# FINITE ELEMENT MODELING OF
# TRACTOR TIRE DEFORMATION

by

DALE LEE HEISE

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Stanley Clark

Major Professor

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# INTRODUCTION

With much of standard tractor's power lost between the wheel and the ground and the advent of Caterpillar's rubber-track type tractor, it is time to take a closer look at the design of the traditional tractor tire. A tire is a composite structure composed of a compliant, non-linear, incompressible rubber matrix with layers of high tensile strength rayon or polyester cords formed into a torid like shell. This prestressed nonhomogeneous structure then undergoes cyclic loading causing large nodal rotations and large deformations with significant interlaminar shear strains. Because of the complexity of a tire, in the past the design and construction was almost an art rather than a science.

Traction research with tractor tires has shown which attributes of different tires are the most beneficial. This type of testing is quite costly with these large tires because of higher construction and testing costs. This is where the finite element method (FEM) of structural analysis can be quite useful to predict the internal stress and strain throughout the tire. Also the FEM can predict the inflated shape and the deflected shape of a tire under load. Exact predictions of these and other items may not be possible or are at least very difficult to produce. However, trends can be predicted with some effort which would probably reduce the actual tire testing necessary in the intermediate stages of the tire design process. Before new tires can be designed with the FEM, though, accurate analysis of a current tire is necessary.

This research focuses on using the ANSYS Engineering Analysis System finite element program from Swanson Analysis Systems Inc. to model an 18.4R38 Dyna Torque Radial 1* made by Goodyear Tire and Rubber Company. The goal is to predict the deformation of the tire due to air inflation pressures from zero to eighteen pounds per square inch. This would be the first step toward building the 3-D model that could predict deformation due to vertical and horizontal loads of an actual tire.

## REVIEW OF LITERATURE

### TIRE IMPROVEMENTS

There has been a great deal of traction and tractive efficiency studies since the rubber tractor tires first came on the market. Burt et al. (1982) found that research results throughout the world show twenty to fifty-five percent of the energy delivered to tractor drive wheels is wasted in the traction elements. This finding shows that there is still potential for increasing the efficiency of tractors by designing a better tire. The last major improvement in tires was the introduction of the radial tire. The radial tire showed marked improvement in tractive efficiency over the conventional tire in studies by Turnage (1976) and Hausz (1980).

There are several other factors that can be modified to increase tractive efficiency. Taylor et al. (1967) showed that increased diameter with the same cross section size, normal load, and deflection gave increased pull and coefficient of traction. By increasing the tire diameter the inflation pressure can be decreased and deflection kept constant increasing pull even more because of the longer contact area. This shows a longer tire print is desirable.

Dwyer and Heigho (1984) found the tractive efficiency of wider tires is usually less than that of conventional tires at the same vertical load. They also found that increasing the spacing between dual wheels by up to one tire width produces a small but significant improvement in tractive efficiency. Their findings showed that a narrower footprint with wider spacing between tires results in improved performance, if duals are used.

Taylor (1973) studied the effects of the lugs. He varied lug spacing with a pitch from 5.85 to 9.36 inches; he did not give an optimum pitch for the various soil conditions tested. Also varying lug angle from forty to eighty degrees did not effect tractive efficiency significantly at travel reductions from ten to thirty percent. Dwyer (1975) found small differences in tread pattern of modern agricultural tractor tires are unlikely to make a significant difference in tractive efficiency. Also lug heights between 0.8 and 2 inches show optimal performance for firm and soft soils respectively.

Turnage (1976) showed without exception, that a flexible tire is superior to a stiff tire in developing larger values of pull coefficient and tractive efficiency over the very broad range of clay and sand strength values considered. Abeels (1982) after doing much research and testing found that a Camel Shoe (CS) sidewall design transfers the forces to the ground much more efficiently to increase tractive efficiency. This CS cross section gave a much more uniform weight distribution on the soil with less sinkage. The CS design improved ride comfort by lessening the effects of the soil surface on the tractor.

Compaction due to slip is maximum between fifteen and twenty-five percent slip with constant load as shown by Raghavan et al. (1977). Stafford and Mattos (1981) found an increase in speed on loose tilled soil decreased compaction by as much as fifty percent. These two findings show that decreasing the percent slip and increasing the speed will decrease compaction and require a more flexible tire to absorb the surface irregularities at the higher speeds.

The trends these studies show is that the optimum tire will have a more flexible sidewall with lower inflation pressure allowing greater deflection. This increased deflection produces the longer footprint and more uniform pressure distribution. Also the softer tire will allow for increased ride comfort at higher speeds. All of these design changes will be difficult to implement at one time but any of these modifications would help to increase the tractive efficiency of today's tires.

## TIRE MATERIAL PROPERTIES

Before a tire can be mathematically modeled with the FEM the elastic properties of the materials that make up the tire must be known. Determining these material properties is very important because they dictate the accuracy of the FEM results. The most abundant material is rubber. Rubber is a virtually incompressible, nonlinear material, with a low Young's modulus. However in the low strain regions that occur in a tire, it is generally treated as a linear, homogeneous, isotropic material, with two independent elastic constants as stated by Walter (1981). These are Young's modulus, E, and Poisson's ratio, $\nu$. Young's modulus for the different rubber compounds found in a tractor tire range from 500 to 1000 psi. Poisson's ratio is .49 for most rubber.

The cords provide the strength for the tire. They are very strong in tension and are considered linear for the strain rates occurring on a tire. The hundreds of continuous, oriented, polymeric filaments that constitute the typical cord used in tires should be considered as transversely isotropic with five independent elastic constants: an extensional Young's modulus, an extensional Poisson's ratio, a transverse Young's modulus, a transverse Poisson's ratio, and a torsional shear modulus, Walter (1981). However, only an extensional Young's Modulus and Poisson's ratio are needed to determine the ply properties. The Young's moduli for the tractor tire under consideration are $8 \times 10^5$ psi with a Poisson's ratio of .65, Goodyear (1987).

After determining the individual rubber and cord properties the ply properties then need to be determined. A unidirectional ply composed of equally spaced cords embedded in a rubber matrix is shown in Figure 1. The FEM requries a Young's modulus, E, in each direction and three Poisson's ratios.

The field of micromechanics can be used to derive equations for predicting the lamina elastic constants. One of the most popular sets of relations is the Halpin-Tsai equations. From Walter and

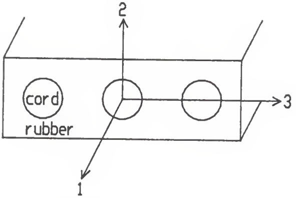


Figure 1. Unidirectional specially orthotropic ply.

Patel (1979) for a calendered ply of cord and rubber these equations are:

$$E_1 = E_c v_c + E_r (1-v_c)$$

$$E_2 = E_r (1+2v_c)/(1-v_c)$$

$$\nu_{12} = \nu_c v_c + \nu_r (1-v_c)$$

$$\nu_{21} = \nu_{12} E_2/E_1$$

where

$E_c$, $E_r$ = Young's moduli of cord and rubber, respectively,

$\nu_c$, $\nu_r$ = Poisson's ratios of cord and rubber, respectively, and

$v_c$ = Volume fraction of cord in calendered ply.

The relation for $E_1$ and $\nu_{12}$ are known as the law of mixtures and $\nu_{21}$ follows the symmetrical nature of the stress-strain law while $E_2$ is semi-empirical in nature.

Another set of common relations are the Gough-Tangorra equations from Walter and Patel (1979):

$$E_1 = E_c v_c + E_r(1-v_c),$$

$$E_2 = \{4E_r(1-v_c)[E_c v_c + E_r(1-v_c)]\}/[3E_c v_c + 4E_r(1-v_c)],$$

$$\nu_{12} = .5$$

$$\nu_{21} = \nu_{12}\, E_2/E_1.$$

For this theory, the rubber matrix is assumed to be incompressible and the cord is treated as a unidirectional load-carrying member with no transverse properties. These equations give very similar results to the Halpin-Tsai equations.

For the generally orthotropic layers as shown in Figure 2, occurring in the tread belts of the radial tractor tires under consideration, the lamina properties become more complex.

Walter and Patel (1979) present the angled ply properties where the Gough-Tangorra relations were used to represent the lamina properties as follows:

$$E_\phi = E_c v_c \cos^4 + 4G_r(1-v_c)$$

$$- [E_c v_c \sin^2\theta\cos^2\theta + 2Gr(1-v_c)]^2/[E_c v_c \sin^4\theta + 4G_r(1-v_c)] ,$$

$$\nu_{\phi\xi} = [E_c v_c \sin^2\theta \cos^2\theta + 2Gr(1-v_c)]/[E_c v_c \sin^4\theta + 4G_r(1-v_c)]$$

$$E_\xi(\theta) = E_\phi(\pi/2-\theta)$$

where

$G_r$ = Shear modulus of rubber.

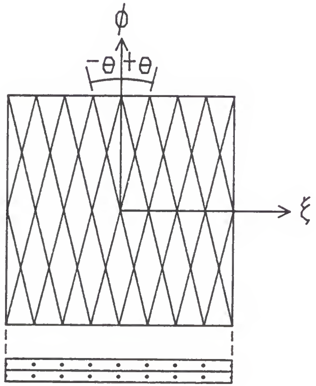


Figure 2. Pair of angled generally orthotropic plies ($\pm\theta$).

A phone conversation with Goodyear Tire and Rubber Company provided the approximate values for longitudinal and transverse Young's moduli for the carcass plies and the belt plies. These values proved to be a factor of 2 greater than the values calculated from the previous equations. A discrepancy between the empirical, theoretical, and actual laminar properties is not surprising. These values are very difficult to derive because of the complications caused by the difference in magnitudes of $10^3$ in the Young's modulus between the cord and rubber, the incompresssibility of rubber, and nonlinearity of both materials. Test results do not accurately account for the prestressed conditions that are present in the actual tire after construction. Finally, the models used generally make several simplifying assumptions that may need to be compensated for to predict accurate results. Further research is necessary in this area to increase the correlation between these methods of determining elastic constants.

## THE FINITE ELEMENT METHOD

Upon determining the design changes needed to improve the efficiency of a tire and predicting the elastic constants of the materials in the tire, a tire model can be developed. The FEM will be used to model the tire but a brief definition or explanation of the FEM is in order. Huebner and Thornton (1982) say the finite element method is a numerical analysis technique for obtaining approximate solutions to a wide variety of engineering problems.

The method is most useful in approximating solutions to problems where the boundary conditions and governing equations do not allow a simple analytical solution.

The actual FEM requires several steps to reach a solution. The first step is to divide the continuum into elements. These small sections break down the complexity of the region into many simple regions. The second step is to assign nodes, generally at the corners of the elements, and to choose an interpolation function to represent the variation of the field variable over the element. The third step requires the determination of the matrix equations expressing the properties of the individual elements. The assembly of the element matricies into one system matrix is the fourth step. These element matricies are similar because the field variables are the same for adjacent elements at the shared nodes. Modifications of the system equations are also necessary to account for the boundary conditions of the problem. Finally, the sixth and last step is to solve the set of simultaneous system equations to obtain the unknown nodal values of the field variable. If the equations are nonlinear, the solution is much more difficult. Many choose to linearize the problem to avoid this difficulty. There is a great deal of research going on in the field of FEM since it is a relatively new technique. With larger, faster, digital computers the method can become more powerful and accurate in the future.

## FINITE ELEMENT METHOD MODELING CAPABILITIES

Modeling a tire is a problem suited for the FEM because of the complicated shape and non-homogeneous composition. As DeEskinazi and Ridha (1982) point out, the advantage of the FEM is most apparent in its application to larger size off-road tires. Very few alternate tools are available for analysis of such tires and experiments on these tires are both difficult and costly.

The FEM can predict: the inflated shape, deflected shape due to an applied external load, the stress and strain at tread belt and bead area, deformation of cords, and tension distribution in the plies, Yoshimura (1985). The accuracy of these results will vary depending on the complexity of the model and the number and type of invalid assumptions. But, as Hunkler (1982) said, the program can be a very useful tool in predicting the effects of structural design variations. Some design variations that are possible to test with a FEM model are: carcass shape, belt construction layout and angle, bead construction and reinforcement, and the elastic constants of rubber and cord, Yoshimura (1985). Optimum values of these parameters can produce a tire with lower internal strain and lower interlaminar shear resulting in decreased heat generation and fatigue in the tire. This would increase the life of a tire. The tire's contact area and loading conditions from the rim could also be altered.

## 2-D OR 3-D ANALYSIS

The two popular types of FEM models used in tire design today are the 2-Dimensional axisymmetric model and the 3-Dimensional model. The axisymmetric model's advantage is the relatively small amount of CPU time required for a solution. It can predict the axisymmetric deflection and the internal stress and strain. The disadvantage of the axisymmetric model is its inability to predict the deflection and contact area when the tire has an external load.

The 3-D model can predict the deflection and contact area along with the internal stress and strain with external loads and torque. However, the disadvantage as Yoshimura (1985) points out is, if we make a 3-D model large enough to simulate the tire deformation satisfactorily, the computer time on a particular computer will be more than ten CPU hours whereas a 2-D model would be solved in a couple of minutes. To further show this point studies by Cembrola (1985) show if the cord and rubber in each ply were modeled as separate elements, the size of the model for a 3-D analysis would be too large for the present generation of computers. As a result, the 3-D model is more suitable for solving a specific problem rather than a routine tire design.

## OBJECTIVES

1) Determine the composite elastic constants of the tractor tire materials.

2) Develop ANSYS FEM model to predict deformation of the radial tractor tire due to inflation pressure.

3) Measure the deformation of an actual radial tractor tire to verify the ANSYS FEM model.

# METHODOLOGY

## Determination of Elastic Constants

The first step in determining the composite elastic constants is to obtain the individual material elastic constants. These values were obtained from a labeled drawing from Goodyear Tire and Rubber Company for the 18.4R38 Dyna Torque Radial 1* tractor tire. The radial carcass plies are made of polyester cords with an end count of 27 ends per inch at a tire diameter of 40.5 inches. The plies are 0.039 inches thick and the ply cords are 0.0198 inches in diameter. The circumferential tread belts are made of rayon cords with an end count of 18 ends per inch. The rayon cords in the four belts are at an angle of 19 degrees to the circumference layed up left-right-left-right. The thickness of these individual belts is 0.058 inches with a cord diameter of 0.0266 inches. There is a hard rubber apex along the steel cord at the bead of the tire. The sidewall is made of a soft rubber with a harder rubber used for the tread. The elastic constants for these materials are in Table 1.

Table 1

Material Elastic Constants

| | Young's Modulus (psi) | Poisson's Ratio |
|---|---|---|
| Ply Cord | 820,000 | 0.65 |
| Belt Cord | 750,000 | 0.65 |
| Ply Rubber | 1,000 | 0.49 |
| Belt Rubber | 1,000 | 0.49 |
| Tread Rubber | 700 | 0.49 |
| Sidewall Rubber | 500 | 0.49 |
| Apex Rubber | 1,000 | 0.49 |
| Steel Cord | 30,000,000 | 0.30 |

Using these values in the Halpin-Tsai equations for the ply belts results in elastic constants of:

$E_1$ = 176,000 psi  $E_2$ = 1810 psi  $\nu_{12} = 0.5$  $\nu_{21} = 0.005$.

These values are calculated for the ply at a tire diameter of 40.5 inches. The Young's modulus varies from 350,000 psi to 225,000 psi as the ply goes from the rim to the middle of the tread because the end count decreases. This decrease in end count with an increase in the distance from the rim causes the cord volume fraction of the ply to decrease. The cord volume fraction is in the Halpin-Tsai equation thus causing the decrease in $E_1$.

The Gough-Tangorra relations for the belt lamina properties yield the following elastic constants:

$E_\phi$ = 40,500 psi  $E_\xi$ = 2,560

These values stay constant because of the insignificant change in diameter of the belts in the tread area of the tire.

The previously determined composite elastic constants however, are quite low as compared to the values obtained from consultation with Goodyear engineers. The ply elastic constants from Goodyear were $E_1 \approx 350,000$ psi and $E_2 \approx 3,240$ psi. These values are approximately twice as large as the values calculated from the equations. The belt Young's modulus in the circumferential direction was also approximately 350,000 psi. This is about nine times larger than the value calculated. Goodyear also mentioned using a Young's Modulus of 150 psi to model the lugs on the tire for an axisymmetric model. With this lower E value the lug is modeled as a solid layer of a very soft rubber. The values for the elastic constants obtained from Goodyear were used in the FEM model.

## ANSYS FEM Model Development

As stated earlier a 2-dimensional axisymmetric model was used with element type 42 in the ANSYS element library. The X-axis is in the radial direction with the Y-axis being the axis of symmetry which coincides with the wheel axle. The geometric layout for the nodes in the model was from a drawing supplied by Goodyear. Only one half of a cross section was modeled because of the symmetry of the tire. Since triangular elements are more accurate than rectangular elements, the tire plies and belts were modeled with triangles. Because of the smaller load carrying capacity of the rubber, as compared to the plies and belts, larger rectangular elements were used for the rubber where possible. This decreases the computer time required for a solution. An element plot of the FEM model without tread bars is shown in Figure 3 with a blown-up portion in Figure 4. Figures 5 and 6 show the model with tread bars. In modeling the plies each element was one ply thick. The belts were modeled the same. The different kinds of rubber and the steel were then modeled in triangles or rectangles to conveniently fit the geometry.

The Young's Modulus and Poisson's ratio for each material has to be entered into the computer. Even though a ply is of the same material it has different elastic constants, depending on the distance from the Y-axis. Therefore each ply is divided into five material types. Each of the other materials has one set of elastic constants.

There are several options used in ANSYS for this particular analysis. One option is the large deformation analysis. This option will continuously redefine the geometry of the structure revising the stiffness matrix. This option was used because of the possible large strain found in certain locations of the tire model. The stress stiffening option was also used to consider the weakness of the plies in bending without the stiffness caused by the inflation pressure. Another option tried, but found to be unnecessary, was load stepping. Load stepping applies the pressure in small increments and converges on a solution at each increment rather than converging on the solution only at the final

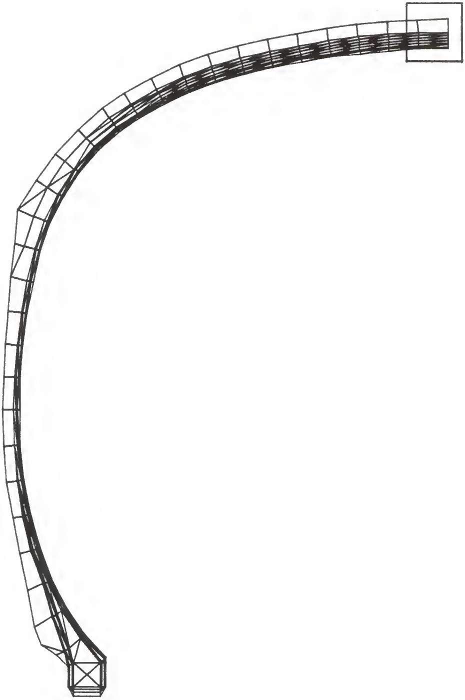

Figure 3. An element plot for the FEM model without tread.

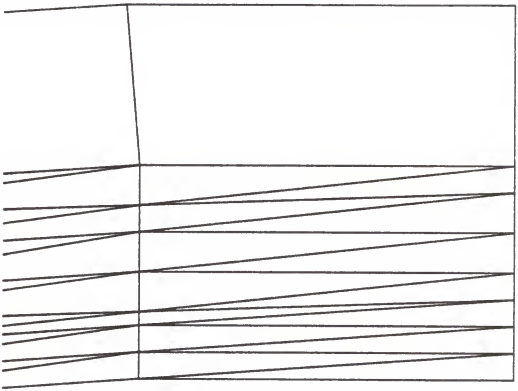

Figure 4. An enlarged section of Figure 3. This shows the detail in the ply and belt elements.

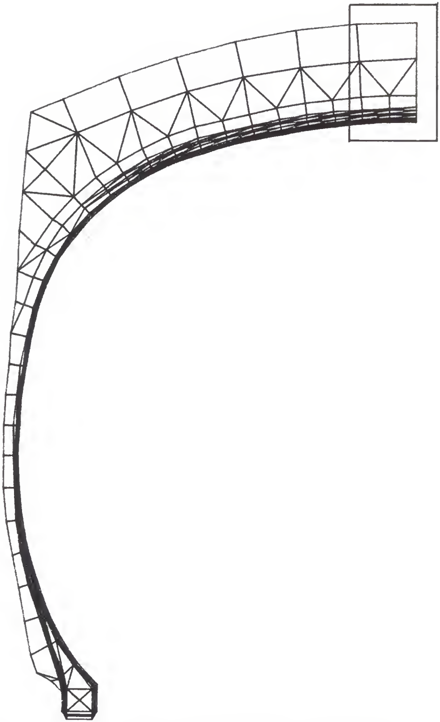

Figure 5. An element plot for the FEM model with tread.

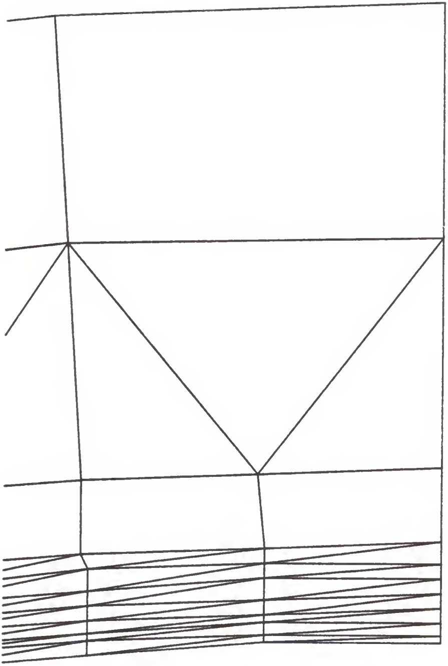

Figure 6. An enlarged section of Figure 5. This shows the detail of the ply and belt areas.

pressure applied in one step. This aforementioned convergence is a part of the iterative solution. It is necessary because of the large deformation and stress stiffening options used. The non-linearity of these options used necessitates the iterative solution. This iterative solution uses an extrapolation/interpolation procedure to increment the solution to the predefined criterion. The default criterion for displacements is a deflection of 0.001. A complete copy of the ANSYS input is in Appendix A.

ANSYS FEM Model Results

The ANSYS computer program converged after the fourth iteration for both the model with tread and the model without tread. The nodal displacements and the internal nodal stresses were very similar for both models. This implies that the tread bars have very little effect on the strength and deformation of a tire when suspended and inflated to 18 psi. A plot of the FEM predicted displacement is shown in Figure 7 with the nodes of maximum and minimum deflection labeled. This shows the outward deflection at the tread centerline and near the middle of the sidewall. There is an inward deflection at the edge of the tread. Increasing the inflation pressure tends to make the cross section more circular. The FEM predicted values at the points of maximum and minimum displacement are in Table 2.

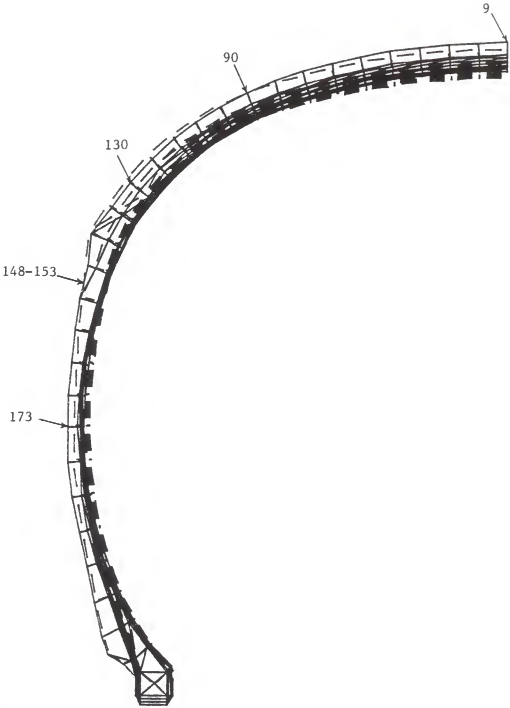


Figure 7. FEM predicted deformation of the tire model without tread at 18 psi. The initial shape is shown in the dashed lines. The nodes of maximum and minimum displacement are labeled.

Table 2

FEM Deflection Predictions

| Node Number | Model Type With Tread | Without Tread |
|---|---|---|
| 9 | .138 | .135 |
| 90 | -.002 | .003 |
| 130 | -.118 | -.111 |
| 148-153 | .007 | .003 |
| 173 | .136 | .130 |

(Displacements are in inches normal to the surface with "-" being inward deflection.)

The average internal stress in the plies was 1000 psi in tension in the direction parallel to the ply cords. Excluding the tire bead area the maximum nodal stress was 2600 psi in tension with the largest compressive stress being 200 psi. More detailed modeling at the bead area may be helpful in determining stress in that region. A stress of 13,000 psi in tension and 2,600 psi in compression were the maximum values of nodal stress of the bead area in the plies.

The tread belts showed a maximum tensile stress of 1500 psi in the $\phi$ direction, which is around the circumference of the tire. This tension occurred at the centerline of the tread. The belts' stress decreased at distances farther from the centerline and closer to the edge of the tread. The stress then became compressive, and at the edge of the tread belt it reached 800 psi in the $\phi$ direction.

The stresses in the different areas of rubber were quite small. The undertread which extends from the tire centerline out to the edge of the tread bars (outside of the tread belts) had maximum stresses of 10 psi in tension and 28 psi in compression. The sidewall rubber's maximum tensile stress was 8 psi and the maximum compressive stress was 13 psi. For the model with the tread bars, the maximum tensile stress in the tread was 5 psi with the highest compressive stress being 3 psi. The stress in most of the tread area was around 1 psi. This low stress explains why the tread had little effect on the displacement results between the two models.

## Experimental Testing

The experimental testing was carried out in the laboratory using dial indicators to measure the deflection and a pressure gage to measure the air inflation pressure. The test set up is shown in Figure 8. The framework was adjustable to allow testing at different locations around the circumference of the tire. The dial indicators were bolted to sections of angle iron which were clamped to the framework. Clamping the angle irons to the framework made the positioning and adjustment of the dial indicators much simpler and faster than drilling the holes and slots needed to bolt the irons to the frame. This flexibility was necessary for locating the dial indicators at the proper angle normal to the original tire surface. The dial indicators were placed against flat places on the tire. They were not located on the tread bars.

Figure 5. Photograph of the laboratory tire displacement measuring setup.

The tire was suspended during the tests. A pressure gage was mounted between the valve stem and the tire to allow continuous monitoring of the inflation pressure. The tire was a tubeless-type but an inner-tube was installed in the tire since the rim was a tube-type rim.

Upon inflating the tire from 0 to 1 psi (in each of the three different locations around the circumference) the tire's centerline would move laterally. The tire at the centerline would rise about 1/8 inch and move to the left (when facing the tread) from 1/4 inch to 1/2 inch. The reason for this phenomena is not apparent, but several ideas are suggested. The upward motion was possibly the result of the tire sagging when it was suspended at 0 psi. An inflation pressure of 1 psi was apparently enough to lift the tire most of the distance it had sagged. The tread pattern was possibly the cause of the movement to the right, but in testing at several locations this was shown to have no effect. Most of the displacement to the right at 0 psi was corrected by inflating the tire to 1 psi.

The dial indicators were placed as near to one radial line around the tire as possible. The tread bars did present some problems in doing this. The location of the dial indicators can be seen in Figures 9 and 10. Dial indicators number 1 through 4 were


Figure 9. Photograph showing the actual location and numbering order of dial indicators 1-5.


Figure 10. Photograph showing the actual location and numbering order of dial indicators 5-12.

located just below a short bar. Dial indicator number 5 was at the end of the short bar. Indicators 6 through 11 straddled the long bar opposite the short bar. Dial indicator 12 was on the sidewall location between dial indicators 10 and 11. The dial indicators were positioned at the nodes with maximum and minimum displacement on the FEM analysis as shown in Table 2 and labeled in Figure 7. To measure the displacement at a location on the tire with the short bar on the opposite side of the tire centerline, the dial indicator location and numbering scheme was reversed. With indicators 1-4 still being just below the short bar and 6-11 straddling the long bar.

The displacements from the incremental tests were taken from 1 psi to 18 psi, rather than 0 psi to 18 psi because of the shifting of the tire. The displacement at the midpoint of the sidewall, node 173, for the three locations was .134 inches outward. The displacement at the tire centerline was .121 inches outward. The displacement at the points around the edge of the tire was much more difficult to determine because of the shifting of the tire. However, for all the tests the deflections in this area were smaller than for the sidewall and centerline areas. In some tests there was a slight negative displacement but it was uncertain if this was caused by the tire shifting or deflection due to the inflation deformation.

# DISCUSSION

The first difficulty in this research was determining the composite laminate material elastic constants. Years of research has gone into determining the empirical equations and testing these equations. Even if the nonlinear composite nature of the laminate tire make-up could be modeled accurately, the method of construction still creates uncertainties. The plies and belts are initially made flat, they are then formed into the torid-like shape of a tire. This manufacturing process could cause a prestressed condition in the tire plies that could affect its strength.

One problem with ANSYS was the possible range of values that could be used for the Poisson's ratio. With the big difference in Young's modulus in the different directions, Poisson's ratio can be no greater than .1 for this ANSYS model. A larger Poisson's ratio results in errors from ANSYS. This low Poisson's ratio does not account for the incompressibility of the rubber and cords. One modeling technique could be to model the tire as solid rubber then superimpose spar elements between the nodes to account for the cords. This was not possible since an axisymmetric spar element was not available from ANSYS. Another technique could be to specify an approximate area for an axisymmetric tensile element for the cords.

The nonlinear rubber and cord is modeled as linear, but at the low strain rates in the tire this should not cause a problem.

Rubber acts fairly linear at low strain rates. Another nonlinearity that does exist is the stress stiffening. This is caused by the weakness of the plies in bending when there is no tension. This would occur at the first iteration. The second and following iterations then account for the bending strength with tension in the belts. The other nonlinear factor that may not have a great affect in this analysis is the large deformation option. This would probably have more of an affect on 3-D tire contact analysis where there would be directional forces and more deflection. The large deformation option recalculates the stiffness matrix accounting for a change in the direction of the applied forces due to nodal displacements and rotations. In this analysis the deflections are not that large and the pressure is perpendicular to the element surface which has very little rotation.

The first variation in the laboratory testing from the ANSYS model was the tube. As stated earlier a tube had to be used because the tubeless tire would not stay on the tube-type rim that was used. However, the very flexible thin rubber tube used has virtually no effect compared to the high strength plies. This assumption was made after observing the very low stress in the rubber on the FEM. The weight of the tube probably has the most effect in causing the tire to sag at 0 psi. The tire sagging at 0 psi caused little problem in determining the tire deflection. The tread area where the dial indicators are located raises about 1/8 inch from 0 psi to 1 psi inflation pressure. This sag is probably from the weight of the tire and the tube because the sidewalls are quite flexible and the tire is quite heavy.

The lateral shift is caused by a small sidewall stiffness since a pressure of 1 psi removes most of this shift. The manufacturing process could cause the slight stiffness. Another possiblity is that the new tire had been stored in such a manner as to cause this offset. This offset might be worked out with time.

One possible solution to the tire shifting problem, which caused problems in the deflection measurements, might be the design of a new testing framework. If the framework could move laterally with the tread yet keep the same radius on the tire, the deflection normal to the surface on the corners could be more accurately measured.

With the many possible errors the results were quite close to FEM predictions. The centerline deflection at node 9 was measured to be .121 inches. The FEM prediction was .137 inches. This is an error of 13 percent. However, the sidewall deflection measured at .134 inches only .001 inches less than the FEM prediction, represents an error of 1 percent. The precision of the tire dial indicator deflection measurements made at the corners was not good. The shifting of the tire caused problems in creating a "noise" that affected these readings. The measurements generally were lower and some were negative, at least showing the trend of tire displacement as predicted by the FEM.

# CONCLUSIONS

The assumptions made in this ANSYS finite element method appear to be reasonable since the FEM radial tractor tire deflection predictions of the two models agreed quite well with the laboratory deflection measurements. More accurate deflection measurements could be obtained by increasing the complexity of the testing framework for measuring deflection independent of the lateral tire shift. The internal ply stresses varied as would be expected by the predicted deflection. The ply stresses in the direction parallel to the cords varied much like the bending stress in a deflected beam, with compression on the concave side and tension on the convex side of the deflection curvature.

Therefore, the material properties and the geometric shape of the 18.4R38 Dyna Torque Radial tractor tire made by Goodyear Tire and Rubber Company was accurately modeled. This modeling was done by the ANSYS Engineering Analysis System and predicted the axisymmetric deformation of the tire due to air inflation pressure.

## SUGGESTIONS FOR FURTHER RESEARCH

Expansion of this model by choosing a 3-D element from the ANSYS library using the same material properties and ANSYS options would allow analysis of non-axisymmetric loading. This non-axisymmetric loading could include loads such as vertical axle loading and side loading with axle torque applied. The analysis of these loads could include the internal stresses and also, the tire deflection, the ground contact area, and the pressure distribution over this contact area.

This type of analysis would be more useful in determining the tire characteristics that affect the tire's shape. Once these characteristics are determined, the tire could be modified to obtain the longer, narrower, footprint, with more flexible sidewalls, and a more uniform pressure distribution.

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# APPENDIX A

```
/PREP7
/TITLE, TIRE, 3 PLY 4 BELT & TREAD, 6 X 32 TRI, VARIED E1

KAN,0
KAY,6,1
KAY,8,1

ET,1,42,1,,1

EX,10,4000
EY,10,225000
EZ,10,4000
NUXY,10,.005
NUYZ,10,.1
NUXZ,10,.1

EX,11,4000
EY,11,245000
EZ,11,4000
NUXY,11,.005
NUYZ,11,.1
NUXZ,11,.1

EX,12,4000
EY,12,270000
EZ,12,4000
NUXY,12,.005
NUYZ,12,.1
NUYZ,12,.1

EX,13,4000
EY,13,306000
EZ,13,4000
NUXY,13,.005
NUYZ,13,.1
NUXZ,13,.1

EX,14,4000
EY,14,350000
EZ,14,4000
NUXY,14,.005
NUYZ,14,.1
NUXZ,14,.1

EX,2,4000
EY,2,4000
EZ,2,350000
NUXY,2,.49
NUYZ,2,.005
NUXZ,2,.005
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EX,3,700
NUXY,3,.49

EX,4,500
NUXY,4,.49

EX,5,1000
NUXY,5,.49

EX,6,30E6
NUXY,6,.3

EX,7,150
NUXY,7,.49

LOCAL,11,1,15.375,0
N,1,17,0
,4,17.117,0
FILL
N,8,17.349,0
FILL,4,8
N,9,17.61,0
NGEN,9,9,1,9,1,,2.06875

,2,251,9,,,.8125
,2,1,260,,,.8125
,7,2,260,261,,,4.1
CSYS,0
N,275,32.6,8.7
,276,31.6875,8.81
,277,30.8125,8.89
,278,29.9375,8.97
,274,31.3,8.4

LOCAL,12,1,25.4,2.9
NGEN,4,9,73,81,1,,5.14

LOCAL,13,1,26.96,4.06
NGEN,2,9,100,108,,,6.2
,2,9,109,112,,,7.475
,3,1,121,,,.116
,2,1,123,,,.261
,2,7,118,121,,,7.475
,3,1,128,,,.25
,4,6,125,129,,,7.475
,2,1,135,,,.27
,2,1,141,,,.375
,2,1,147,,,.1875

LOCAL,14,1,24.9,-3.62
NGEN,2,6,143,146,,,3.02
,5,5,149,152,,,3.02
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,2,1,157,,,.287
,2,1,162,,,.25
,2,1,167,,,.22
,2,1,172,,,.23

LOCAL,15,1,24.9,-.09
NGEN,3,5,169,172,,,4.56
,2,1,177,,,.25
,2,1,182,,,.039
,2,1,183,,,.22
,2,6,179,183,,,4.56
,2,1,189,,,.039
,2,1,190,,,.2
,2,7,185,190,,,4.56
,2,1,197,,,.039
,2,1,198,,,.219
,2,8,192,198,,,4.56
,2,1,206,,,.34

LOCAL,16,1,23.19,3.9875
NGEN,3,8,200,203,,,8.13
,2,1,211,,,.11
,4,1,212,,,.039

CSYS,0
N,220,20,7.9
,223,19.92,8.01
FILL
N,224,19.81,7.145
,227,19.6875,7.25
FILL
N,230,19.6875,7.133
FILL,227,230
N,231,19.1875,7.133
,237,19,7.25
,234,19.1875,7.25
FILL,231,234
,234,237
N,238,19,7.8125
,244,19.1875,7.93
,241,19.1875,7.8125
FILL,238,241
,241,244
N,245,19.6,7.93
,248,19.6875,7.8125
FILL
N,250,19.86,8.187
,251,20.06,8.5
,252,20.4375,8.625
,249,19.4375,7.53125
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MAT,10
E,2,1,10,10
,10,11,2,2
EGEN,3,1,1,2
,12,9,1,6

MAT,11
E,110,109,118,118
,118,119,110,110
EGEN,3,1,73,74
E,119,118,125,125
,125,126,119,119
EGEN,3,1,79,80
E,126,125,131,131
,131,132,126,126
EGEN,3,1,85,86
,3,6,85,90

MAT,12
E,144,143,149,149
,149,150,144,144
EGEN,3,1,103,104
E,150,149,154,154
,154,155,150,150
EGEN,3,1,109,110
,4,5,109,114

MAT,13
E,170,169,174,174
,174,175,170,170
EGEN,3,1,133,134
,2,5,133,138
E,180,179,185,185
,185,186,180,180
EGEN,3,1,145,146
E,186,185,192,192
,192,193,186,186
EGEN,3,1,151,152
E,193,192,200,200
,200,201,193,193
EGEN,3,1,157,158

MAT,14
EGEN,4,8,157,162
E,224,225,229,230
,225,226,228,229
,227,226,228,228
,230,229,232,231
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,231,232,236,237
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 ,247,246,222,222
 ,222,221,247,247
 ,246,245,223,223
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 ,220,221,213,213
 ,213,212,220,220
EGEN,3,1,205,206
E,212,213,204,204
 ,204,203,212,212
EGEN,3,1,211,212

MAT,13
E,203,204,196,196
,196,195,203,203
EGEN,3,1,217,218
E,196,197,189,189
,189,188,196,196
EGEN,2,1,223,224
E,189,190,183,183
,183,182,189,189

MAT,2
E,5,4,13,13
,13,14,5,5
EGEN,4,1,229,230
,11,9,229,236
E,105,104,113,113
,113,114,105,105
,107,106,115,115
,115,116,107,107

MAT,3
E,8,9,18,17
EGEN,12,9,-1
E,103,104,113,112
,105,106,115,114
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,114,115,123,122
,115,116,123,123
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,129,130,136,135
,135,136,142,142

MAT,4
E,128,135,134,134
,134,135,141,140
EGEN,3,6,-1
E,135,142,141,141
,141,142,148,147
,147,148,153,153
,152,153,158,157
EGEN,5,5,-1
E,177,183,182,182
,177,178,184,183
,183,184,191,190
,190,191,199,198
,198,199,207,206
,206,207,252,215
,215,252,251,223
,223,251,250,250
,223,250,245,245

MAT,5
E,203,212,211,211
,211,212,220,220
,211,220,219,219
,219,220,248,248
,219,248,227,227

MAT,6
E,227,248,249,249
,248,241,249,249
,241,234,249,249
,234,227,249,249

MAT,7
E,9,260,18,18
,260,262,18,18
,18,262,27,27
,27,262,36,36
,262,264,36,36
,36,264,45,45
,45,264,54,54
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,63,266,72,72
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,108,272,117,117
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,124,274,277,277
,277,130,124,124
,130,277,278,136
,136,278,142,142
,277,276,274,274
,272,274,276,276
,272,276,275,275
,272,273,275,275
,260,261,263,262
EGEN,6,2,-1

ITER,-10
D,1,UY,,,9,,ROTZ
,237,UX,,,238
,244,UY,,,245
,260,UY,,,261,,ROTZ

P,1,10,18,,109,9
,118,125,18
,125,131,18,,143,6
,149,154,18,,174,5
,179,185,18
,185,192,18
,192,200,18,,216,8
,224,230,18
,230,231,18

AFWRITE
FINISH
/INPUT,27
FINISH
/POST1
SET,1,10
PRDISP
PRESTR
FINISH
```

# APPENDIX B

Tire Displacement for Test #1

| A Change in Pressure From | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 - 1 psi | .103 | .103 | .069 | .047 | .027 | -.029 | -.037 | -.073 | -.079 | -.097 | -.094 | -.010 |
| 1 - 6 | .129 | .061 | .015 | .033 | .041 | .008 | .007 | -.035 | -.049 | -.033 | -.026 | .039 |
| 1 -12 | .183 | .085 | .026 | .060 | .079 | .028 | .005 | -.033 | -.050 | -.027 | -.019 | .077 |
| 1 -18 | .217 | .107 | .041 | .084 | .119 | .051 | .028 | -.019 | -.040 | -.014 | -.005 | .105 |
| 0 - 1 | .121 | .116 | .083 | 0.54 | .041 | -.031 | -.047 | -.081 | -.090 | -.104 | -.100 | -.015 |
| 1 - 6 | .112 | .054 | .013 | .034 | .029 | .012 | -.001 | -.027 | -.040 | -.034 | -.027 | .042 |
| 1 -12 | .160 | .076 | .024 | 0.60 | .065 | .033 | .018 | -.022 | -.039 | -.027 | -.019 | .076 |
| 1 -18 | .196 | .098 | .038 | .084 | .102 | .056 | .040 | -.009 | -.029 | -.014 | -.006 | .106 |

For this test dial indicators Number 2-4 were placed between tread bar number 2 and 4. Indicators 6-11 straddled bar number 3.

Tire Displacements for Test #2

| A Change in Pressure From | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 - 1 psi | .345 | .430 | .333 | .218 | .022 | -.156 | -.182 | -.389 | -.354 | -.415 | -.416 | -.115 |
| 1 - 6 | .063 | .033 | .026 | .047 | .039 | .008 | .011 | -.012 | -.017 | -.008 | -.007 | .038 |
| 1 -12 | .106 | .048 | .037 | .086 | .085 | .022 | .036 | -.011 | -.017 | .004 | .004 | .082 |
| 1 -18 | .139 | .063 | -.048 | .117 | .128 | .040 | .060 | -.003 | -.006 | .018 | .019 | .115 |
| 0 - 1 | .306 | .358 | .273 | .175 | .031 | -.113 | -.142 | -.282 | -.290 | -.336 | -.226 | -.080 |
| 1 - 6 | .054 | .021 | .023 | .036 | .033 | .004 | .010 | -.011 | -.014 | .001 | -.001 | .039 |
| 1 -12 | .094 | .033 | .021 | .069 | .076 | .018 | .031 | -.005 | -.013 | .013 | .010 | .082 |
| 1 -18 | .128 | .049 | .036 | .101 | .121 | .036 | .067 | .097 | -.007 | .027 | .026 | .117 |

For this test dial indicators number 2-4 were placed between tread bar numbers 50 and 52. Indicators 6-11 straddled bar number 51.

Tire Displacements for Test #3

| A Change in Pressure From | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 - 1 psi | -.029 | -.203 | -.194 | -.077 | .060 | .125 | .135 | .150 | .141 | .194 | .192 | .123 |
| 1 - 6 | .030 | -.004 | -.017 | .002 | .040 | .048 | .051 | .030 | .024 | .034 | .032 | .072 |
| 1 -12 | .066 | .010 | -.014 | .022 | .084 | .083 | .092 | .044 | .036 | .047 | .046 | .117 |
| 1 -18 | .096 | .028 | .000 | .045 | .131 | .121 | .130 | .064 | .055 | .065 | .065 | .157 |
| 1 - 6 | .028 | .000 | -.012 | .001 | .025 | .039 | .042 | .022 | .018 | .025 | .022 | .060 |
| 1 -12 | .062 | .013 | -.009 | .021 | .082 | .075 | .081 | .035 | .029 | .037 | .036 | .102 |
| 1 -18 | .089 | .030 | .004 | .044 | .127 | .110 | .117 | .055 | .046 | .053 | .053 | .137 |

For this test dial indicators 2-4 were placed between tread bar numbers 53 and 55. Indicators 6-11 straddled bar number 54.

FINITE ELEMENT MODELING OF

TRACTOR TIRE DEFORMATION

by

DALE LEE HEISE

B.S., Kansas State University, 1985

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AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Agricultural Engineering

KANSAS STATE UNIVERSITY

Manhattan, Kansas

1987

## ABSTRACT

The ANSYS Finite Element Method computer program was used to predict the deformation of a suspended tractor tire due to inflation pressures from 1 to 18 psi. The tire was an 184R38 Dyna Torque Radial 1* made by Goodyear Tire and Rubber Company. The tire's laminate composite material elastic constants were determined by the Halpin-Tsai and Gough-Tangorra equations and by consultation with Goodyear. The tire was modeled with a 2-D axisymmetric model with stress stiffening and large deformation options. ANSYS FEM displacement predictions were made for models with and without tread lugs. Laboratory results of the actual tire's displacement were measured at a cross section of the tire by 12 dial indicators. These measurements were taken at 3 different locations around the tire. The ANSYS FEM predicted the displacement with 1% to 13% error.