Detailed Tire Modeling for Crash Applications

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Abstract – In many crashworthiness applications the tire and suspension play a significant role in the behavior of the vehicle during the crash. For many of those applications, that role can be effectively modeled with simplified models of those parts. However, in some crash events the tire and suspension need to be modeled in great detail in order to accurately capture the response of the vehicle. To better simulate such events, a new tire model was developed that takes into account the major components of a tire; including the tread, sidewall, steel beads, steel belts and body plies. Laboratory testing was performed in order to help validate the tire model. LS-DYNA, a nonlinear finite element analysis code, was used as the simulation tool. Some important details about properly pressurizing the tire and using relative damping to control excessive tread vibrations were discovered during the research. A significant effort was made to keep the number of elements in the model as low as possible without sacrificing accuracy in order to keep computational costs down. The new tire model was used on several applications including impacting a curb, driving over rocks, and landing on a culvert grate to demonstrate its' effectiveness.

INTRODUCTION

Tires play a very important role in vehicle performance, be it in a high-speed racecar or a vehicle that is driven daily on the highways. The tire is the only part of the vehicle that is in contact with the road. Normally, approximately one square foot on each tire is in contact with the road. Tires greatly affect the handling characteristics of a vehicle, especially when cornering or encountering large bumps. During cornering, large lateral forces are exerted on the tire. When the tire encounters large bumps, such as a culvert grate, a pothole, or curbs, the tire deforms and acts somewhat like a nonlinear spring.

As a specific example, in order to properly evaluate the performance of a transverse culvert safety grate, the tires must be capable of behaving properly as each tire leaves contact with the roadway and then comes into contact with each bar on the culvert. The tires, in combination with the suspension system, control the vehicles' behavior as it passes over the grate. Even larger deflections could be expected during more severe crash events such as tires impacting guardrail posts or the body structure of other vehicles. Currently available tire models do not adequately capture tire behavior under such impacts. Thus, a research project was undertaken to develop a more detailed, yet computationally cost effective, tire model for use in impact simulations. A typical tire found on a ¾ ton pickup truck will be used as the target model; however, the technique developed will be applicable to most tires.

Components of a tire

A typical tire is composed of many different layers and materials. This composite of layers has been under continuous development since the tire was first invented and still continues to change today to improve performance and reduce costs. The typical components are shown in Figure 1. Nylon overlays are not found in every tire and are generally found in high speed rated tires. These nylon layers aid in holding all the components together, which under high speeds may come apart. The tires normally used on an original pickup do not contain these nylon overlays. Descriptions of the other components and how they were modeled are provided later in this paper.

PREVIOUS TIRE SIMULATION EFFORTS

Significant computer simulation research into tire models has been conducted in recent years. Initial models consisted of simple airbag models to represent vehicle tires. However, it was found that these simple models did not accurately represent the behavior of vehicle tires, and more detailed modeling of tires was needed. More recent tire models have focused on investigation of quasi-static tire loading and tire interaction with the roadway surface. For the purposes of this research the authors were more concerned with the behavior of automobile tires under impact loading conditions and large deformations. Summaries of previous research into tire models applicable to impact are summarized below.

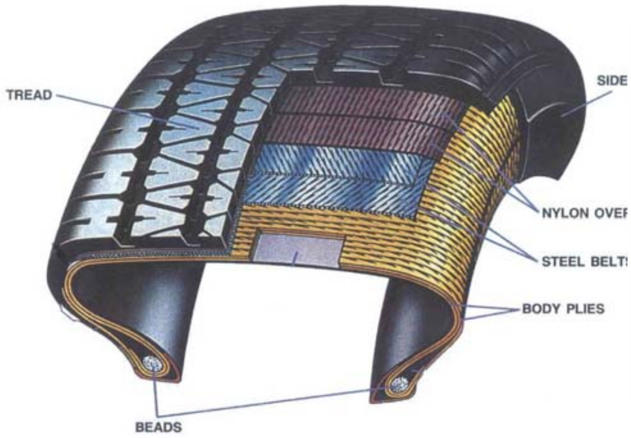

Figure 1. Components of a Tire

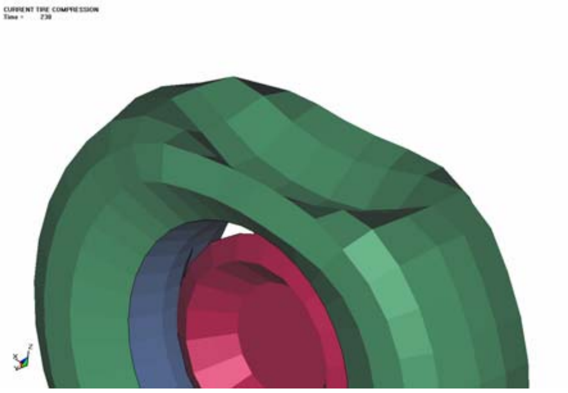

Figure 2. Original – Unrealistic Cupping

Vertically Loaded Tire

A LS-DYNA model of a standard 195/65 R15 sedan tire was developed by Hall, Jones, and Mottram [1]. The purpose of the model was to develop a simulation of a tire under vertical load with a focus on replicating the proper tire loading and contact patch geometry. The tire model consisted of 56,400 shell and solid elements. Materials used in the tire model consisted of hyperelastic rubber for the main body of the tire, an orthotropic elastic material for the plies and bands, and mild steel for the bead. The authors found a good correlation between the load-deflection characteristics of the tire, but concluded that further research was required to develop an accurate representation of the tire contact patch. A second version of the tire model was developed for rolling tire simulations, but the number of elements was increased to almost 140,000. Both levels of detail are prohibitive for most roadside hardware crash simulations due to the CPU requirements to run such models.

Tire Model for Durability and Crash Applications

Researchers from the Japan Research Institute, Sumitomo Rubber Industries, and Nissan Motor Co. developed a tire model for durability and crash applications [2]. Initial work in the development of the tire model led to a detailed and complex model of the tire that consisted of 22,801 solid and shell elements. The detailed model had separate layers for the tread, belt, band, carcass, and sidewall. The researchers found that the detailed model was computationally expensive and wished to reduce the size of the model to make it more practical when used in conjunction with full-size vehicle models. In order to build a reduced model, the various layers in the tire were combined and represented with a single layer of shell elements, the number of materials was reduced, and the mesh size was significantly increased. The reduced model of the tire had only 2,642 elements. This model was simulated under vertical load as well as rolling over a small cleat and a curb. Results correlated well with test data.

Modeling Tire Blowout in Roadside Hardware Simulations

Orengo, Ray, and Plaxico developed a tire model of a 245/75R16 light truck tire for use in roadside hardware simulations [3]. Development of the tire model found that simple airbag type models of tire behavior were not sophisticated enough to properly capture tire behavior. Thus, the researchers resorted to a more complex “anisotropic model” that incorporated critical tire structural components such as the bead, radial fibers, belt, tread, and sidewall. Debeading of the tire occurs when the tire bead is separated from the rim allowing the air inside to escape. A debeading failure mode was included in the model by incorporating an internal trigger made of shell elements that stopped the simulation if the tire bead was displaced sufficiently. The simulation was then restarted with the tire bead detached from the rim. Results from the compression testing compared well for 50 mm of deflection, and tire blowout was successfully reproduced using the model.

ORIGINAL TIRE PERFORMANCE

The previous wheel and tire on the University of Nebraska-Lincoln (UNL) truck model was relatively simple with respect to the actual individual components. The tire was modeled with a single layer of shell elements, a thickness of 5 mm, an elastic material and a constant pressurization of 483 kPa (70psi). A finer mesh was used on the front tire compared to that on the rear tire to aid in contact with roadside safety equipment during crash test simulation. The wheel, or rim, was also constructed with shell elements with a uniform thickness of 5 mm. A rigid material with a density of 7.86E-06 kg/mm^3 was specified for the wheel.

In order to evaluate how the original tire model being used behaved, a simulation similar to the laboratory testing performed (described later in this paper) was developed. The wheel and tire model was placed on a planar rigid wall while another moving rigid wall was placed above the tire. The top rigid wall was given a displacement of 125 mm and then pulled back up to its original position.

The force required to compress the simulated tire was significantly higher than found in laboratory testing. One important feature to note is how the simulated tire underwent severe cupping action, as illustrated in Figure 2. This occurred on both the top and bottom side of the tire during the compression. An overall statement for the previous tire model is that it was too stiff and did not deform under compressive loading in a manner similar to reality.

WHEEL AND TIRE GEOMETRY

In order to properly model deformations in a tire, one of the most important factors, aside from actual material properties, is the geometry of the materials. The size designation for the tires used on C2500 pickups crash tested at MwRSF is a LT245/75R16. The LT stands for light truck. The first letter or set of letter specifies the tire type. Other possible designations instead of LT could be T for temporary/spare tires or P for passenger vehicle tires. The next number in the sequence, 245, stands for the width of the tire in millimeters, measured from sidewall to sidewall. The width of the rim that the tire is mounted on can affect this number, so this measurement is when the tire is mounted on its intended rim size. The next number, 75, allows for calculation of the tire height based on the tire width and is referred to as the aspect ratio. This number represents the measurement of the distance from the bead to the top of the tread and is the percentage of the width. So in this case, the distance from the bead to the top of the tread would be 75% of 245 mm or 183.75 mm. The next letter, R, represents how the tire is made. Nearly all tires today will have an R since it stands for radial construction. Before new radial tires were made, D for diagonal bias or B for bias belted, were used. The last number, in this case 16, stands for the diameter of the rim that the tire is designed to be used on. This number, unlike the other measurements, is specified in inches. In this case, 16 inch diameter rims are used on the truck.

Measuring the multiple thickness and radii is rather difficult to do on both the rim and tire. To aid in this process, a wheel and tire from a C2500 pickup were cut in half using a vertical band saw.

With the wheel and tire cut in half, both the wheel and tire could be traced onto a large piece of paper to create a cross section drawing that showed the thickness. A centerline was drawn through the middle of the thickness since a large portion of the wheel and tire would be modeled using shell elements. Thickness measurements could easily be made on the exact part using a caliper to ensure a higher degree of accuracy than using the traced drawing. X and Y coordinates were measured at critical points to a drawn centerline and then brought into Hypermesh. The cross section was drawn using lines between those coordinates and then spun around the centerline. Since the tread would be represented with solid elements, the outer edge of the tread profile was used for its' cross section; which was then spun about the centerline to create the tread mesh.

MATERIALS – GENERAL DISCUSSION

Obtaining the steel, rubber and fabric material properties for each part of the tire is not easily accomplished. Once the tire has been formed one cannot separate the parts to perform testing on them. Many different stiffness and types of rubber are used in tires. Some are lower stiffness to allow for more flexibility and adhesion, while others have a higher stiffness for wear or durability. The cross section continuously varies in thickness and different materials are used throughout the tire. Therefore, doing something like tensile testing of the composite material was not possible. Each of the components in the tire contributes to the overall behavior of the tire. Generally in computer simulation it is advisable to be sure that as many of the individual components behave properly by using some sort of validation method. However, in the case of a tire, this was not possible. Instead the tire had to be tested as a whole composite and compared to laboratory data that could be collected.

Rubber material properties can vary greatly, ranging anywhere from rubber bands to the bottom of your shoes. In some cases manufactures are willing to share detailed material properties. In the case of tires, each company refrains from disclosing their material data because they do not want the competition to find out how their tires are made.

In the tire, not only were the rubber properties important, but also the properties of the fabric used for the body plies. Fabric can vary as greatly in properties if not more than rubber; the angles that the fabric is woven at, the density of the weave, and the thickness of the individual fibers are some of the items that can affect material properties. With the fabric encased in rubber, none of these properties can be found without significant work.

TIRE MODEL

The new tire model is composed of five different sections: solid elements for the tread, shell elements for the sidewall material, and beam elements for the bead, steel belts, and body plies. Each component is discussed in detail below; refer to Figure 3 for visualization of the separate component modeling techniques described.

Tread

The tread is the component of the tire that is in contact with the ground. Tire treads generally have some form of pattern because differing patterns can create different traction properties. Some are designed to move water through the contact patch, others to provide better traction in conditions such as mud and snow, and others for just all around performance.

Solid elements were used to model the tread, with three elements across the cross section in order to effectively model bending stresses. A selective reduced fully integrated solid element was specified. Modeling the actual tread pattern would require large amounts of computation time due to the small elements that would be necessary as well as requiring a separate model for each different tread pattern.

The tread material was modeled using a hyperelastic rubber, with a density of 1.10E-06 kg/mm^3 and a poison's ratio of 0.495. Other material properties required for hyperelastic rubber were obtained from Goodyear and then altered during simulation of laboratory compression testing.

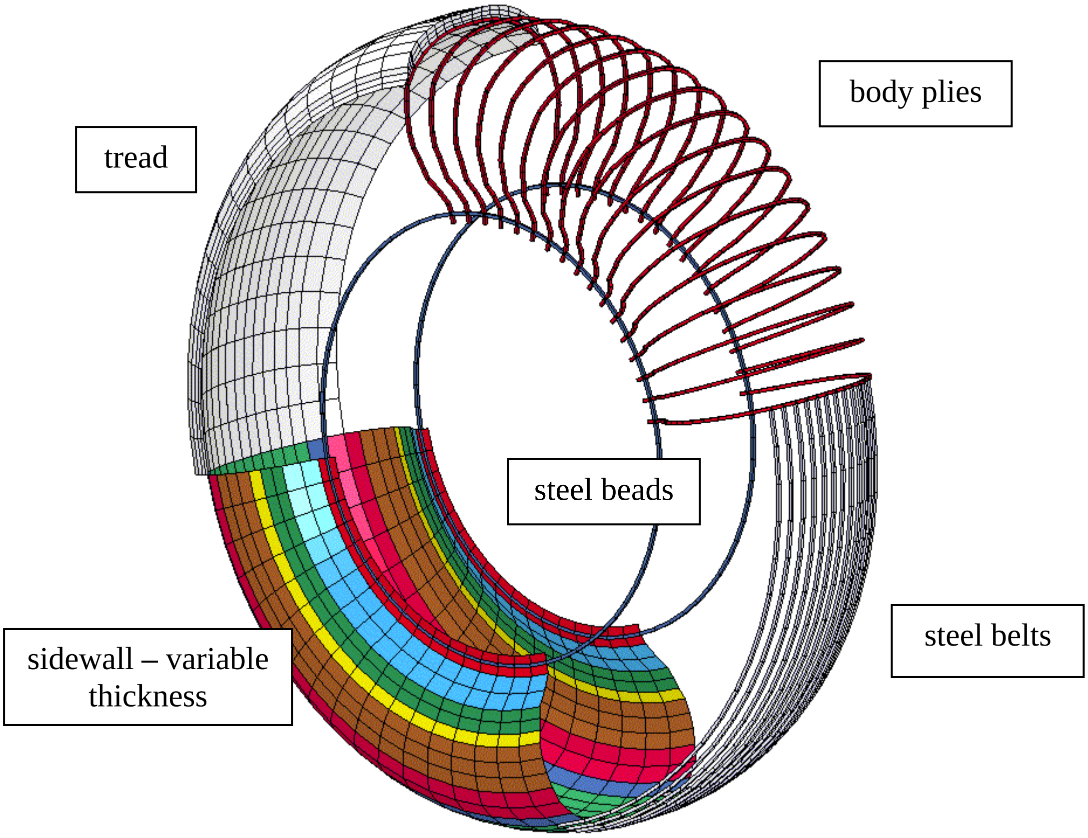

Figure 3. Tire Components Modeled

Sidewall

The sidewall is the portion of rubber that runs from the rim of the wheel up to the tread. The sidewall provides lateral stability to the tire and also provides resistance to the vertical compression of the tire. Higher sidewall stiffness increases cornering stiffness to provide better driver control, but increases tire compressive stiffness, which yields a harder suspension.

Shell elements were used to model the sidewall geometry. Eight separate parts and sections were used around the tire so that each part could have a different thickness. The thickness of the sections, starting on the inside and working outward are 13.0 mm, 20.5 mm, 16.0 mm, 11.0 mm, 7.25 mm, 10.0 mm, 11.0 mm, and 5.85 mm. Fully integrated shell elements were used since the default Belytschko-Tsay elements resulted in significant hourglass energy.

The sidewall rubber was modeled using an elastic material, with a density of 1.10E-06 kg/mm^3, a Young's modulus of 0.03 GPa, and a poison's ratio of 0.45.

Steel beads

Tire beads carry forces exerted on the sidewall that would otherwise cause the sidewall to separate from the rim and therefore lose air pressure; they somewhat lock the tire onto the rim. Tire beads are constructed with a high strength cable that is encased in sidewall rubber. The reinforcement layers in the sidewalls wrap around the steel beads.

To model the steel beads that run near the inner portion of the tire, resultant beam elements were used. The bead material was modeled using an elastic material, with a density of 7.86E-06 kg/mm^3, a Young's modulus of 200 GPa, and a poisons ratio of 0.28. The beams were placed in the middle of the first section thickness of the sidewall. Nodes were merged between the beam elements and the shell elements so they were essentially glued together.

Resultant beams required the specification of a cross sectional area, a shear area, as well as the second moments of area, I_{ss} and I_{tt}. Each bead on the tire is made up of twenty-four individual wires. I_{ss} and I_{tt} were calculated for each wire; since each bead is composed of 24 wires, the I_{ss} and I_{tt} for the bead were found by multiplying that value by 24. This resulted in an I_{ss} and I_{tt} value of 5.964 mm^4. The cross sectional area was calculated by finding it for one of the individual wires, then multiplying that value by 24, yielding a cross sectional area of 42.41 mm^2. The shear area was calculated by taking 0.9 multiplied by the cross sectional area, resulting in 38.17 mm^2.

Steel belts

Steel belts play an important role in the function of a tire. These belts provide puncture resistance as well as help the tire to stay flat so that it makes the best contact with the road. Located under the tread, belts are composed of many steel cables that are encased in rubber. Each cable consists of seven individual wires similar to the steel bead. Each wire has approximately a 0.35 mm diameter. There are two layers of these cables in the tire. Each layer has 64 cables in it and the cables are spaced approximately 2.5 mm apart.

In order to model the steel belts, resultant beam elements were used. Initially a layer of shell elements in this area was used to simulate the cables, but this proved to be an ineffective method, so the beam element method was chosen instead. Using one beam for each steel wire, or even for each cable would result in a very large number of elements. The steel belts were approximated by 12 sets of beams running around the tire. Similar to the steel beads, the nodes were merged so that the beams were essentially glued to the sidewall and tread. Since there are only 12 sets of beams running around the tire, that means that each circle of beams will have to provide the equivalent strength of approximately 11 cables. Just like the steel beads, an elastic model used was with a density of 7.86E-06 kg/mm^3, a Young's modulus of 200 GPa, and a poisons ratio of 0.28.

For a round cable such as the steel beads, I_{ss} and I_{tt} would be the same, but since each beam has to approximate 11 cables, spaced 2.5 mm apart, I_{ss} and I_{tt} are different. Space limitations prevent derivation here, but details are provided in Boesch [4]. The final value found for I_{ss} was 463.0735 mm^4 and for I_{tt} was 0.0567 mm^4. The cross sectional area was 7.4082 mm^2 and the shear area was 0.9 multiplied by the cross sectional area which was 6.6674 mm^2.

Beam orientation validation

Beam elements are defined using three nodes with a local r-s-t coordinate system. This coordinate system defines the orientation of the beams' cross section. The r-axis is defined as the line between nodes one and two. The s-axis will fall in the plane created by the three nodes, while the t-axis is perpendicular to that plane. When the nodes were selected to create the beam elements for the steel belt, nodes were selected in a clockwise manner for nodes one and two. Node three was selected as a node located at the center of the tire in the plane of that section of beams; therefore each circular set of beam elements had the same third node.

In order to be sure that the orientation method used was correct, a simulation was performed to compare how the beams acted under compression. Two circles of beams were made, similar to those found in the tire. One set was given the properties of I_{ss} and I_{tt} listed above and then for the other set, the values were reversed. Both rings of beams were crushed between rigid walls.

Results from the simulation are shown in Figure 4. Notice that the forces are near zero when the beam section is defined properly, like a flat rubber band that basically falls under its own weight, as shown by the ring on the right in Figure 4. When the beam section moment of inertias are reversed, like flat circular disc, the forces are greatly increased. These drastically different results show that it is critical that the beam orientation be specified correctly.

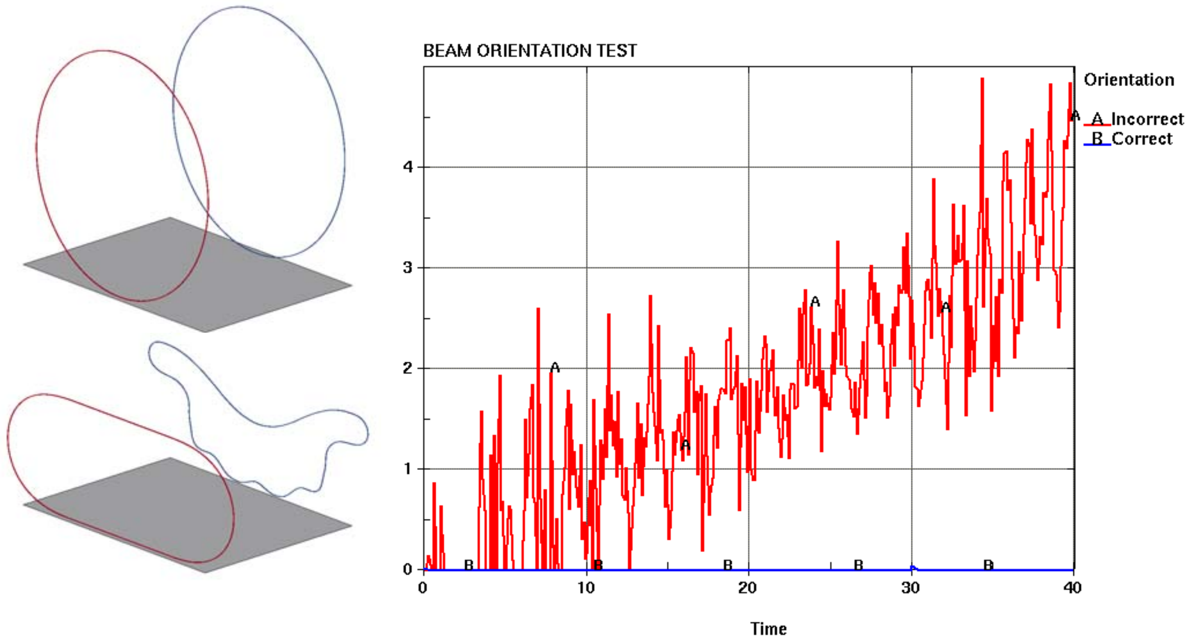

Figure 4. Importance of Beam Orientation

Body plies

Body plies increase the lateral load capacity of the tire and add sidewall stiffness. The body plies are generally made of a polyester material that runs perpendicular to the direction of the tread and steel belts. These body plies serve as the main reinforcement in the sidewall material. Different types of tires contain a different number of layers of plies. The plies are also encased in rubber to aid in adhesion to other components.

Two different attempts were made to model this part of the tire. The first attempt was made using a layer of fabric material constructed with shell elements covering the entire inside surface of the tire. The nodes of the shell layer were merged to the nodes of the sidewall and tread. When using this technique, the forces required to vertically compress the tire were too high; reasons for this are detailed in Boesch [4]. Therefore an alternative to the entire layer of shells was needed.

The alternative method used for modeling the body ply layer was using resultant beam elements that ran perpendicular to the tread going from one steel bead to the steel bead on the other side. For orientation, one single normal node was used for each U-shaped section of beams. This node was approximately located at the center of the tire. The cross sectional area of the beam was 0.785 mm^2 (a circular cross section with a radius of 0.5 mm), I_{ss} and I_{tt} were 0.049 mm^4, and the shear area was 0.707 mm^2. An elastic material was used for the ply beams, with a density of 1.39E-06 kg/mm^3, a Young's modulus of 5 GPa, and a poison's ratio of 0.28.

Modeling the body plies with beams allowed the different materials to behave somewhat independently on the sidewalls, which affects the vertical compressive strength of the tire. However this method still allows the tire to get lateral stability from the beams. The beams are only tied together in the radial direction by the sidewall rubber.

OTHER CRITICAL MODEL FEATURES

Tire pressure

Pressure in tires can be modeled in different ways. One method of doing this is to define a pressurized control volume, referred to as an airbag in LS-DYNA due to its' developmental history. Another alternate method would be to specify a pressure load on a set of shell elements. One benefit of using a control volume airbag is that as the volume changes, the pressure will also change. This is not the case when a pressure load is defined.

LS-DYNA has several different control volume airbag definitions; two of which have been commonly recommended for tires. One of them is called a simple airbag model. This model allows the user to define the airbag using several thermodynamic and other types of properties. To model the pressure within a tire, the exit area is defined as zero so no air is allowed to leak out of the tire under normal usage.

Another airbag type, called a simple pressure volume model, requires the user to input a coefficient relating the pressure to the relative volume, an option to use a load curve to define this coefficient as varying, an optional load curve for the coefficient to be used during dynamic relaxation (i.e., pre-loading), and a scale factor for the pressure. Because of the pressure-volume relationship of this model, it is the model of choice for this research.

Tire volume

For all airbag types within LS-DYNA, the airbag definition is given to a set of parts that form a closed boundary. For correct behavior, all shell normals must be oriented outwards from the control volume. Further, if a correct volume and behavior is desired, then it is important that the closed boundary be precisely defined. Errors can result when either: (1) not enough parts are used to completely define the enclosed volume, or (2) when parts (or elements) used to define the volume are not actually part of the enclosed volume. A brief discussion of these errors follows, details are provided by Boesch [4].

If not enough parts are used in the definition, LS-DYNA will automatically detect the resulting holes. If holes are detected, they are assumed to be covered by planar surfaces. For a tire, if only the tire parts are used to define the volume, a hole exists where the wheel would normally cover. However, the actually mathematical holes calculated would be the "circular" shaped holes on the outer boundary of the tire. This results in a volume similar to a cylinder; as opposed to the "donut" shape volume of an actual tire. In this case, the volume turns out to be nearly twice the ordinary volume of a tire.

To enclose the volume the wheel was added to the airbag definition. This caused errors in the control volume definition. To fix this, the wheel was divided into two parts; an inner rim (center section or web area) and an outer rim (or hoop). However, problems were observed when inserting this tire into the vehicle model. The volume of the airbag changed depending on the orientation of the tire. The problem ended up being in the definition of the parts in the airbag. In the same manner that including the inner rim in the airbag definition caused problems, including the rim lips in the airbag definition caused problems. Note that the rim lip is outside the control volume. The elements on the rim lip were moved to another part definition. Several subsequent component simulations demonstrated that the orientation of the tire no longer affected the volume of the tire.

Tire vibrations

During development, vibrations in the tire occurred on a regular basis. These vibrations could be caused during inflation of the tire, due to tire rotation and due to tire impacting another object. Often the vibrations would lead to instabilities that were quite interesting; as shown in Figure 5. Numerous techniques for damping these vibrations were attempted. Techniques using airbag damping, part stiffness damping and part mass damping were all somewhat effective in that the tire vibrations could be damped out but these methods resulted in the unwanted side effect of stopping the tire and wheel from rotating.

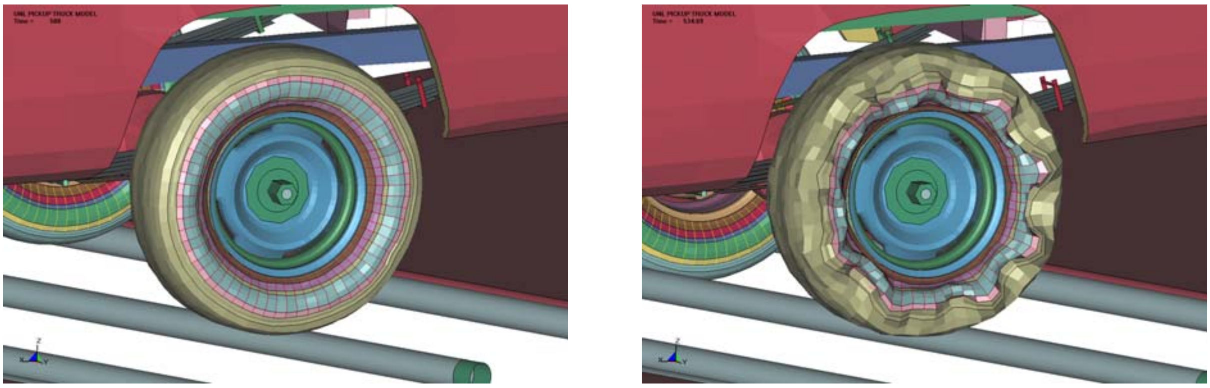

Figure 5. Tire Vibration Problems: Tire at 500 ms and at 535 mm

In order to fix the vibration problems, two items were added to the model: (1) 2^{nd} order objective stress updates (activated in LS-DYNA using control accuracy flags), and (2) relative damping. Relative damping damps motions of a body relative to the movement of a rigid body, in this case being the rim. Using this definition allows motions, such as rotation and translation to occur since it is also occurring to the rim, but the small vibrations inside the rubber material is damped.

VALIDATION

Width expansion due to pressurization and gravity loading

The width of the filled tire was monitored because depending on the material properties, the tire expands more or less during pressurization. Thus, various sidewall-to-sidewall measurements were made on a tire for both un-pressurized and pressurized conditions. Similarly, the tire compresses and expands after it is loaded by the weight of the vehicle through the suspension system. In this case, the changes are not uniform as they are due to pressurization. Results showed that the simulated tire exhibited the correct width expansions due to pressurization and gravity loading.

Compression verification/validation

Compression simulations were performed on the new tire model in both a single-sided compression mode to compare with data obtained from Goodyear, and a double-sided compression mode to compare to laboratory testing performed at UNL. For both testing and simulation, tire pressures were set at 483 kPa (70 psi); the same as used for crash testing.

Single-sided compression

The only data available for single-sided compression testing of the appropriate truck tire was obtained from Goodyear. However, this data was limited to just 35 mm of compression and was simply a linear curve. Nonetheless, for many situations in roadside safety simulations, the tire will only deform about that much; thus, a comparison between test and simulation is important.

Simulation of the single-sided compression test was achieved by placing a rigid, fixed ground below the tire and then prescribing a displacement to the wheel towards the ground. Forces on the ground, as well as the wheel displacement, were recorded in order to compare to test results.

The force versus displacement curve is shown in Figure 6 along with the desired data obtained from Goodyear. The force data compares favorably with the Goodyear data for approximately the first 25 mm, beyond that the force begins to be higher compared to the linear interpolation. At this point in time the pressure inside the tire started to rise. Recall that Goodyear supplied linear data for the first 35 mm of displacement.

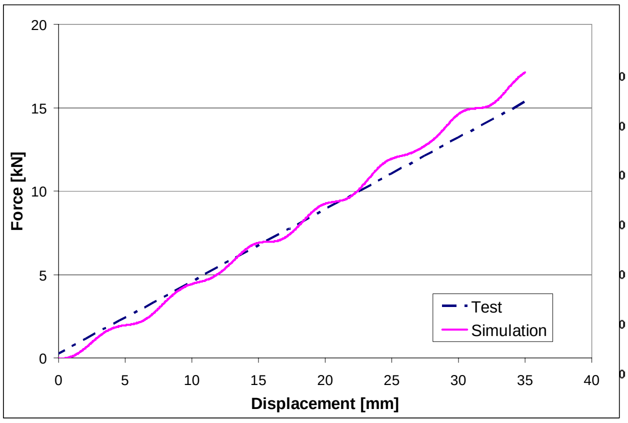

Figure 6. Single-sided compression

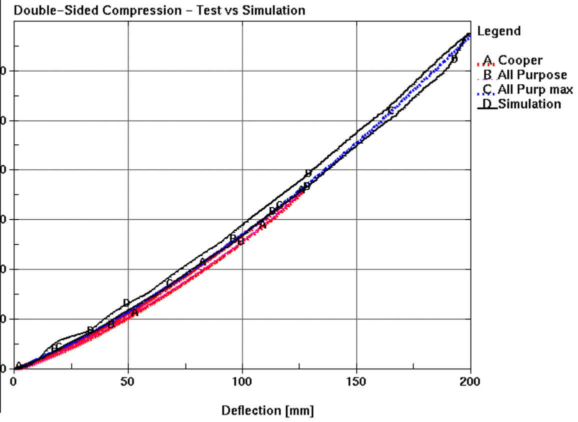

Figure 7. Double-sided compression

Double-sided compression

Laboratory testing was performed on two different tires: one tire was a Cooper Discoverer AST LT245/75R16 120/116N and the other an All Position Radial XRT LT245/75R16 M+S. Tires were mounted onto an eight-lug rim and placed in a press. Raw data was obtained in the form of force versus displacement. Each tire was loaded to 125 mm of total displacement and then unloaded; results are shown in Figure 7. The All Position tire was then loaded to 200mm of deflection in what was considered to be an extreme loading situation. Loads in the All Position tire were nearly identical to the Cooper tire. Additionally, the tests show that a linear approximation for the first part of the displacement of the tire is correct; however the behavior does become non-linear as more displacement occurs.

Simulation of the double-sided compression test was achieved similarly to the single-sided case. Except, in this case, the prescribed motion of the wheel was replaced by a rigid moving wall placed above the tire, moving towards the ground. Images of the double-sided simulation results at 125 mm and 200 mm of displacement are shown in Figure 8, along with a cross sectional view at maximum displacement. The force versus displacement curve for the simulated tire is also shown in Figure 7. The simulation follows the general trend of the desired compression.

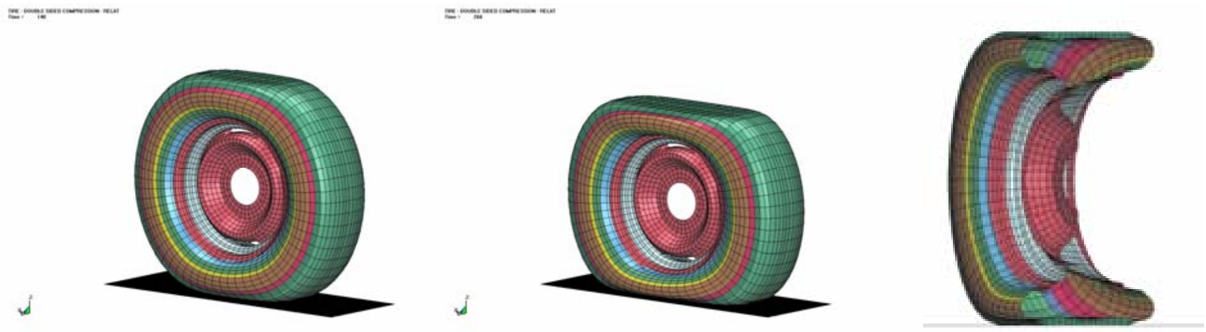

Figure 8. Double-sided compression results

A huge benefit of simulation is that it allows detailed investigate into many areas that may be of interest or concern. As an example, the pressure versus volume within the tire could be useful in determining the onset of tire blow-out. Additional information available would include the energy absorbed by all the individual components that make up the tire; this information helps determine the contributions each component makes in the overall behavior of the tire.

APPLICATIONS

Throughout the development of the new tire model, it was often subjected to several different impact conditions in order to keep focus on its' future use and to uncover any problems due to the modeling techniques used. Final simulations of the tire, once implemented in a truck model, for impacts as a result of driving over a culvert grate, over rocks, and up a curb looked reasonable and qualitatively accurate with old videotape of such scenarios (see Figure 9).

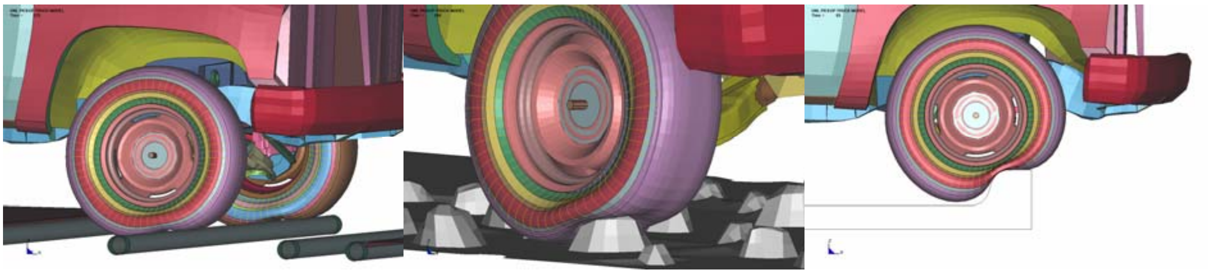

Figure 9. Applications of the new tire model

CONCLUSIONS

A new tire model for impact simulation was developed that included the major components involved in an actual tire. The new model compares very favorably to laboratory data, with respect to force versus displacement, performed at an air pressure of 483 kPa; which is the pressure used in full-scale crash testing. This model not only deforms under impact better than previous models, it also returns to its original shape in what is believed to be a little more accurate way. This provides for more accurate forces being applied to both the impacted device and to the vehicle suspension system; which in turn provides more accurate vehicle kinematics. One of the most critical aspects learned from the modeling effort was the use of relative damping for the tire in order to keep it stable throughout the simulation events. Additionally, other types of damping, including airbag damping, mass damping and stiffness damping, were not effective in controlling undesirable vibrations in the tire.

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REFERENCES

1 W Hall, R P Jones, and J P Mottram, 'Tire Modeling Methodology with the Explicit Finite Element Code LS-DYNA', Tire Science and Technology, Tire Society, Inc. , Akron, OH, Vol. 32, No. 4, October/December 2004, pp. 236-261.

2 M Shiraishi, N Iwasaka, T Saruwatari and K Hayashi, 'Developing a FE-Tire Model Library for Durability and Crash Simulations', 7th International LS-DYNA Users Conference, 2001.

3 F Orengo, M H Ray, C A Plaxico, 'Modeling Tire Blow-Out In Roadside Hardware Simulations Using LS-DYNA', 2003 ASME International Mechanical Engineers Congress, November 15-21, 2003.

4 D A Boesch, Front Suspension and Tire Modeling – For Use In Culvert Grate Impact Simulation, M.S. Thesis, University of Nebraska, Lincoln, NE, 2004.