Triumph Motorcycle Rear Wheel Load-Deflection Evaluation
Part II
By

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Summary:

An earlier load vs. deflection evaluation of the new Triumph Bonneville (NTB) rear wheel spokes[2] was revised and repeated to address several concerns with the original study[3,4]. The major concerns, written by "Joeswamp", a contributor to the TriumphRat.Net, included: 1) the original test used a single, common, hub simulator rather than simulators tailored for each spoke's unique geometry and 2) the original test used a spherical countersink rather than a "straight" conical countersink. These geometric differences were a concern because the original test may have allowed the spokes to flex freely in the hub rather than become "locked in" so that they become constrained by the hub. If the spokes "lock in" there should be a difference in the relative stiffness between the inner and outer hubs. The hypothesis is then: *the tension in the outer spokes relaxes too much relative to that of the inner spokes when they are pointed downward and/or rear brakes are applied. Since the left outer spokes start out with less tension than the right outer spokes, they end up at the lowest tension. Therefore they are most likely to loosen and fatigue*[5]*.* Other concerns, related to test repeatability and manufacturing variation among the spokes were also addressed.

Despite the changes, the repeated test produced nearly the same results as the original test. The additional constraint from "locking in" the spokes in the hub did produce a difference between the stiffness of inner and outer spokes, but not enough that outside spokes would come near to loosing their tension under vertical load or braking. Even with extremely high wheel loads, the spokes deflect only a few thousandths of an inch and there are still hundreds of pounds of tension in all the spokes. The original conclusions stand: *the Triumph Bonneville rear wheel spokes should have adequate design load margin for worst case expected road loads. Nevertheless, like all spoked wheels, variations in wheel set-up as well as operating conditions can cause the Bonneville rear wheel spokes to become overloaded. If overloaded, the spokes yield, permanently loose tension, and ultimately cause the broken spokes that have been experienced on the Bonneville. The risk of broken spokes cannot be eliminated on the Bonneville rear wheel or any other spoked wheel but it can be reduced by checking and maintaining the spoke tension.*

Objective:

The objective of this re-evaluation was to assess the load vs. deflection characteristics of actual Triumph Bonneville spokes in a geometry representing the hub attachment as specified by Joeswamp and then to use those load/deflection data to analyze the rear wheel's response to loads.

Test Geometry:

The test geometry matched the original test with two exceptions. First the hub simulators were machined to match the geometry shown in Figure 1. This geometry was recommended by Joeswamp to more effectively "lock in" the spoke at the hub interface so that it would not be free to rotate as the spoke flexes (as it may have been in the previous test using a spherical countersink). The second geometric change was to use individual hub simulators representing each type of spoke. The simulators matched the hole dimensions, countersink, and recesses of Figure 1 as well as the individual spoke to hub angles and dimensions depicted in Figure 2. Figure 3 shows the resulting angles and dimensions of each Pull Test Fixture and Figure 4 shows the individual hub simulators.

The spoke load vs. deflection testing was performed by putting the Pull Test Fixtures into the Spoke Pull Test Assembly described in Reference 2. The Test Assembly consists of a movable frame comprised of two chrome steel shafts connected at the top and bottom by square steel bars. The movable frame slides between two bronze bearings attached to a steel plate. One end of the pull test fixture is fastened to the steel plate and the other is fastened to the moveable frame. The Test Assembly is placed in a hydraulic press which provides force to the moveable frame through a hydraulic load cell. The load cell has a piston area of one square inch so that a pressure gauge attached to it can directly read the load force. The downward deflection is measured by a dial indicator. The original test used a 2000 psi pressure gauge for the load cell. Accuracy was improved by replacing that gauge with a 1000 psi "process gauge" rated at 1% accuracy.

The movable frame weighs about 10 pounds. Therefore, force measurements had to be corrected to account for this weight to get the actual spoke load.

Test Procedure and Results:

Eight sets of load vs. deflection tests were performed. First, one of each of the four types of spokes was tested in its unique pull test fixture. Then the tests were repeated using the same simulator but another complete set of four fresh spokes. Each test was performed by holding the test fixture spacing at the "zero point" dimensions shown in Figure 3 while preloading the spoke to 400 pounds for left side spokes and 475 pounds for right side spokes[2]. Each spoke was then loaded so it deflected +/- 0.010 inches from the zero point. With fresh spokes and hubs, several deflection cycles were needed before the system "bedded in" and gave repeatable results. Once it was clear that the results were repeating, data was recorded for four cycles; two with loads ascending and two with loads descending. The multiple cycles not only assure that the spokes are stabilized, but also give an indication of the frictional and other repeatability errors of the test set-up because the frictional loads are reversed.

The load vs. deflection curves for each of the spokes are shown in Figures 5 through 8. The curves show the eight sets of measured data points (indicated as Spoke 1 Data and Spoke 2 Data), the average for this set of testing, and the results of the common hub testing of Reference 2 (indicated as "C. Hub Test"). The left spokes and the right inside spokes show almost identical load vs. deflection curves as the original test of Reference 2. Only the right outside spokes have slightly different, somewhat "stiffer" results.

Figure 9 shows a comparison of the average load vs. displacement curves for each type of spoke. Figure 10 shows the "average stiffness" comparison and shows that, as expected, the outer spokes are "stiffer" than the inner, although only by 15 to 20%.

Wheel Computer Model Load Assessment:

Although there was no major difference between the results of this and the previous test, the wheel load assessment was repeated.

The load/displacement curves of Figure 9 were used in a computer model[2] of the Triumph Bonneville rear wheel to determine the type of loading and deflection that the spokes experience on the road and to compare those loads and deflections with the limits identified in the load vs. deflection tests. The model directly uses the Figure 9 load vs. displacement curves by reading them as tables and linearly interpolating between measured data points.

Figure 11 shows the preloads that balance an unloaded Bonneville rear wheel with the lowest preload, the Left Outside, being set at 400 pounds, a value based on the Reference 2 preload test. The geometric force balance and minimum preload variation then results in preloads of 404, 472 and 475 pounds for the Left Inside, Right Outside, and Right Inside spokes respectively.

Figure 12 shows how the entire wheel responds to a vertical load. Vertical loads consist of the weight of the bike, rider, passenger and luggage. At rest, the weight is distributed between the front and rear wheel but under high acceleration, all the weight can be put on the rear wheel (a "wheelie"). The vertical load also is increased (and decreased) by vertical accelerations from the road surface, potholes, etc. With all the spokes in work, the Bonneville wheel is quite stiff in the vertical direction, deflecting only 0.005" with a vertical load of over 3000 pounds (read from the line with red filled squares using the left scale), almost 5 times the total bike weight. The wheel reacts to these loads by increased tension in the upper spokes and reduced tension in the lower spokes. The maximum and minimum spoke loads are also shown in Figure 12, and are read on the right scale. Figure 13 shows how the spoke loads vary with position. Even with the 3100 pound wheel load, the maximum spoke load is about 700 pounds and the lowest spoke load is about 250 pounds. These values neither overload nor loose tension in any of the spokes

Joeswamp also pointed out that bicycle wheels have fairly flimsy rims compared to the stiffness of the spokes[6]. Assuming Triumph Bonneville rims are similar, they could cause the bottom spokes to loose all their tension, come loose and fail. It is very questionable that a heavy motorcycle rim and tire are as flimsy as a racing bicycle wheel, but that possibility was included in the model. Lacking test data, it was assumed that a worst case is where the rim is flimsy enough that vertical loads cause the bottom of the wheel to "buckle" so that the deflection at the bottom of the wheel is ten times as much as the deflection at the top of the wheel. The individual spoke loads for a 3100 pound vertical load on this "flimsy" wheel are shown in Figure 14. The bottom spokes only loosen by another 50 pounds and still have almost 200 pounds of tension.

The individual spoke deflections under the 3100 pound vertical load are shown in Figures 15 and 16 for the rigid and flimsy rim case respectively. Even with these very large loads, the worst spoke deflection is less than 0.010". It can be seen that the pairs of inside and outside spokes work together.

The wheel experiences side loads (parallel to the axle centerline) when the bike is banked for turning and from side impacts to the tire from road obstacles. Figure 17 shows the wheel response to side loads in each direction of over 3 times the total bike weight (+/- ~2000 pounds). Total side loads are shown by the line with the filled red squares and are read on the left scale. Maximum and minimum loads for individual spokes are read from the lines marked with *X* and * using the right scale. As with the vertical loads, very high side loads can be accommodated.

Acceleration and braking loads are transmitted from the hub to the rim by twisting the hub, around the axle centerline, relative to the rim. From the wheel geometry, the outside spokes have increased tension with acceleration loads while the inside spokes have increased tension with braking loads. Figure 18 shows the wheel response to acceleration (plus loads) and braking (negative loads), expressed in terms of the tire contact load. (The curves are identified as in the previous two figures and the appropriate scales also match the convention of Figures 16 and 17). During braking, most of the bike's weight shifts to the front wheel so even a hard, 1G, stop probably only generates about 250 pounds of tire contact load and has only a slight change from preload on the individual spokes. Acceleration loads can be a 1G, or slightly more, tire contact load and result, not just from acceleration, but from overcoming wind and road drag at steady speed. Even in the limits of the tire loads plotted in the figure, about 3 times the total bike weight, the spoke loads are in the tested range for all the spokes.

Figures 19 and 20 show the individual spoke loads and Figures 21 and 22 the corresponding deflections for the case of typical rear wheel loading under hard, 1G, braking, with 400 pounds on the rear axle, for the case of a “rigid” and “flimsy” wheel rim respectively. The tension loads have shifted to the inside spokes while the outside spokes have reduced tension. Even with these high braking loads, the individual spokes deflect only a few thousandths of an inch and the tension only changes slightly from preload.

Finally, Figures 23 through 26 show spoke loading and deflection for a heavily loaded (900 pounds on the rear wheel) bike accelerating at 1G while in a 20 degree lean; again respectively for “rigid” and “flimsy” rims. All three types of loading – vertical, side, and acceleration are taking place. As in all the previous figures, the individual spoke loads are in the tested region and deflections are less than 0.006 inches.

Conclusions:

The test and analytical work documented here have several limitations:

a) Only two sets of spokes were tested so there is little data on sample variation.

b) No fatigue testing was performed.

c) The original build processes, preloads and any cold working cycles used by Triumph or their supplier are unknown.

d) Motorcycle wheels are subjected to a wide range of loads and abuse that cannot be included in any computer model.

Nevertheless, this evaluation does lead to the following conclusions:

1) **The original test results and conclusions are still valid:**

   a. **The spokes, hubs and rims have been designed to produce a wheel where all the spokes work together and have adequate margin so that the spokes will not normally become overloaded or unloaded, even with fairly extreme wheel loads.** Based on static load testing, there is nothing indicating a design issue.

   b. **The spokes will yield and permanently set in the stretched condition if overloaded. Once they set, their load capability is near zero.** Since the spokes operate in conjunction with their neighbors, once one spoke is overloaded and loosened, its partners loosen as well. When this happens, some of the spokes are indeed “along for the ride” and the peak loads on the other spokes increase – further compounding the trouble. This is the most likely cause of spoke failures in general as well as on the Triumph Bonneville. Although the computer model predicts the spokes should live a long happy life - hard impacts on potholes, rough roads and high speeds, hitting curbs, and similar experiences are known to overload, loosen and ultimately break spokes[7,8,9]. The spokes have a complex geometry where small yielding is likely to occur at lower load values then inferred from the data. Finally and most importantly, initial adjustment and subsequent servicing can easily overload the spokes. ¼ turn of the nipple puts a 0.006 inch displacement on the spoke. That’s about 200 pounds of load and the same as the whole range of normal operation.

   c. **The spokes will not initially loosen from becoming under loaded.** The spokes act in unison and balance unloading with loading. Because of the “bending” mode a spoke has to be allowed to loosen by almost 0.032 inch to become unloaded. The normal unloading range is well under 0.010 inch. However, a spoke that has yielded from overloading will then always be under loaded.

d. **The spokes get better when retightened.** The retighten evaluation of Reference 2 shows that the spokes become less likely to yield after they have been loaded past the first yield point and retightened. That characteristic is well known in the literature and is used in similar industrial applications. It is also used by bicycle wheel builders who are known to over-stress their spokes to increase the yield resistance[10].

2) **The spokes require several load cycles to "bed in".** A new spoke in a new hub simulator took approximately 15 cycles to "bed in" so that each load cycle would repeat. A new spoke in a used hub simulator took approximately 4 cycles to "bed in". Until the spoke "beds in" the spoke becomes looser after each cycle. It then needed to be retightened and recycled. With each cycle, the loosening was less until the load vs. deflection cycle became repeatable.

Recommendations:

Spoked wheels have advantages over single piece cast or machined wheels. They are more flexible and are able to keep going even with one or more broken spokes. Unlike single piece wheels they can be repaired in the field; by simply replacing spokes. These advantages have made spoked wheels the primary choice of off-road riders. On the downside, the major disadvantage of spoked wheels is that they generally preclude using a tubeless tire and make a flat tire more difficult to repair on the road. They also contribute to flat tires if the broken spoke gets driven into the tube. The Motorcycle Safety Foundation has this to say:

> *Although tubeless tires significantly reduce the likelihood of a blowout and resulting loss of control, tube-type tires are still fitted to many cruiser models in order to use wire-spoke wheels for appearance reasons. However, alter-native wire-spoke wheel designs exist that may be used with tubeless tires. Wire wheels may also be sealed for use with tubeless tires. The Hurt Report listed puncture flats as the primary motorcycle vehicle failure leading to crashes*.[11].

The new Triumph Bonneville has the spoked wheel design solely for appearance purposes – the original Meriden Bonneville had spoked wheels. It is probably impossible to prevent a broken spoke with Bonneville wheels or any other spoked wheel. Therefore, from a pure safety standpoint, an owner should consider replacing the wheels with one piece wheels that can use tubeless tires. However, there are many owners (the author included) who have had thousands of trouble free miles with the original wheels. This evaluation shows that there is sufficient design margin that broken spokes should be rare. Based on the conclusions of this study, the following is recommended:

1) **Have the 500 mile check done by a skilled wheel technician.** This is probably the primary lesson from this study. Whatever preloading and servicing was done when the bike was built will be "worked" out during the first 500 miles. The spokes will "break in" just like the engine and flexing will relieve stresses in the high yield areas. If the spokes are checked and loose spokes retightened, all the spokes will be back to as close to ideal condition as practical.

2) **Recheck the spokes frequently.** The spokes continue to "work" and will also re-adjust to every change made in tension by adjustment.

3) **Don't tighten anything more than necessary.** The spokes have a stiffness of 25,000 to 40,000 pounds per inch. One turn of the nipple is 0.7mm or 0.028 inches. A single turn can change the load by 1000 pounds. The accepted method of adjusting spokes is to listen for a "ping" instead of a "thud" when tapping the spokes. If a "thud" is found, the nipple should be turned only enough to obtain the "ping".

4) **Triumph should issue a Service Bulletin describing how to maintain the spokes.** Successful "tuning" of the spokes has been shown to produce a very strong and robust wheel. However, testing has shown that it takes several cycles to "bed in" the spokes. Also, the correct tension is unknown. A service bulletin describing the recommended procedure for initial set-up and subsequent maintenance would assure that the wheels achieve in service the robustness they appear to have in the laboratory.

Acknowledgements:

The author acknowledges the assistance of triumphrat.net forum members joeswamp and johnyC.

References:

1) http://proepowersystems.com/Proeschel_Resume.pdf
2) http://proepowersystems.com/RAT/Triumph Bonneville Rear Wheel Load-Deflection Evaluation.pdf
3) http://www.triumphrat.net/971541-post136.html
4) http://www.triumphrat.net/971542-post137.html
5) http://www.triumphrat.net/972979-post151.html
6) http://www.triumphrat.net/955357-post134.html
7) http://www.britbike.com/ubb/cgi-bin/ultimatebb.cgi?ubb=get_topic;f=10;t=006401;p=1
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9) http://hdforums.com/m_2695711/tm.htm
10) http://www.sheldonbrown.com/brandt/stress-relieving.html
11) http://www.nhtsa.dot.gov/people/injury/pedbimot/motorcycle/00-NHT-212-motorcycle/motorcycle43-44.html

***Figure 1** – Joeswamp's Locking Hub Geometry*

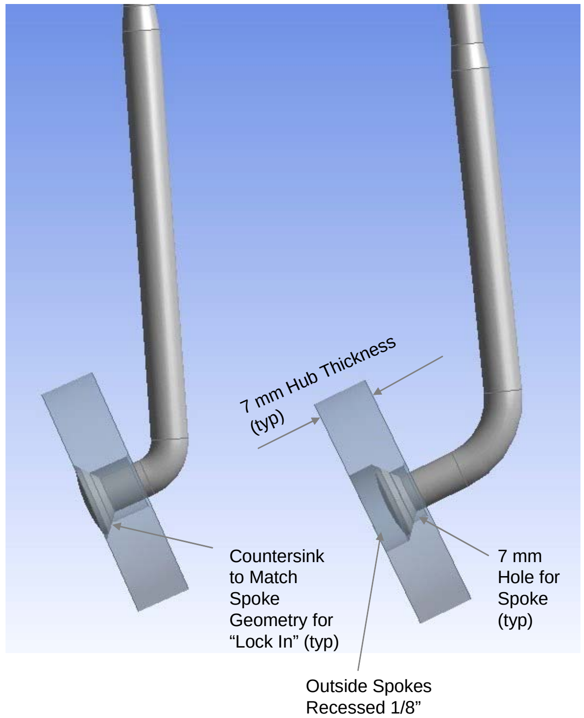
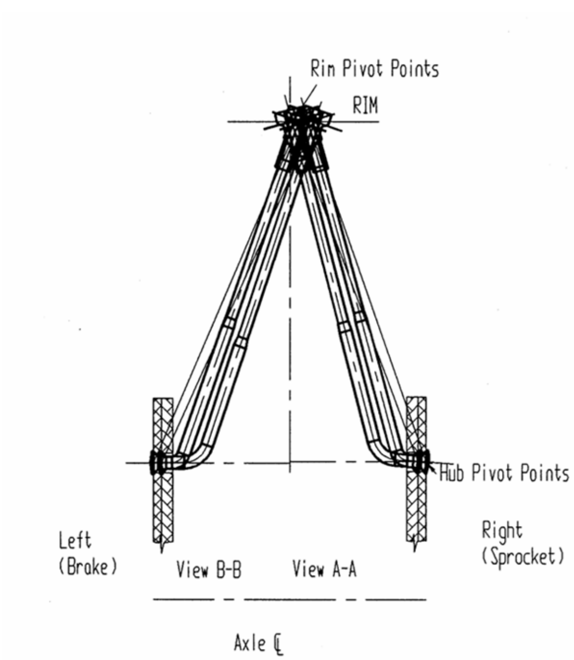
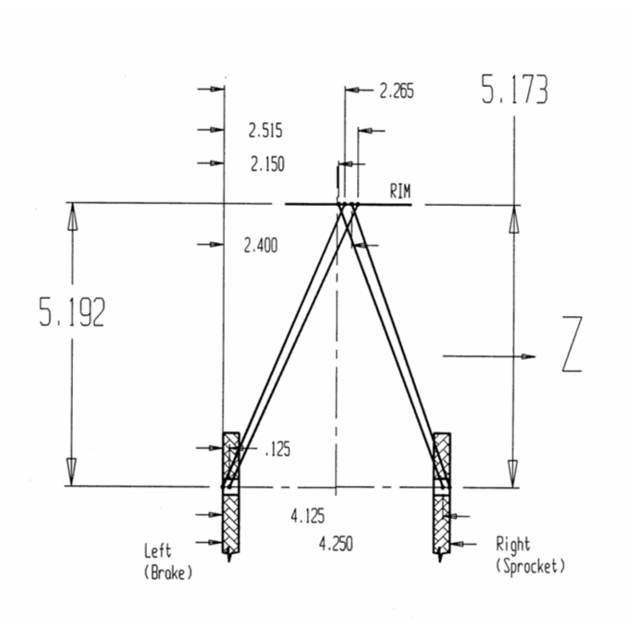


***Figure 2** – Hub and Spoke Relation*





(See Reference 2 for more info)

Figure 3 *– Individual Pull Test Fixture Geometry*

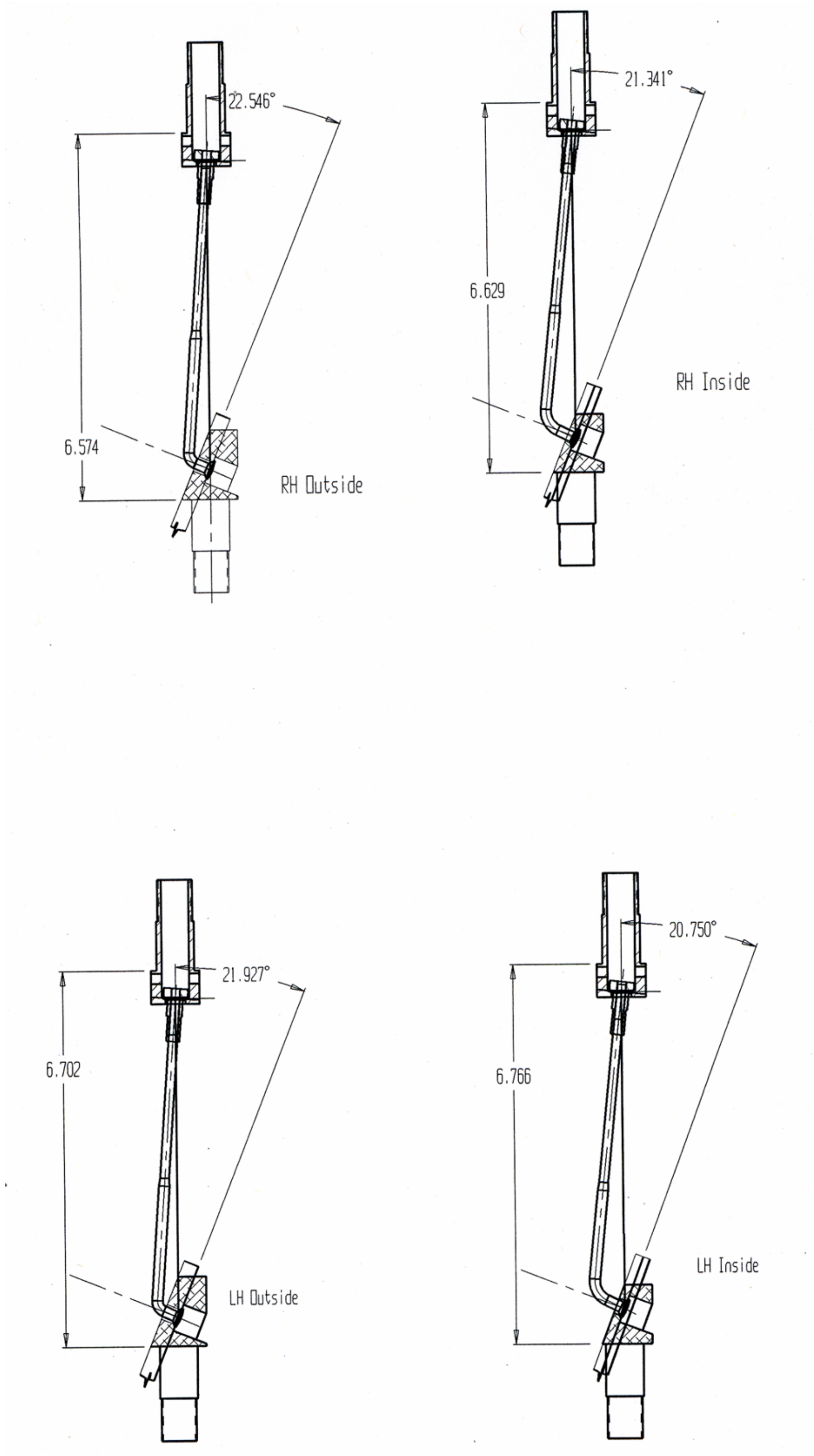


Figure 4 *– Individual Hub Simulators*

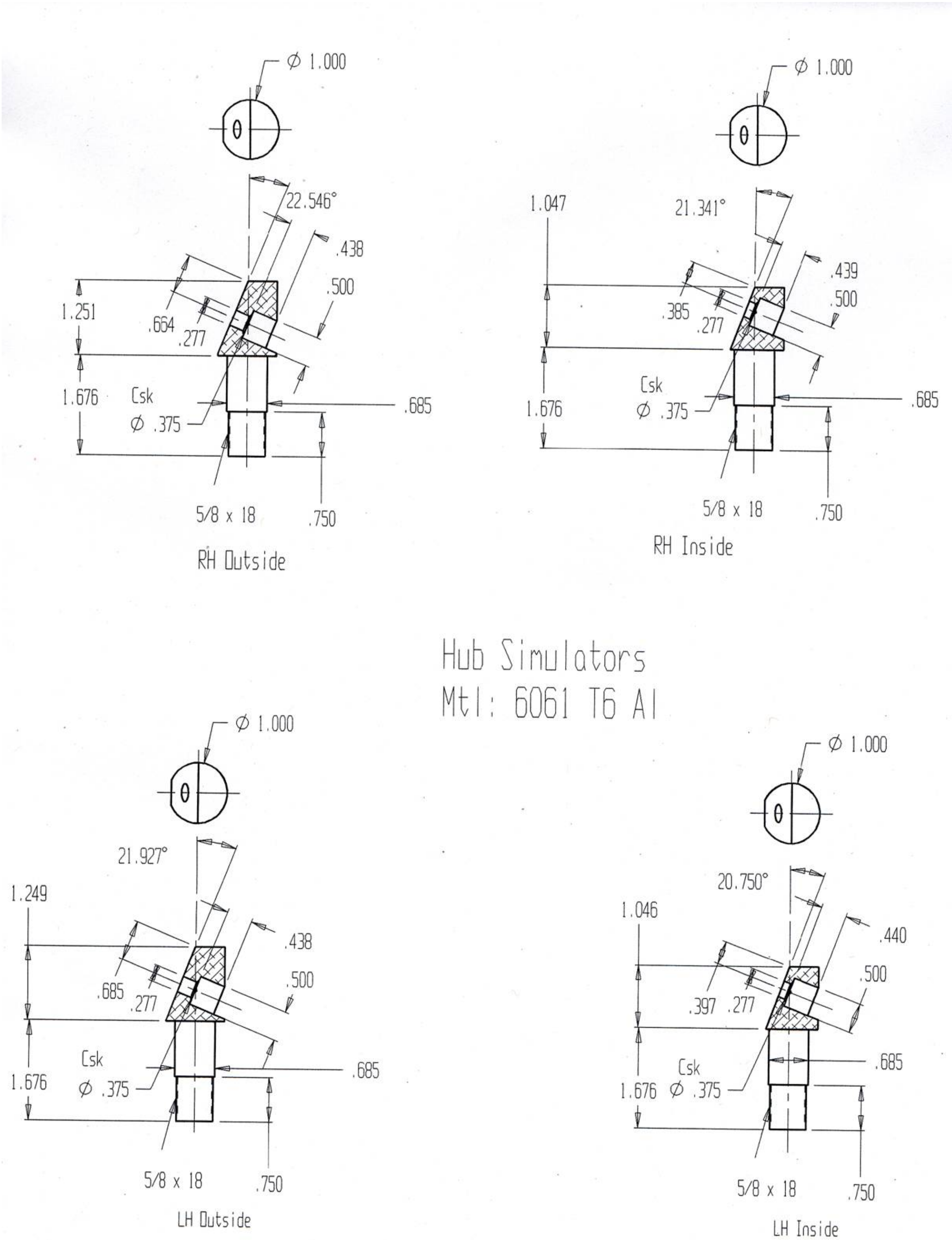


Figure 5 *– Left Outside Load vs. Displacement*

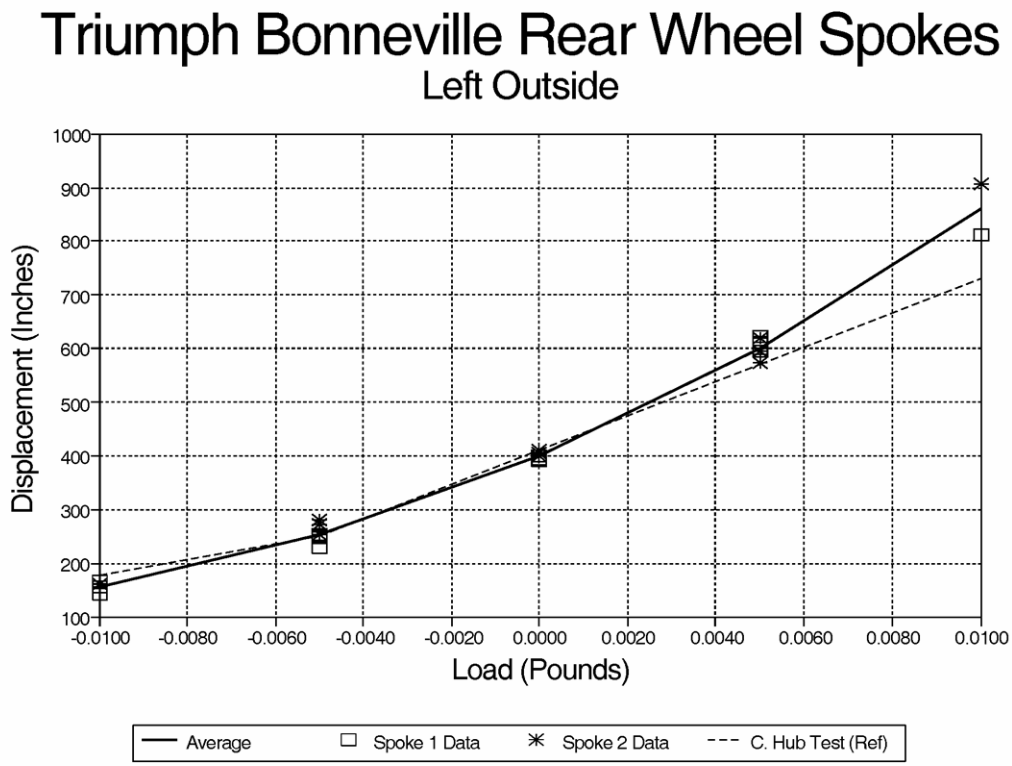


Figure 6 *– Left Inside Load vs. Displacement*

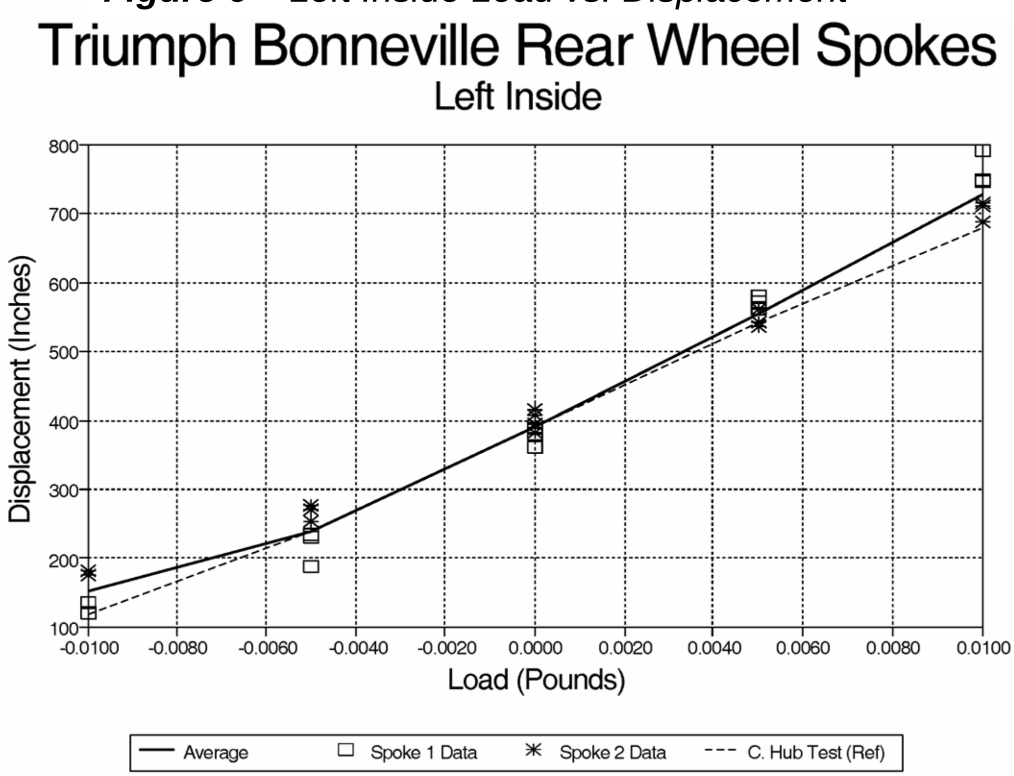


Figure 7 *– Right Outside Load vs. Displacement*

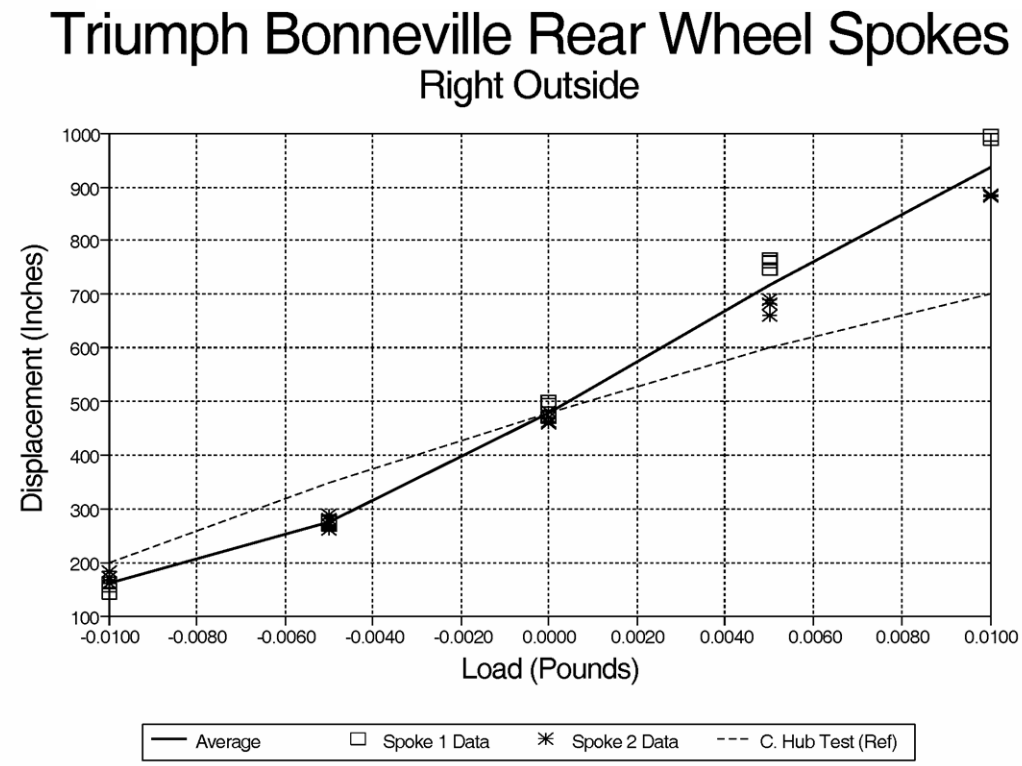
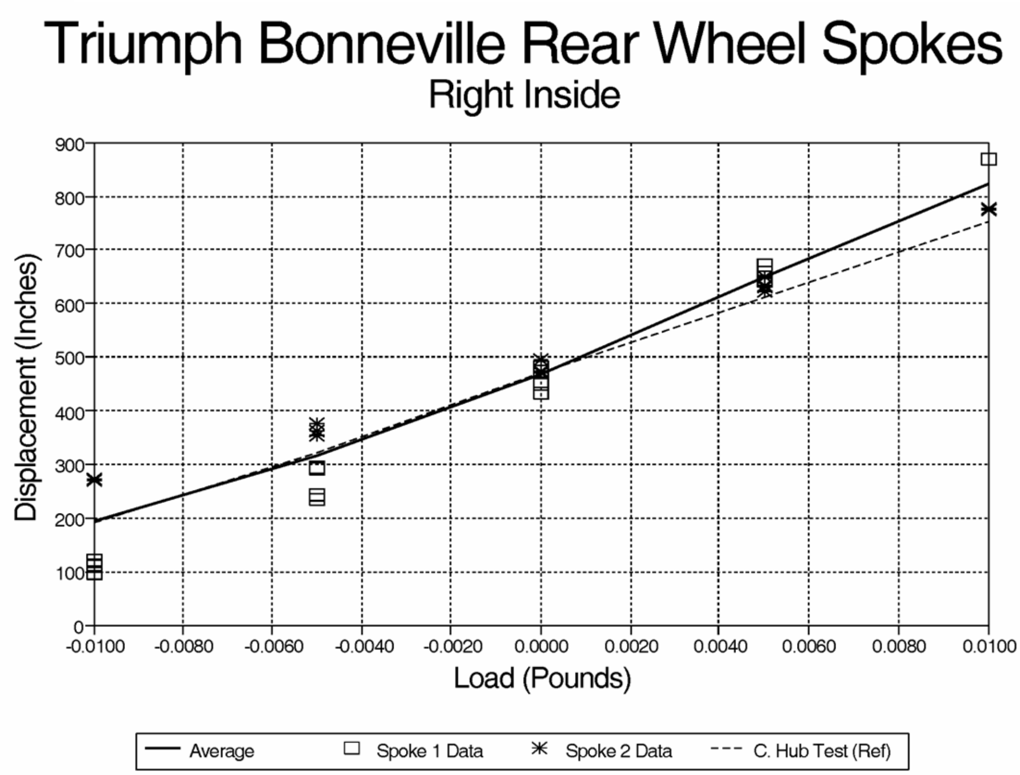


Figure 8 *– Right Inside Load vs. Displacement*



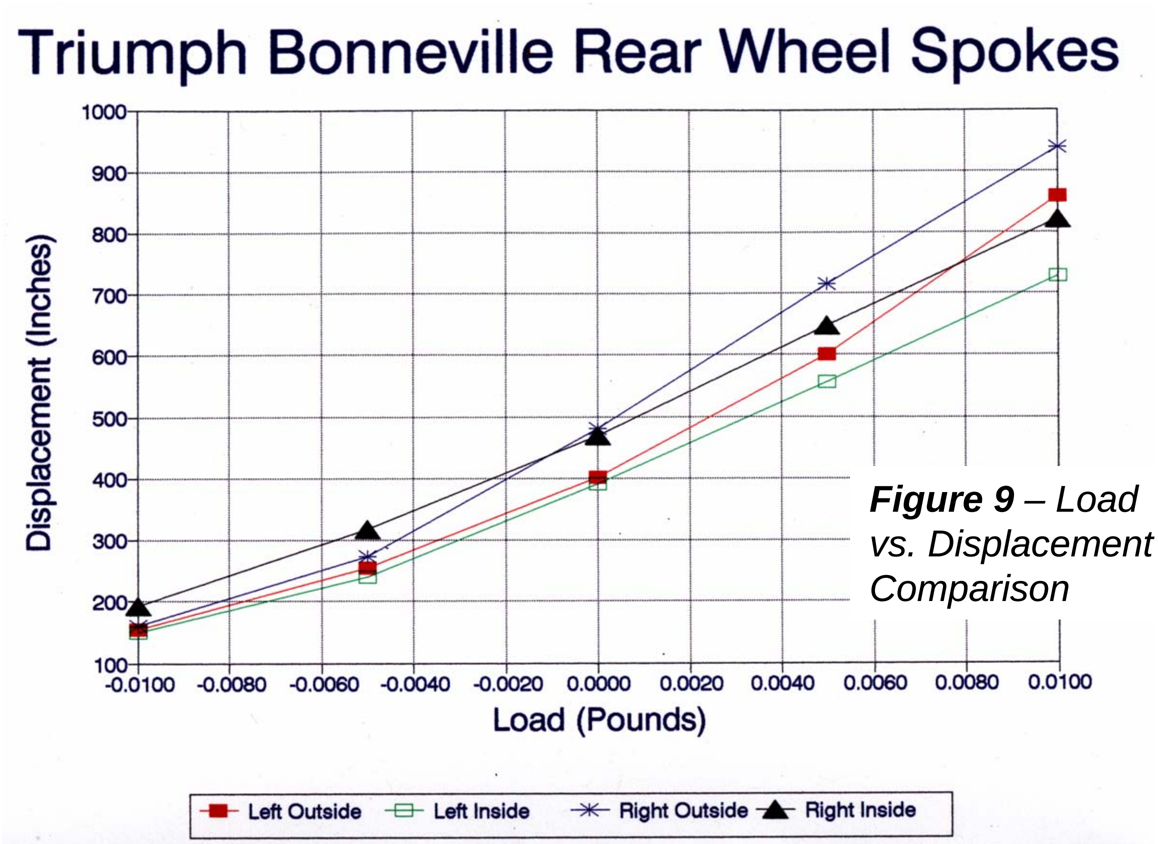


***Figure 9** – Load vs. Displacement Comparison*

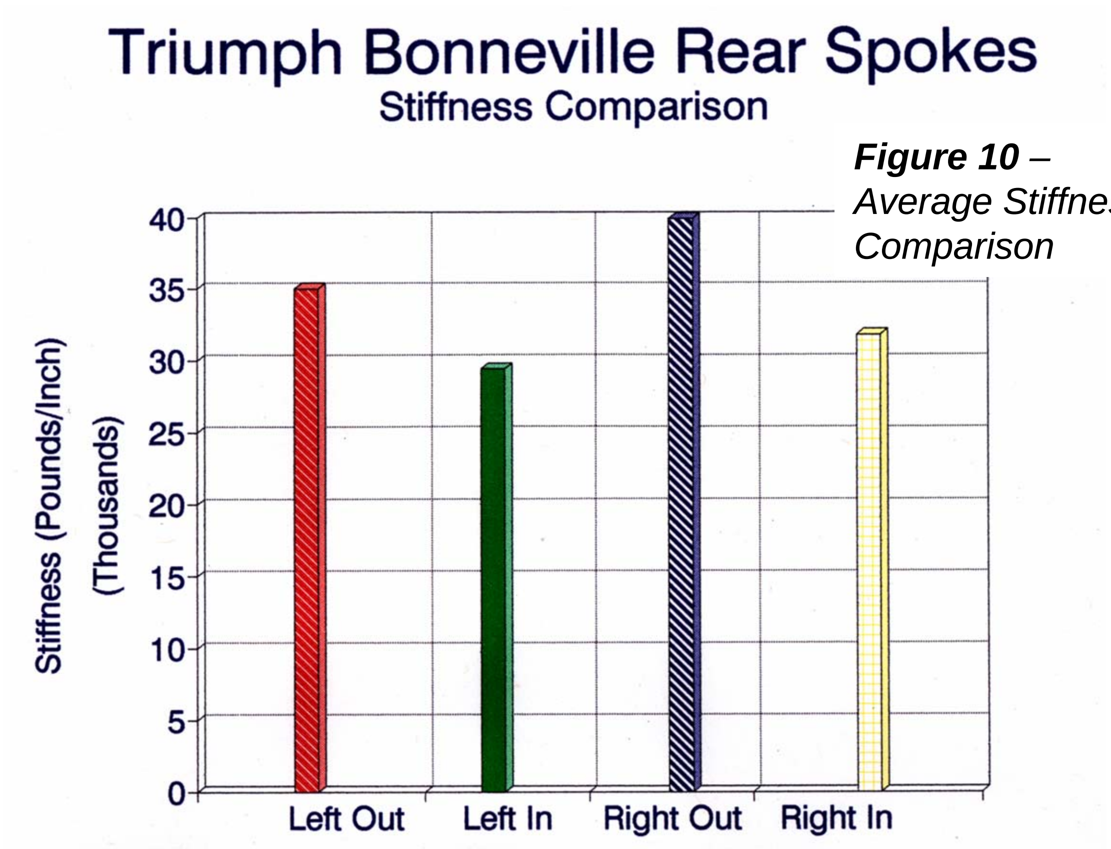


***Figure 10** – Average Stiffness Comparison*

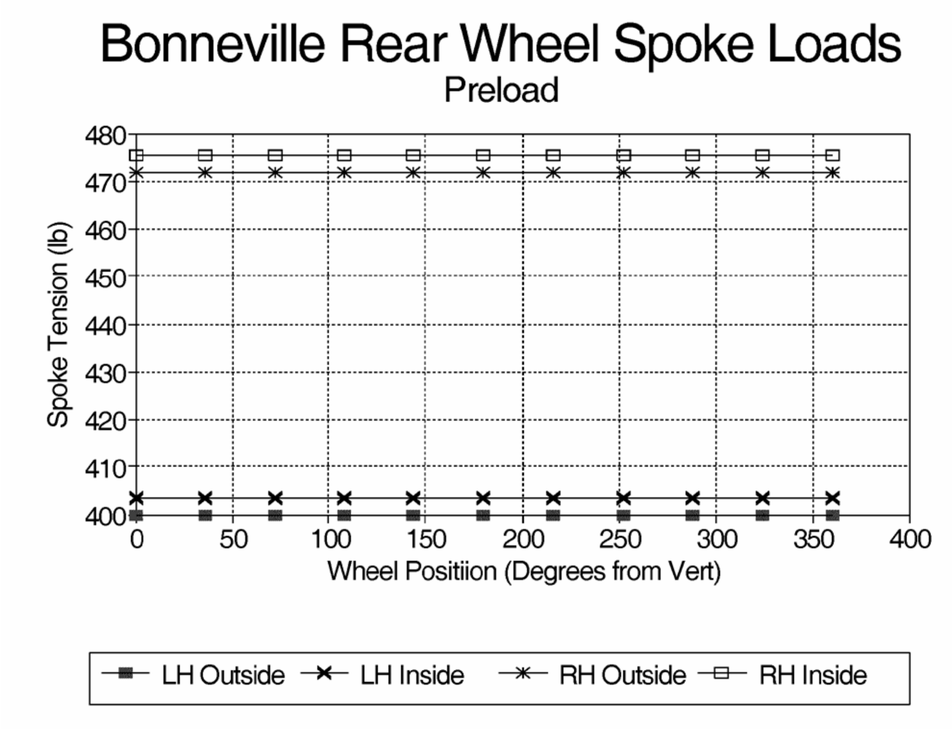


***Figure 11** – Rear Wheel Spoke Preload*

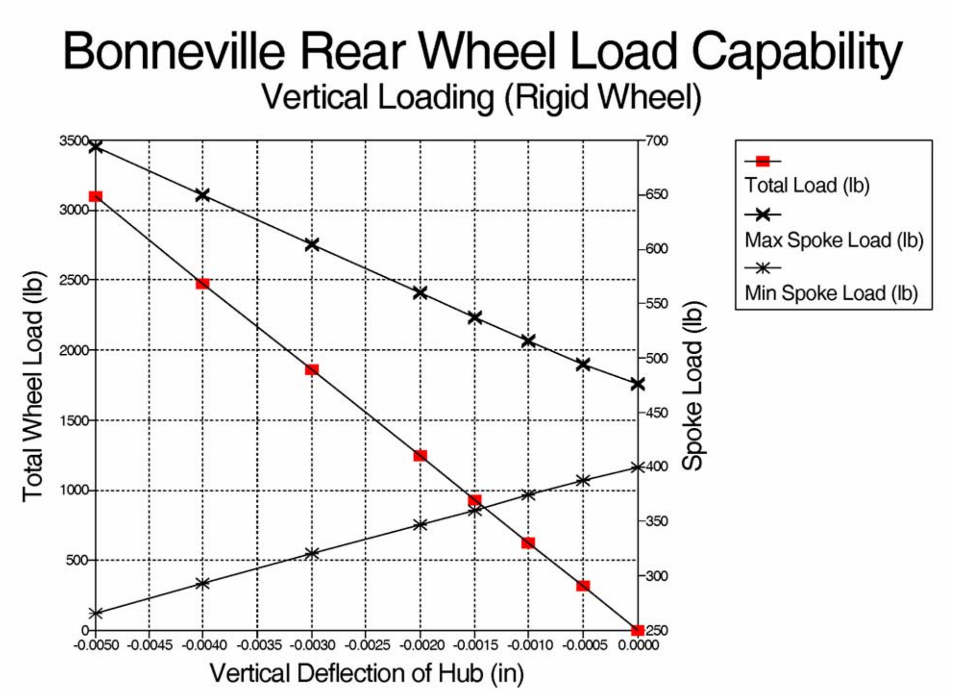


***Figure 12** – Rear Wheel Vertical Load Capability (Rigid Wheel)*

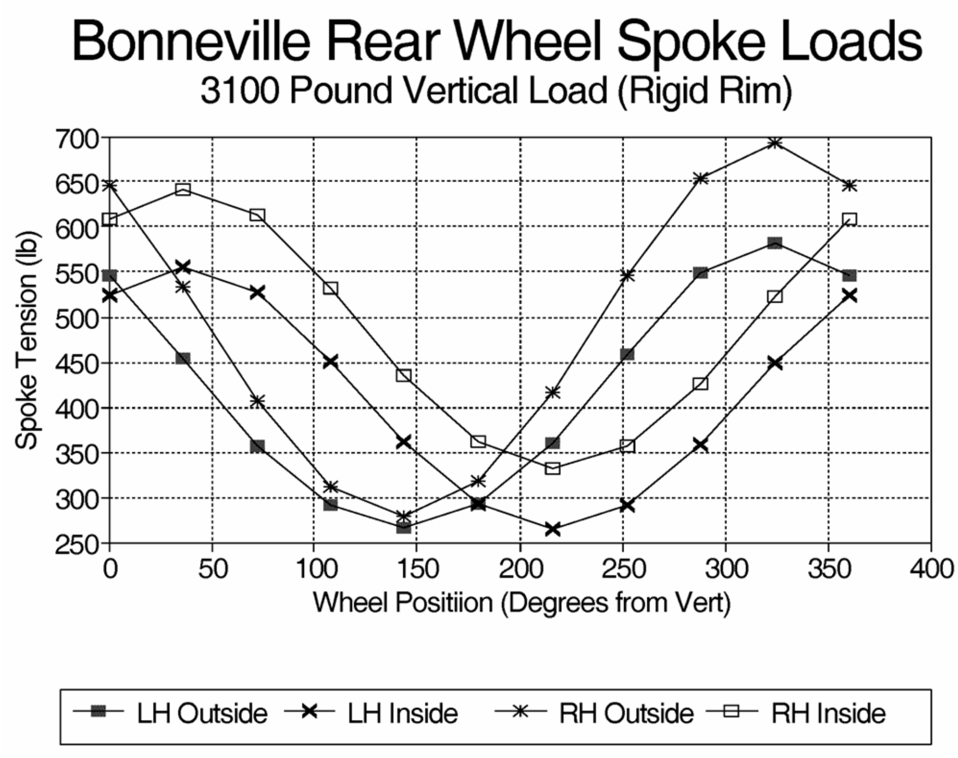


Figure 13 *– Rear Wheel Spoke Loads – 3100 Pounds on a Rigid Rim*

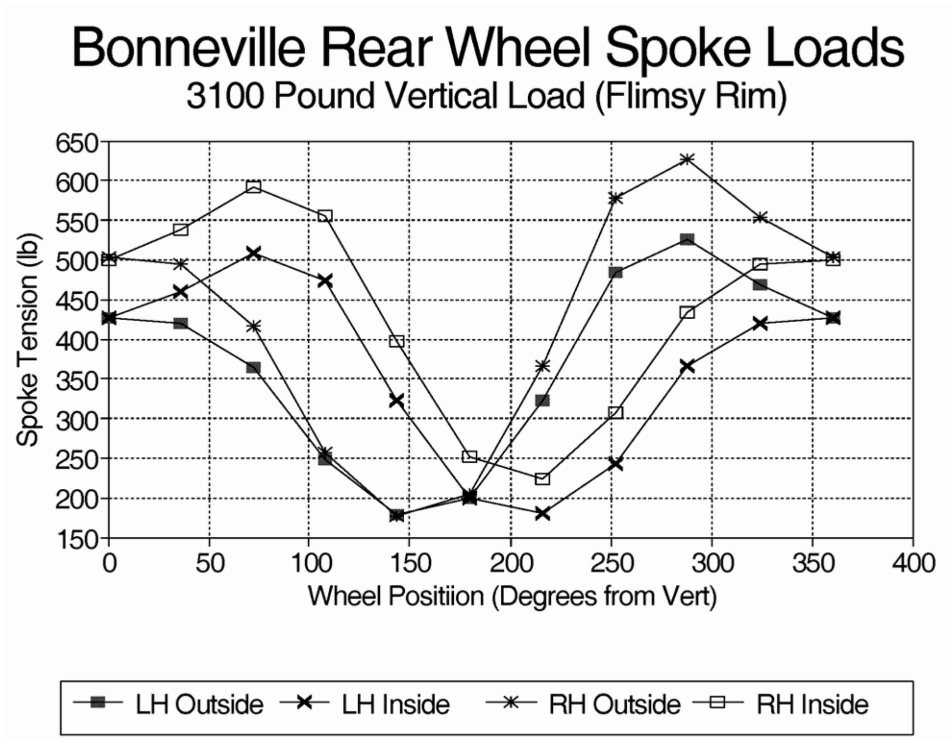


Figure 14 *– Rear Wheel Spoke Loads – 3100 Pounds on a "Flimsy" Rim*

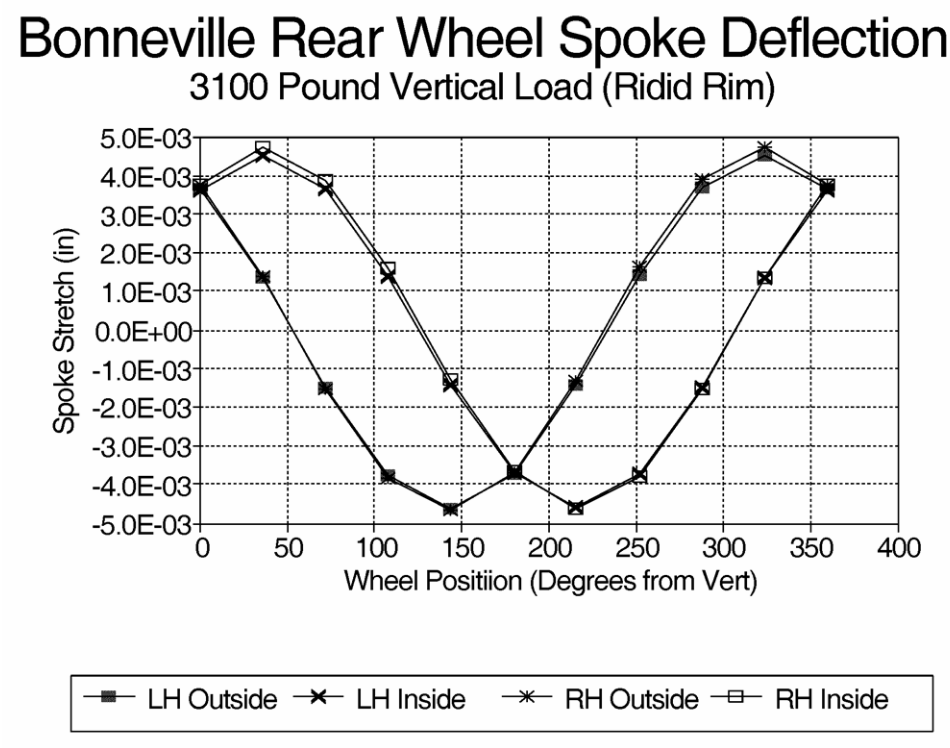


Figure 15 *– Rear Wheel Spoke Deflection – 3100 Pounds on a Rigid Rim*

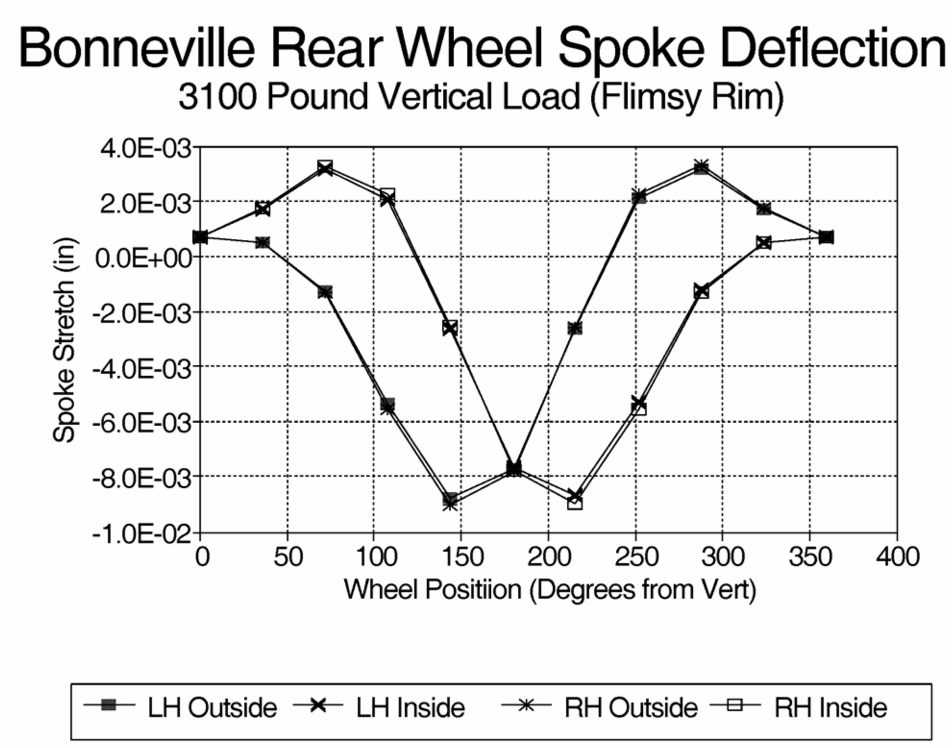


Figure 16 *– Rear Wheel Spoke Deflection – 3100 Pounds on a "Flimsy" Rim*

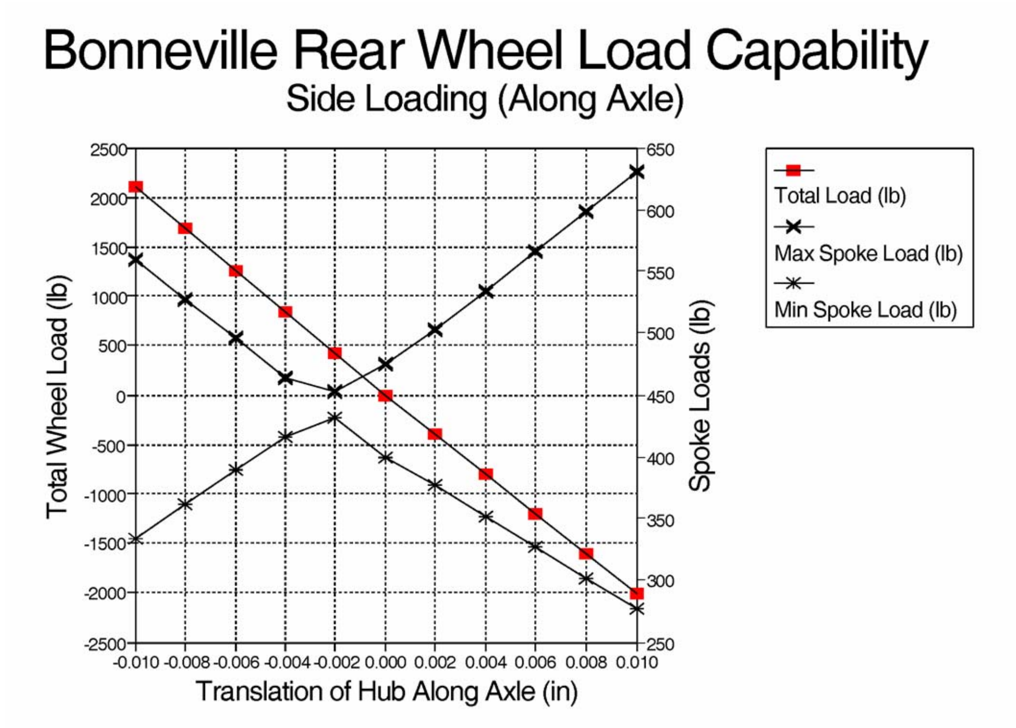


Figure 17 *– Rear Wheel Side Load Capability*

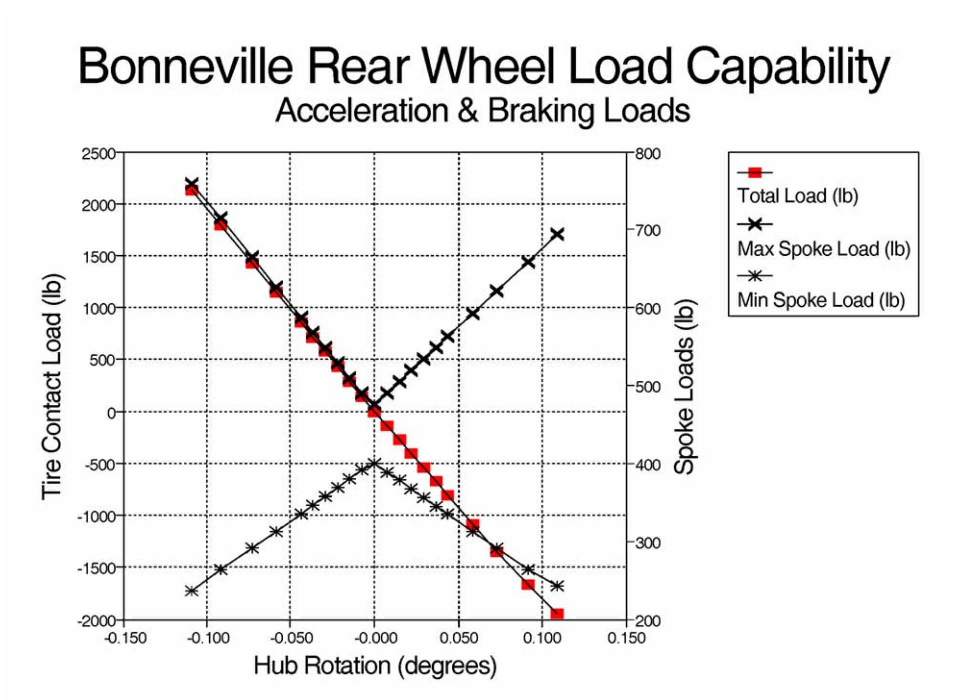


Figure 18 *– Rear Wheel Rotational Load Capability*

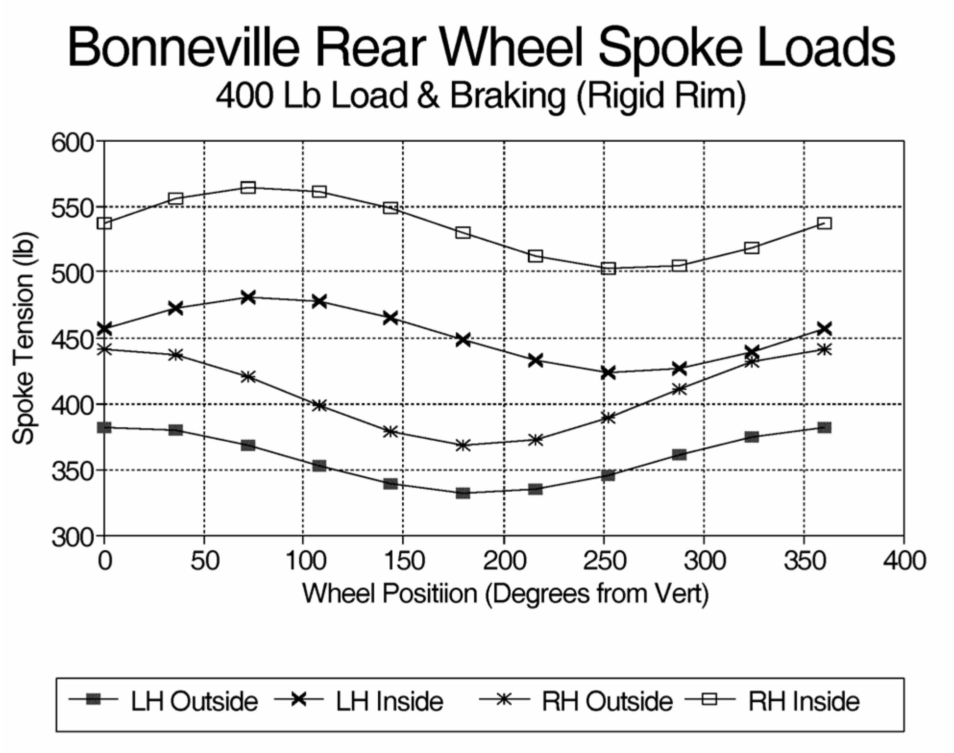


Figure 19 *– Rear Wheel Spoke Loads – Typical Braking (Rigid Rim)*

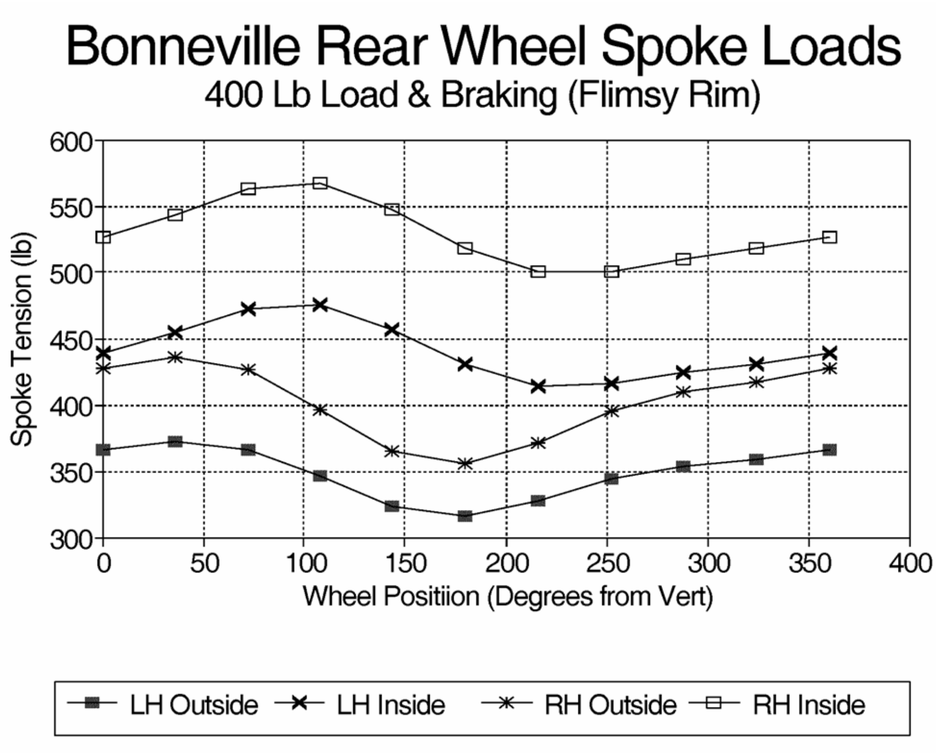


Figure 20 *– Rear Wheel Spoke Loads – Typical Braking (Flimsy Rim)*

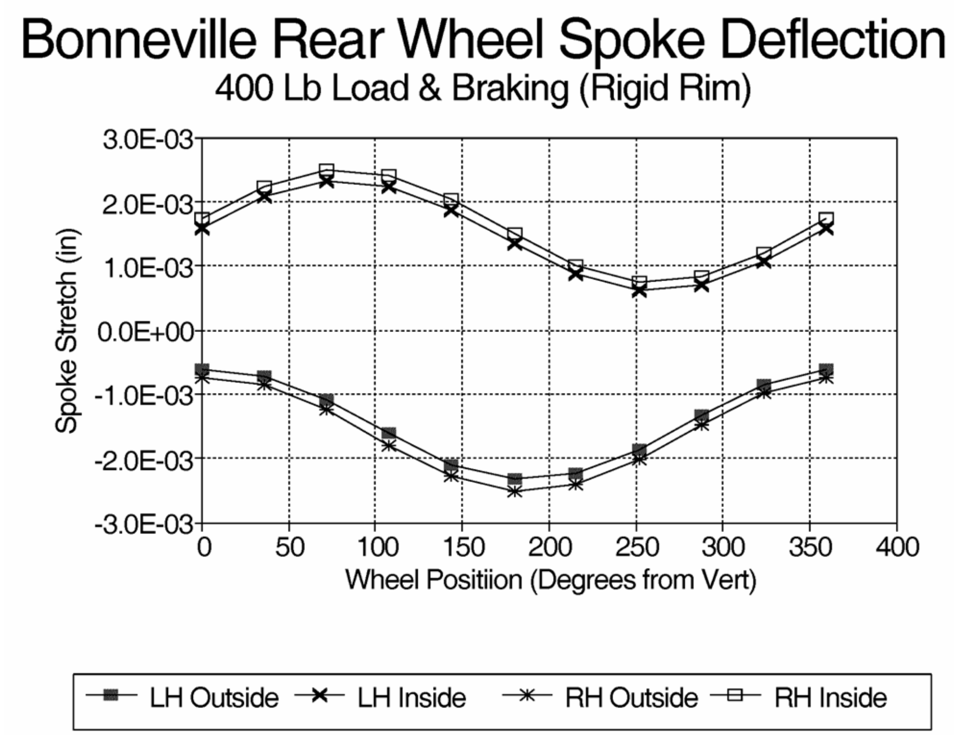


Figure 21 *– Rear Wheel Spoke Deflection – Typical Braking (Rigid Rim)*

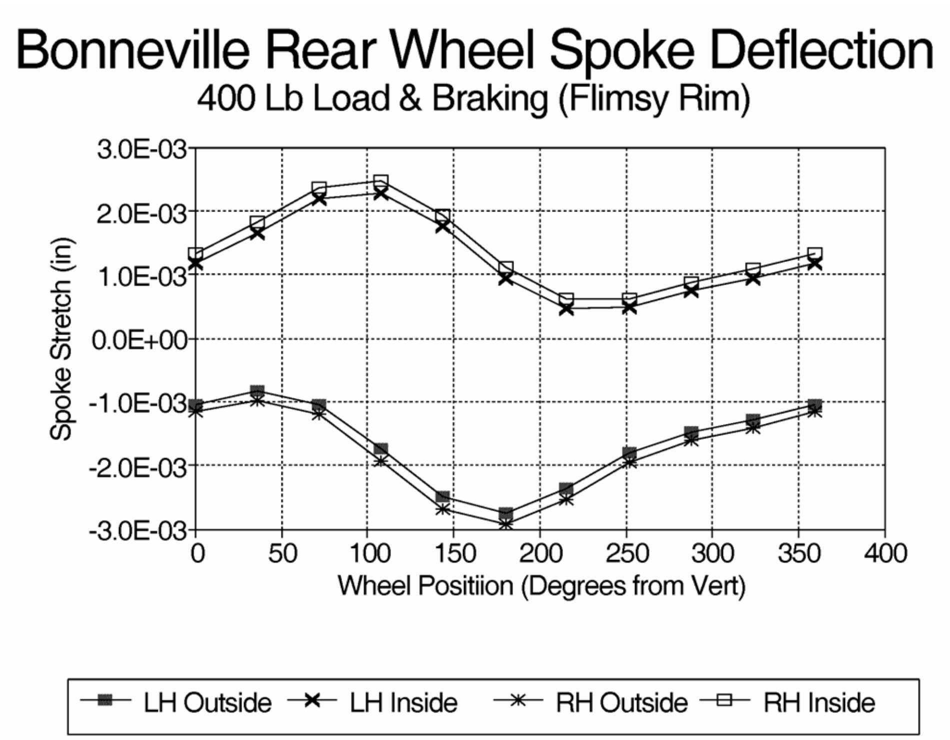


Figure 22 *– Rear Wheel Spoke Deflection – Typical Braking (Flimsy Rim)*

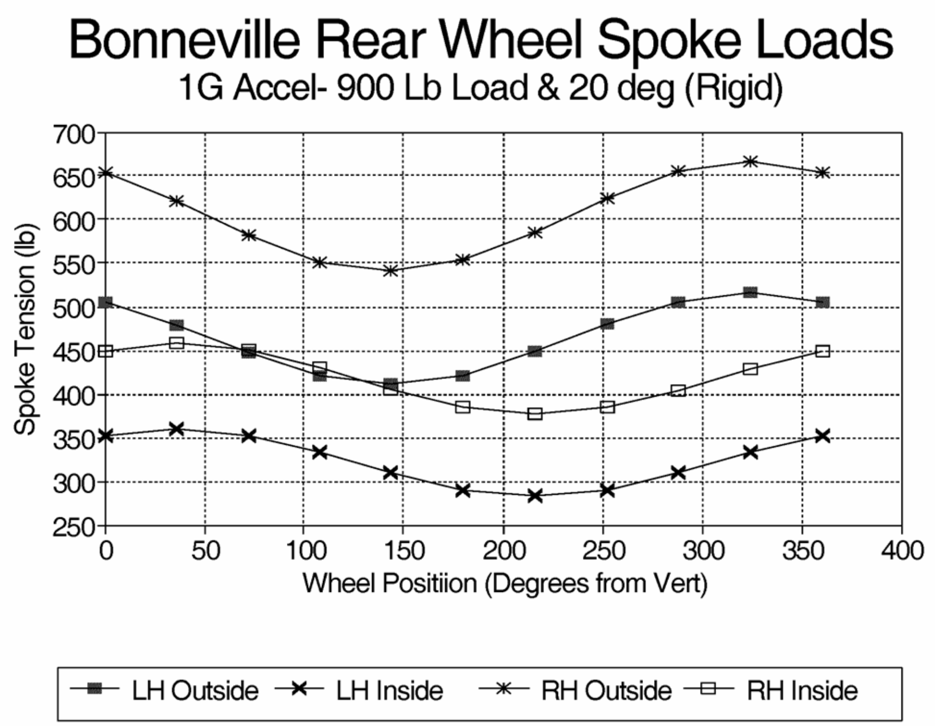


Figure 23 *– Rear Wheel Spoke Loads – High Loads (Rigid Rim)*

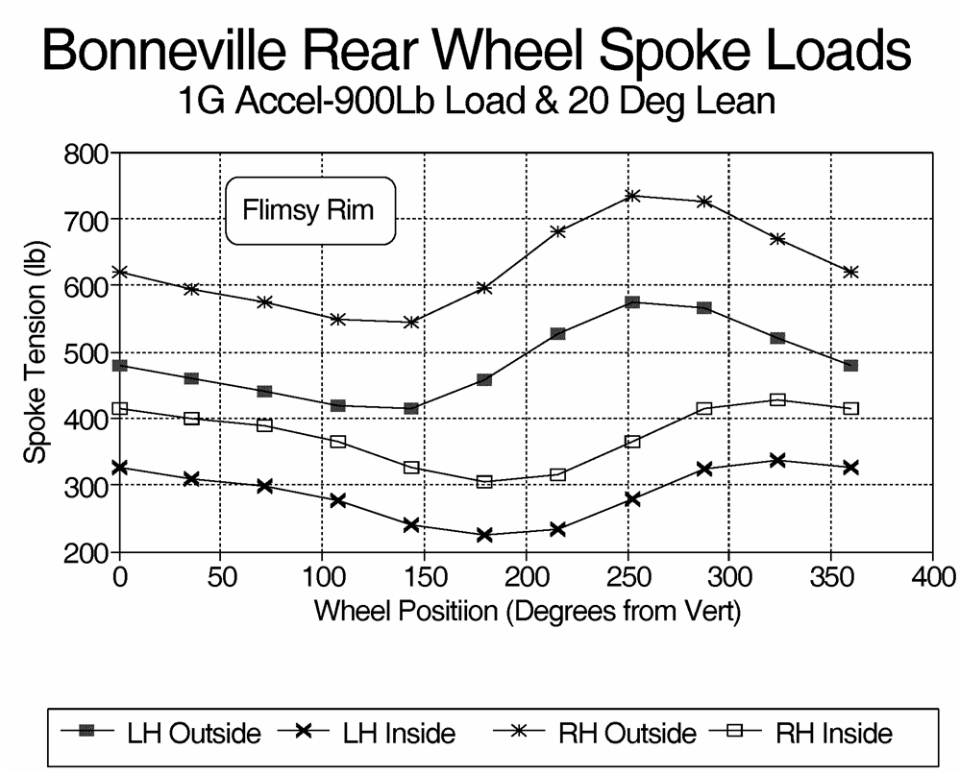


Figure 24*– Rear Wheel Spoke Loads – High Loads (Flimsy Rim)*

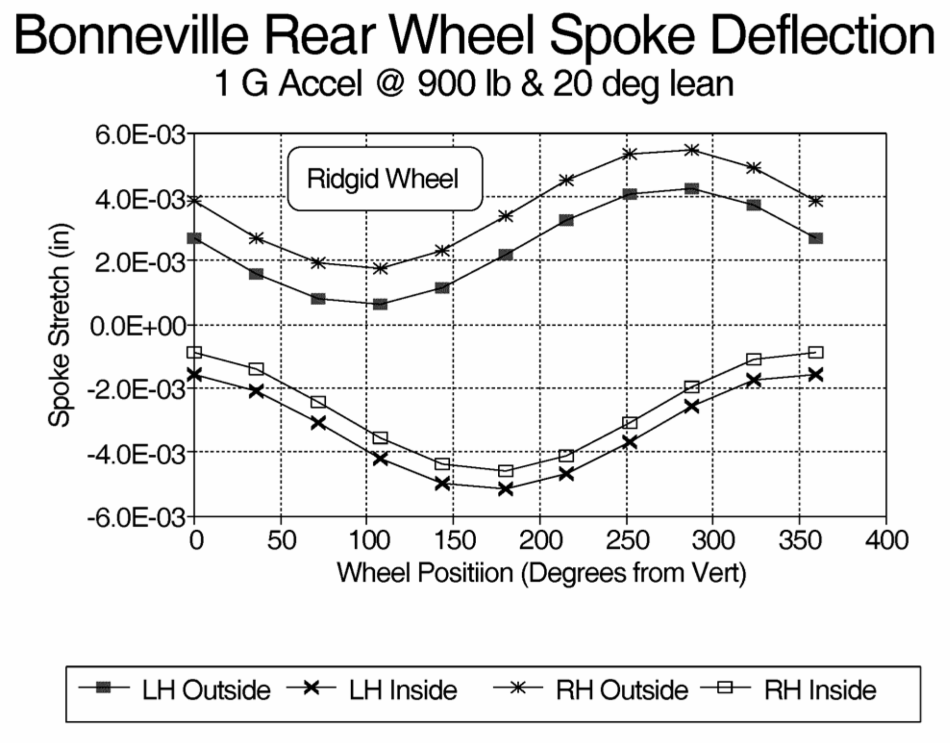


Figure 25 *– Rear Wheel Spoke Deflection – High Loads (Rigid Rim)*

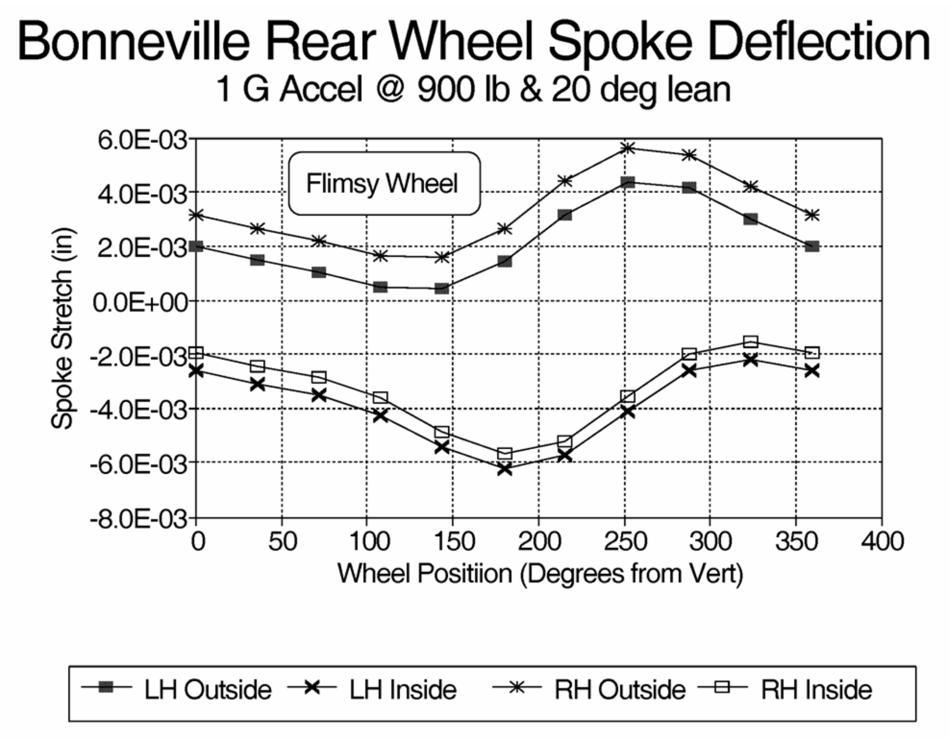


Figure 26 *– Rear Wheel Spoke Deflection – High Loads (Flimsy Rim)*