be no output voltage $V_O$ because there will be no potential difference between the two halves of the bridge. For most common strain values in this experiment, there will be an output voltage on the order of several millivolts.
Figure 5. Wheatstone Bridge circuit, with strain gauge in “quarter bridge” configuration. Vin is the voltage supplied (in this case approx. 5V), R1 through R3 are the precision resistors, and RG is the strain gauge. Vo is the output (measured) voltage.

\[
\frac{R_1}{R_2} = \frac{R_G}{R_3} \implies R_G = \frac{R_1}{R_2} R_3
\] (2)

The change in resistance is related to the physical deformation by a proportionality constant known as the Gauge Factor, which is unique to a particular strain gauge and provided by the manufacturer (4).

\[
\epsilon = \frac{\Delta L}{L} = \frac{\Delta R}{R R}\] (3)

Where \( \epsilon \) is the strain, \( L \) is the length, \( R \) is the resistance, and \( K \) is the gauge factor.
Equation 4 shows the relationship in a generic Wheatstone bridge circuit, with terms corresponding to Figure 5. This relationship can be derived from Kirchoff’s circuit laws, examining the current at the circuit junctions, and the voltage in the different loops. (3)

\[ V_{out} = V_{in} \left( \frac{R_3}{R_3 + R_G} - \frac{R_2}{R_1 + R_2} \right) \]  (4)

From here it follows that strain is related to the voltage output of the circuit, as shown in equation 5:

\[ \epsilon = \frac{4V_{out}}{V_{in}K} \]  (5)

2.2 Stress and Young’s Modulus

Stress is the load placed on a structure. A generic curve is diagramed in Figure 6, which shows the general response of a material under increasing loading. The first region, A, is of particular importance. This is the elastic region, where a material can be deformed and return to its original dimensions provided the yield stress is not exceeded (1). So, this section of the curve has a linear relationship. This experiment will be conducted in this portion of the curve for the particular material. Overloading would result in a permanent deformation that isn’t eliminated when the load is removed. The slope of this section is Young’s Modulus, also known as the modulus of elasticity, which is unique to a particular material. For the particular metal used in the experiment, 6061 Aluminum alloy, the manufacturer provides the Young’s modulus of 10x10^6 lbs/in^2. For reference, lead has a modulus of about 2.3x10^6 lbs/in^2 and steel has a modulus of about 29x10^6 lbs/in^2. 6061 Aluminum is a very common aluminum alloy used in planes, bike frames, boats and various fixtures. Aluminum was chosen for this experiment because it is easy to work with in terms of cutting and drilling, and also easy to show its strain.
Figure 6. Stress/Strain curve. A: Elastic region. B: Yield strength. C: Strain-hardening. D: Necking. X: Rupture. This is a generic graph; one for a particular material would generally look like this, but certain regions could be skewed. Graphs such as this are created through experiment and measurement of a sample.

2.3 Trusses

Trusses are a combination of members, which provide the strength of a single solid beam, but with less material used. Another advantage of a truss is that it only needs to be supported at its ends. An example of the practicality of this would be a bridge, which can cover large spans with little to no need for supports in between, which aren’t always feasible. There exists almost an infinite set of possible truss designs, but some of the most basic, common and practical ones are shown in Figure 7 (7).

Part of the definition of a truss is that no member is continuous through a joint. For example, in the King’s truss in Figure 7, the vertical line along the top of the truss from end to end is not one continuous piece (2). It is two separate and distinct members joined by a rivet at the vertical
intersection in the middle. This allows for each closed structure of a truss to be solved for independently, as will be outlined in a later section.

The King’s post is the simplest, with the fewest number of members, and therefore having the lowest weight per length, and lowest amount of material used. It is generally used for spanning short distances, as it is essentially one large triangle, and to cover a large span would leave long, uninterrupted beams with a very large structure vertically. The King’s post has the longest member lengths relative to span width of any of the trusses.

The Queen’s post is in the middle of the three for material used, but still quite simple. An interesting part of this design is the square in the middle, which is statically indeterminate (8). This means that it cannot carry a load as is. It requires a diagonal component connecting the
corners represented in Figure 7 as a thin dashed line; otherwise a load could skew its shape. This diagonal is known as a zero force member, as it carries no load, but serves to keep the truss aligned so that the truss can carry the load as it should. In fact, to prove this in my testing, I used some thin twine in an x pattern, which would break if more than a couple pounds of force were put on it, but it did not fail. This square shape tends to be used in special circumstances, like when a particular bracket is needed to attach to something, or the constraints of a building space necessitate avoiding a particular region in space where a triangular truss might otherwise intersect. They are also used for the top level of house roofs, as they allow for a lot more standing room than a traditional pointed roof on the top floor. The queens post can span a slightly larger width than the king’s post without being too tall or having too long of members, but is still constrained in this sense.

The Warren truss, and variations of it, is the standard in truss design. They are what most people think of when they think of a truss. It comes at the cost of using a lot of material, and therefore having a lot of dead weight. The Warren truss can be very, very long compared to the other two truss styles, as it is a repeating pattern with members that can be quite short relative to the width of the gap that it spans, and as the gap gets wider, the Warren style doesn’t need to grow vertically in size as fast as the others.

2.4 Method of Joints

The key idea of a truss is that it distributes the load it carries among its members. The forces in the members of a truss under load can be solved for using a process known as the method of joints (2). Take the example truss in Figure 8.
Figure 8. L. Basic sample truss. Load P is applied at the apex. One of the supports is assumed to be on a horizontal roller, so that there is no x component of force and no torque about the support. Also let us suppose that this is an equilateral triangle. R. The reactions at the supports from the applied load.

The first step is to find the sum of the forces in the y axis. There is the force of P in the negative y axis, and so for the sum of the forces to be zero (since the truss is at equilibrium), there has to be a positive force at each of the supports, A and B. Since this is an equilateral triangle with symmetrical loading, the force at A is equal to the force at B, and both are 0.5*P.

Now that the force at each joint is known, trigonometry can be performed to find the force components in each member. For this case it turns out that members AB and AC both have a compressive (positive) load of 0.58*P due to symmetry, while AC has a tensile (negative) load of 0.29*P.

This method can be applied for the loads in each member of a truss; this is merely an example of how to apply it and solve a truss.
III. Experiment

3.1 Experimental Set-up

For this project, the different truss designs seen in Figure 7 will be fabricated out of 6061 aluminum alloy, with cross sectional dimensions of 1/8” by 3/4”. The goal will be a small scale test of the relative strength of the different truss designs, to see which design most effectively minimizes the strain in its component members. The trusses will be placed under a variety of loading conditions, and the strain in their members measured. Obviously as the strain increases in a truss component the closer it is to failure, so the goal will be to test to find the design that best distributes and minimizes the forces in its members under loading.

The method of joints was used to solve for the forces in each member of the tree trusses, to see which components should have the largest strain in them. Strain gauges were applied to the three members of each truss with the highest theoretical strain, which are referred to as the “major force member”. The major force members are diagrammed in Figure 9, and are arbitrarily numbered. These are later referred to by the truss name and gauge number, for example: “King’s G2” for gauge number two on the King’s post truss. Strain gauges are applied with a thin glue that dries very hard, so as to best transmit strain from the member to gauge. Wire leads to the circuit are soldered to the gauge, and they were covered in a light coating of tape to protect them from damage.
Figure 9. Gauge location on the three trusses. Numbering is arbitrary.

Figure 10. Picture of experiment set up- Queen’s Post under load. The ends of the truss are hanging from wire attached to a clamp on two opposing tables. A scrap metal bar was used in conjunction with two wire hangers to distribute the load evenly in the middle of the structure, about the two corner points of the square. Note the circuit leads attached to the strain gauge.
A truss will be attached between tables, each end hanging from a wire loop as shown in Figure 10. This is because if it were bolted in place or resting on the tables themselves, a moment would be generated, resulting in a different distribution of forces in the members. In a full size bridge one end would be on rollers for this same reason, but for the practicality of this small test, a wire “hanger” accomplishes the same result (9). Wire leads will be attached to the strain gauge and measuring circuit.

3.2 Procedure

1. Attach the truss to the wire hangers, and attach circuit leads to one of its strain gauges as seen in Figure 10.

2. Record the voltage output with no load, and then continue recording the voltage output as the load is increased in 2.2 lb. increments, up to 15.4 lbs.

3. Perform three trials of step two for each gauge, and for each gauge on each truss.

3.3 Notes

Quantitatively, the gauge factor is usually near 2; the particular kind I used had a factor of 2.13

As an aside, there are several types of strain gauges. I ultimately chose the wire type described in this section because they have a low cost for the level of accuracy they provide, which is actually quite high. They are also very easy to apply and work with, and quite durable compared to alternate styles (10). This type of gauge is commonly used in industry; the ones I used were intended for use in a real-world scenario.

For this application, I used tape to hold the wire leads so they didn’t get torn off, but otherwise left the gauge uncovered for ease of access.
Bumping the truss can make the voltage “jump” and change unpredictably, due to shifting that occurs of the load, and out-of-plane bending that occurs in the members.

This process occurred for each gauge on each truss style, until satisfactory data was recorded for each.
IV. Results

The strain results I measured were as expected: strain increased linearly with loading for all of the structures. I chose to most prominently display the maximum force member, as found by the method of joints. This is the particular member of a truss design that has the most stress directed to it. I did this to directly compare the largest strains in each of the trusses.

![Stress/strain curve for gauge 1 on the King’s post.](image)

This data is least linear of all that I measured. This is likely due to the nature of the King’s post itself: I was able to visually detect bending and warping going on with this structure as the load was increased. Trusses like the ones I am testing are meant to stay in one plane, and by warping out of plane there were unexpected strain values.
Figure B. Stress/strain curve for gauge 1 on the Warren truss.

This data has the best linear fit and repeatability of all of my measurements. It has a negative slope because it is in tension, so the strain increased in the negative direction as the load increases.

Figure C. Stress/ Strain curve for gauge 2 on the Queen’s post.

This has a negative slope as the tension causes the load to be negative. Trials two and three show a good linear fit as expected.
From Figure D it can be seen that the Queen’s post has the lowest strain, with the Warren in the middle, and the King’s post exhibiting the highest strain. Also of note is the difference in variability between them. The Warren has the most linear fit, followed by the Queen’s post and the worst is the King’s post.
V. Conclusions

My data proved my hypothesis incorrect. The Warren truss did not have the lowest amount of strain in its members of the three trusses. I was correct, however, that the King’s had the greatest strain in its components. I attribute these findings to the nature of the designs, but they still each have their own strengths in different applications.

The King’s post exhibited the highest overall strain reading in the entire experiment, 109 microstrain. One reason for this is it has the longest uninterrupted member of any of the designs, and this member is where the high reading occurred. Also, the King’s post has the fewest number of components, so there are fewer pieces for the force to be distributed to.

The Warren truss was in the middle. While it was composed of equilateral triangles, so each member was the same length, one in particular (and likely, its mirror on the other half of the truss if measured) reached 74 microstrain under load. This is fairly high for something that is a standard in engineering design, but in addition to the positive attributes of this style mentioned in the background section I found that while the one segment has a large strain, the rest of the truss was very, very low. A practical solution to this is that the high strain member can be made of stronger/thicker material (at a higher price and weight addition to the structure), while the rest of the truss is made of much smaller members.

The Queen’s post surprisingly had the lowest strain in its major force member, at 45 microstrain. I was unsure how this one would perform, due to it having a sort of combination of the attributes the other two trusses possessed. I think it ended up being the lowest overall for just that reason. It has the simplicity of the King’s post that leads to a low dead weight on the structure, with the some of the extra support and shorter individual member lengths from the Warren truss.
VI. Acknowledgments

I would like to thank Dr. Xie, Dr. Murray and Dr. Mackie, and the rest of the Linfield Physics faculty and students, as well as all of my family and friends who helped inspire me to do this project.
VII. Bibliography


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