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MODELING TIRE BLOW-OUT IN ROADSIDE HARDWARE SIMULATIONS USING LS-DYNA

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ABSTRACT

Often when vehicles interact with roadside hardware like guardrails, bridge rails and curbs, the interaction between the roadside hardware and the tire causes the tire to lose its air seal and "blow-out". Once the seal between the rim and rubber tire is lost, the tire deflates. The behavior of the deflated tire is much different than the behavior of an inflated tire such that when this behavior is observed in real world crashes or in full-scale crash tests, the vehicle kinematics are strongly coupled to the behavior of the deflated tire. Accounting for this behavior in LS-DYNA models is crucial in many types of roadside hardware simulations since the forces generated by the deflated tire often introduce instability into the vehicle that can cause rollover or spinout. This paper will present a method for accounting for tire deflation during LS-DYNA simulations and will present examples of the use of this type of improved model.

INTRODUCTION

Finite element models of pneumatic tires have been developed by others to investigate stresses and deformations in order to evaluate the performance of commercial tires [1]. The objective of such analyses has lead, necessarily, to very sophisticated models that take into account ply orientation, ply overlapping and mechanical properties of different layers of the composite structure of the tire.

This approach is necessary and practical if the objective of the study is the design and analysis of the tire itself ignoring the many other components of the vehicle. On the other hand, this approach becomes computationally inefficient for analyses involving large-scale overall response of the vehicle during impact with other structures, such as roadside hardware, where the tires are only one aspect of many intricate parts that must be modeled.

In most cases, the simulation of vehicle impact into roadside hardware has been approached using relatively simple models, where the particular aspects of the tire structure were not reproduced. Typically, the tire has been modeled with isotropic membrane elements (thin shells) which may be effective when the dynamics of the tire are negligible. A more realistic model is needed when the tire interacts significantly with other elements of the roadside environment, for instance, in those conditions where the tire directly plays an important role in the vehicle kinematics and stability.

BASICS OF TIRE MECHANICS

A basic understanding of pneumatic tire mechanics is required in order to develop a simplified model that produces realistic behavior of the tire under the types of loading to which the tire will be subjected. The most common tire construction technology in use today is the radial construction, thus our attention will be focused on this type of pneumatic tires.

The tire plays an important role in the vehicle's dynamics since it must absorb road irregularities while providing a vibration-free motion on smooth roads. There are two conflicting requirements: flexibility is needed to absorb road bumps, while the need for a vibration-free ride requires a rigid round wheel. This conflict is further aggravated by the fact that a pneumatic tire is a doubly curved surface, geometrically a non-developable surface that must be deformed to provide a contact area on flat pavement.

Clark [1] identifies some of the basic requirements for the structure of a pneumatic tire:

- No appreciable change of size upon inflation,
- Ability to envelop obstacles without sustaining damage,
- Ability of part of this envelope to deform from a surface of double curvature to a plane surface, and
- Enough rigidity to develop substantial forces in any direction.

Inflated shell structures, having a surface of double curvature made solely of a single isotropic material, have always failed to meet the requirements stated above.

A pneumatic tire has several structural elements, the most important of which is the carcass, made up of many flexible filaments that have a high Young's modulus (e.g., synthetic polymer fibers or fine hard drawn steel) embedded in a matrix of low modulus polymeric material like natural or synthetic rubber. In order to build a demountable tire carcass that can be fitted on a wheel rim, the layers of high modulus filaments are wrapped around the bead coils made of strands of hard drawn steel wire.

Tension in the carcass cords is set up by inflation pressure that is resisted by the tension developed in the steel wire bead coils. The rubber that encases the steel wire coils is pressed against the rim by the inflation pressure; this reaction between rim flanges and tire bead enables traction and braking forces to be transmitted by friction.

Demounting of a conventional tire is made possible by a well in the rim base, also known as drop center. The shape of the rim is usually tapered with a five degree angle to the flange to pretension the tire bead upon inflation.

The third important structural element of the tire is the tread, the only part of the tire that contacts the road surface. The tread must be made of abrasion-resistant materials and must provide high friction with the road in order to transfer the traction, cornering and braking forces. In belted radial tires, the belt is essential to the functioning of the tire. Without it the radial ply of the carcass can become unstable.

MECHANISM OF LOAD CARRYING: INFINITE FLEXIBLE MEMBRANE

Consider an inflated toroidal structure made of an infinite flexible membrane such as a toy balloon mounted on a rigid rim. The air pressure puts the membrane in tension as it assumes a shape determined by equilibrium and compatibility conditions. The membrane tension is resisted by a reaction at the edge of the rim. If a flat plate is pressed against the membrane while the structure is supported by the rim, a reaction will develop between the membrane and the plate, proportional to the product of the area of contact and inflation pressure.

The question arises as to how the reaction is transferred to the rim. Considering that the air pressure is constant everywhere on the surface of the rim and that the surface over which the pressure acts is also constant, the resultant of the air pressure on the rim is zero whether the tire is loaded or not.

These simple considerations highlight the fact that the mechanism of load reaction from tire-rim interface is substantially different from the mechanism between the tire and the road surface.

A closer look at the geometry of the deformed shape of the tire shows that the curvature of the membrane side walls is greater in the region between the plate and the rim. Hence, because of the greater curvature, the membrane stresses in the region are lower than elsewhere on the membrane wall, since the tension is equal to the product of the inside pressure and the radius of curvature. Further, the local distortion of the membrane causes an increase of the angle between the side wall membrane and the rim cross section; this causes the decrease of the radially outward component of the tension in the membrane. Figures 1 and 2 illustrate this behavior.

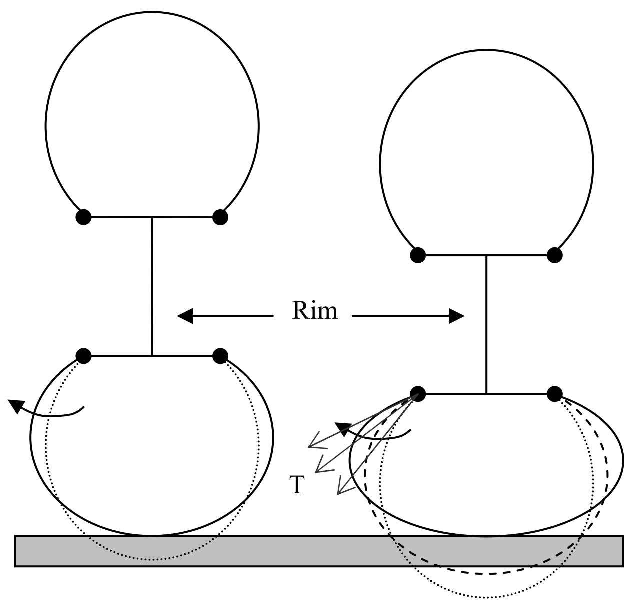


Figure 1: The deflection of the sidewalls reduces the radially outward components of the membrane.

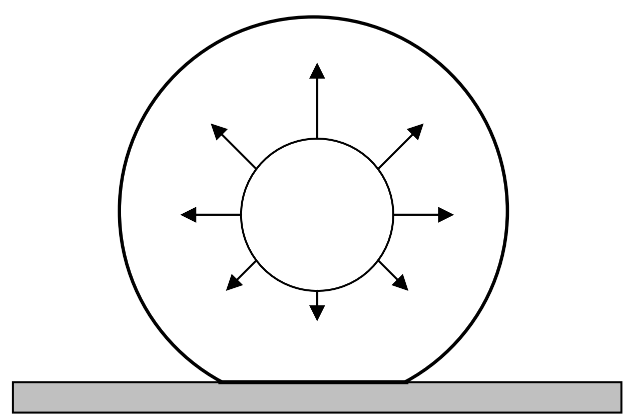


Figure 2: Distribution of the radially outward component of the membrane tension along the rim edge.

The net effect due to the reduced tension in the sidewalls and the reduction of the radially outward component in the region of the contact is that the rim "hangs" in the tension of the undeflected region. This system of load transmission is analogous to the one present in a spoked wheel where the hub hangs by the spokes in tension on the top of the wheel. Figure 3 illustrates the difference between a solid tire and a pneumatic tire in the load transfer mechanism.

Usually a tire has a considerable bending stiffness that supports a significant part of the load. Bending stresses will be present in the tire's walls especially where the radius of curvature decreases. High bending stresses will be present around the edge of the contact surface with the ground. This will lead to a non-uniform contact pressure distribution between the tire and the ground.

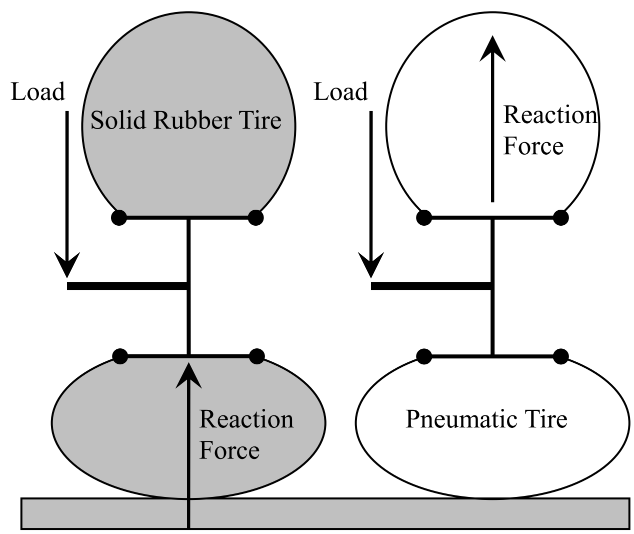


Figure 3: Load carrying mechanism comparison between a solid and an inflated tire.

MECHANISM OF LOAD CARRYING: TIRE STRUCTURE

When a tire is inflated, the cords in the reinforced rubber are in tension and the tire assumes a shape compatible with equilibrium and compatibility conditions. When the tire is loaded against a planar surface the rubber tread is compressed and the tire assumes a flat shape in the contact patch; if there were no tread, the tire inside surface would be flat. In this case, the tensions in the cords in the flat area are no longer related to the inflation pressure since the curvature is zero. This means that the tension in the cords is primarily transmitted from the adjacent free wall of the tire and locally modified around the edges due to the bending stresses.

In a commercial tire the bending stiffness of the different plies and the changing thickness of the rubber in the cross section cause the actual contact pressure with the roadway to be greater than the actual inflation pressure and to vary in the x and y directions in the contact patch. Consequently, the reaction load of the tire is greater than the product of the inflation pressure and the area of contact.

Clark [1] points out that those processes of load carrying seem to be linearly additive. The load transfer mechanism can be modeled as two different mechanisms acting in parallel. The first is analogous to the behavior of the infinite flexible membrane, where in the bottom part the tension in the cords is reduced and the local deformation causes a reduction of the radially outward component of the tension.

The second mechanism involves the tread. The tread can be thought of as a uniform belt around the whole periphery of the tire. This belt is tensioned under the inflation pressure, since it is curved except in the area where the pressure forces are transferred to the ground by compression without producing any resultant pressure on the belt (i.e., belt in this area has zero curvature). As a consequence, the absence of reaction forces in this area of the belt causes a force on the top sector of the tire to be unbalanced as shown in Figure 4. This resultant force pulls the bead coils against the base of the wheel rim, thus transmitting an upward force to the rim. Both mechanisms lead to the same type of load transfer mechanism with the rim suspended because of the tension in the shoulders of the undeformed upper part.

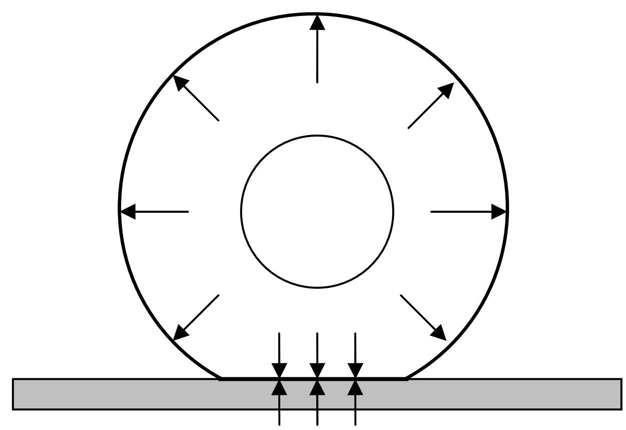


Figure 4: Load transfer mechanism from ground to wheel by effects of inflation.

ISOTROPIC SHELL TORUS MODELING TECHNIQUE

A tire model composed of isotropic shells with uniform thickness is an attractive modeling approach since it is simple and computationally efficient. Unfortunately, this modeling technique leads to very unrealistic tire behavior especially in cases where the tire undergoes large deformations. A simple isotropic shell model will perform adequately only if the inflation pressure is very high and the thicknesses of the side walls, as well as the thickness of the tread, are unrealistically thin. In such a simple model the bending stiffness becomes negligible and the tire works like an inflated balloon as described previously. Often the shells have to be so thin that the tire starts expanding, thereby increasing the external dimensions.

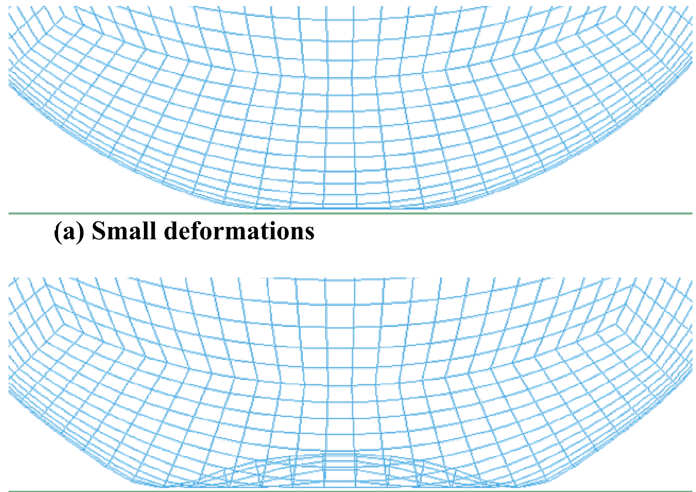
When the pressure is reduced and a more realistic thickness of the tire sidewall and tread is modeled, the elastic response of a double curvature surface becomes important.

Under small loads the tire model will behave linearly as it is loaded against the ground and its response will be somewhat overly stiff. As the load increases, the shell surface will begin reversing itself inside the tire assuming a lower deformation energy state. A simple finite element model of a loaded hemispherical shell as shown in Figure 5 illustrates this behavior, which is common for elastic panels with double curvature. Figure 5b shows the typical behavior of isotropic double curvature shell surfaces for large deformations. In the footprint area the deformed surface changes its concavity assuming a low energy deformation state. The deformed shape reduces the net footprint area. This behavior is not consistent with the real tire deformation.

LS-DYNA supports membrane elements that have no out-of-plane bending stiffness. The use of this type of element solves the problem of dimensional stability of the tire under inflation pressure, but, since it has no out-of-plane stiffness, the membrane is computationally unstable, especially where the curvature of the surface is small. Furthermore, when the membrane element undergoes large deformations, unrealistic pleats form where the flat geometry creates a possible hinge line. Since membrane element formulation does not account for bending, these large bending deformations are not associated with any deformation energy. The folding of the elements also causes mesh tangling that leads to permanent deformation of the tire (Figure 6). This behavior will cause numerical instabilities in the contact algorithms and will eventually terminate the run. To reduce the number of these tangled pleats, a very refined mesh is required, making this modeling approach impractical.

Shell elements with a reduced bending stiffness could be used to avoid the formation of hinge lines. Many static finite elements codes support this type of element. To our knowledge, however, LS-DYNA does not include this type of element in its element library. One possible solution is to superimpose two sets of elements: one layer of membrane elements and coincident layer of shell elements with both layers of elements sharing the same nodes. This will allow the analyst to impose different properties governing the membrane behavior of the model and the bending behavior. Of course this solution will result in twice the number of elements but it could lead to a better performing model than one using only shell or membrane elements.

Some preliminary analyses with this type of superimposed element model proved somewhat successful. However, unrealistic deformations of the tire in the area of contact (e.g., the formation of an "inverted hump" in the tire tread in the region of contact with the ground surface) suggested that the model needed further improvement in order to accommodate the type of loading that the tire model would be subjected to in non-tracking impacts.



(a) Small deformations

(b) Large deformations

Figure 5: Double curvature shell surface (Hemisphere) compressed against a planar surface.

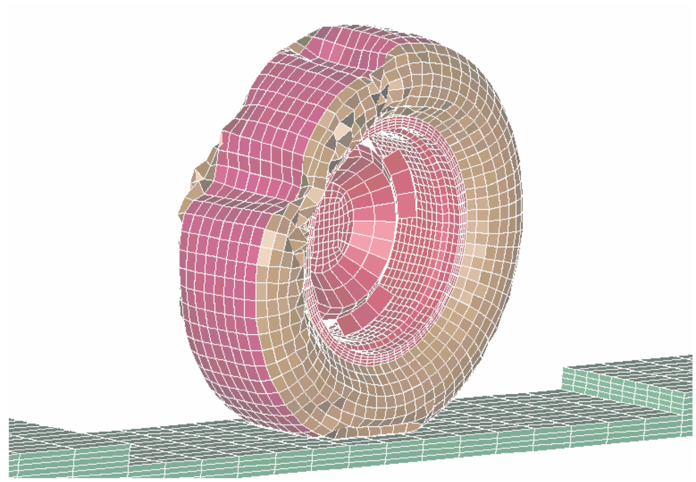


Figure 6: Membrane tire - permanent deformation due to mesh tangling.

ANISOTROPIC MODELLING TECHNIQUIE

The critical parts of the tire structure that affect the overall tire mechanics tire must be incorporated in the model.
These are:

- Bead coils,
- Radial fibers,
- Rubber sidewall,
- Under belt radial fibers,
- Steel belt, and
- Tread.

In addition to the structural elements, some non-structural elements were also included in the model. For example, a membrane between the two bead coils was introduced to describe a closed volume for defining an inflating air pressure. The rim also plays an important role since its geometry is the contact surface for the bead coils.

Bead Coils

The bead coils are generally made of hard drawn steel cable. This structural element can be effectively modeled using two rings of beam elements. In order to best transmit contact forces between the tire bead coils and the wheel rim, the bead coils were modeled using two rings of shell elements with elastic properties and a relatively high Young's modulus (100 MPa).

Radial Reinforcement

The radial reinforcement in the shoulders was modeled using beam elements with properties of steel equivalent to a distributed layer of radial steel fibers. The same approach was used to model the under-belt layers of radial plies. The element formulation adopted was the Belytschko-Schwer beam element.

Figure 7 shows the model of the radial reinforcements and of the bead coils.

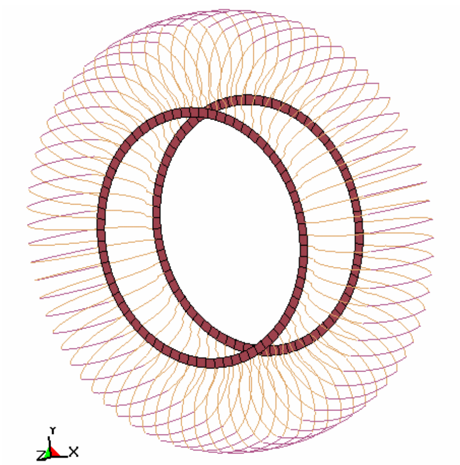


Figure 7: Finite element model of the radial reinforcement fibers and of the bead coils.

Shoulder Rubber Matrix

All the radial beams were interconnected with a set of Belytschko-Tsay shell elements with warping stiffness option turned on in LS-DYNA with the properties of rubber. The material properties were found in literature [1] and represent common values used for the shoulder rubber in tire manufacturing (E=4.5 MPa, υ=.49, ρ=1.1 kg/m^3). This element formulation proved to be very efficient in this complex application where high deformations, element warping, and a rotating reference frame provide a critical test for element stability.

Steel Belt

The steel belts were modeled with Belytschko-Tsay shell elements with uniform thickness and with properties of steel.

Tread

The geometry of the tread plays an important role in the performance and stability behavior of the model. Its primary role is to uniformly distribute the pressure load from the contact with the roadway to the belt and to the under-belt carcass reinforcing fibers to prevent the formation of an "inverted hump" that could result in local implosion of the tire periphery in the contact area. This requires the geometry of the external surface that undergoes contact with the roadway to be different from the belt geometry.

Thick-shell elements or solid elements should be used to accurately model the variable thickness in the tread geometry. Under-integrated thick-shell elements were used successfully in static loading simulations and for simulations where the tires roll on flat and smooth surfaces. Unfortunately, in a verification simulation involving the tire model rolling over a series of "pot-holes", hourglass modes were excited, causing instability of the analysis.

Since the tread rubber has a low Young's modulus relative to its mass density, it is feasible to model the tread with solid hexahedronal elements (i.e., even though the element dimensions would be relatively small, the critical time-step for analysis is not reduced). For computational efficiency, the tire tread was meshed using one point under-integrated elements with three elements through the thickness to avoid hourglass modes.

The use of these solid under-integrated elements coupled with stiffness hourglass control suppressed the hourglass modes without affecting the time step, resulting in a computationally efficient model. Due to the low modulus of the rubber tread, the automatic-single-surface contact with interior contact flag turned on was necessary to prevent negative volume of elements that may collapse during impact with the ground.

Figure 8 shows the complete model of the tire's structural parts.

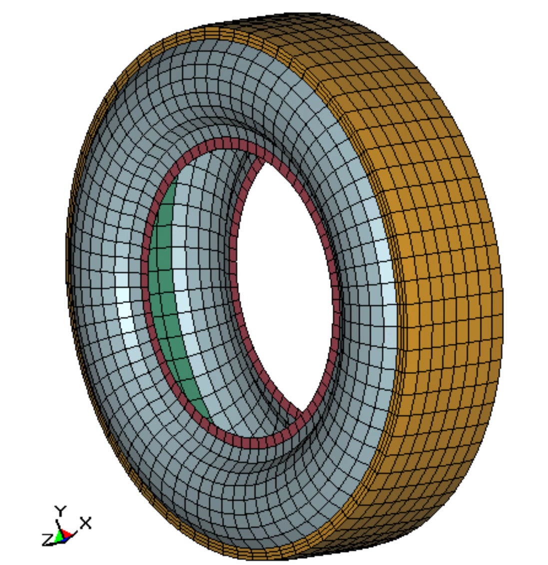


Figure 8: Model of all structural parts in the tire structures.

“Virtual” Elements

To inflate the tire with a gas under pressure an airbag must be defined. LS-DYNA defines this kind of simple pressure airbag only on a geometrically closed volume. For this reason a membrane has to be present between the bead coils to have a toroidal closed geometry. This membrane must be extremely flexible since it has no structural purpose. However, since it is involved in contact with the rim bed, its thickness must be reasonable to avoid contact instabilities (Figure 9).

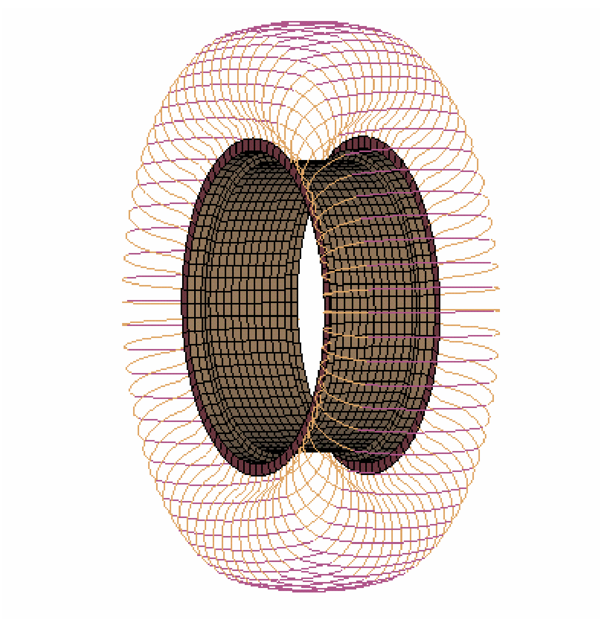


Figure 9: Tire model with the “virtual membrane” used to define a closed volume of the air-bag definition in LS-DYNA.

Material densities were, where necessary, mass-scaled to achieve the correct overall weight of the wheel and to maintain a time step greater than 3.5 microseconds.

MODELING TIRE DEBEDDING

When a vehicle leaves the roadway it is likely that the tires will interact with objects on the roadside such as curbs, guardrail posts, and other roadside appurtenances that may lead to deflation of the tire. Tire deflation in these cases is due to transverse overloading of the side shoulder of the tire that causes the bead coil to separate from the flange of the rim and slide toward the well in the rim base. When the coil falls off the edge of the well, the air seal is immediately lost and the tire deflates completely.

To model this failure mode an imaginary disk was included in the model attached to the rim base near the drop center curbside edge. This surface is used as a sensing switch, exploiting the functionality of the TERMINATION-_CONTACT card in LS-DYNA. This modeling option in LS-DYNA makes it possible to interrupt the analysis when the nodes on this virtual surface contact the bead coils. After the simulation is interrupted, a simple restart file can be created which allows the analyst to reset the inside pressure of the tire to zero and restart the simulation at the same point in time with the tire deflated.

In order for this modeling technique to work, the geometry of the wheel rim that interacts with the tire must be modeled accurately. Ignoring the geometry of the rim can lead to an overly stiff model. For example, if the rim base is modeled as a flat cylindrical surface, then as the bead coil is pushed inward during impact with a curb, the bead coil will tighten around the rim because of the non-circumferential displacement caused by friction. This leads to a self-locking mechanism that completely prevents any further movement of the bead coil. This self-locking mechanism is similar to the one that occurs when a rope ring is tightened around a pole; the rope can slide along the pole when the rope is not under tension but will lock when the rope is pulled tangentially along the pole. Thus, it is important for the tapered part of the rim base and the center drop to be accurately modeled if a debedding failure of the tire is of interest in the analysis. Figure 10 shows the finite element model of the rim and the sensing witch surface of the tire debedding.

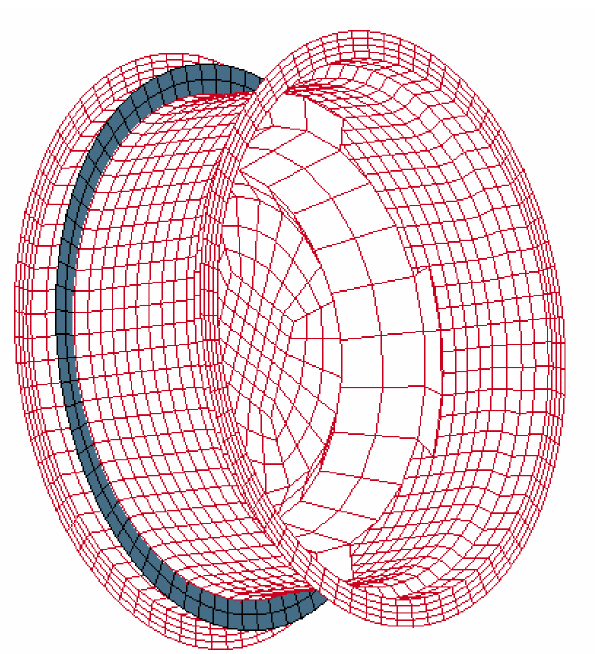


Figure 10: Model of the rim with the center well and the debedding sensor surface (fill color).

EXPERIMENT DESCRIPTIONS

Two experiments were conducted on the spare tire of a 1995 C2500 Chevrolet pickup truck mounting Uniroyal Laredo Lt 245/75 R16 tires in order to verify the utility of the model.

The first test, called a "debedding test," was carried out to calibrate the debedding sensing switch membrane. The entire wheel was mounted on an INSTRON 8803 testing machine. The wheel was bolted to a steel hub clamped to the bottom of the testing machine (Figure 11). A symmetrical “side pusher” was used to “blow out” the tire (Figure 12). For safety reasons and accuracy the test was conducted in displacement controlled mode with a compression speed of 25.4 mm per minute. Under this testing condition the seal between the rim and the tire was gently broken and the tire could gently “blow-out” without an "explosion."

The tire under testing conditions was inflated to 0.24 MPa (35 psi). At 78 mm the tire began to deflate and at 82 mm the seal was completely broken (Figure 13).

The deflection of the side pusher was neglected since the magnitude of this was negligible with respect to the magnitude of the deflection of the tire shoulder. Wood was used for the contact interface to avoid damaging the tire sidewalls by pinching the rubber.

The second test was intended to measure the global stiffness of a pneumatic wheel assembly with respect to a vertical displacement applied to the rim. The test was performed using the Instron 8803 testing machine. The rim was bolted to a steel hub clamped in the vise of the testing machine as shown in Figure 14. The tire was compressed against a rigid surface made of steel. The test was conducted in displacement control up to 13.345 kN load, which is greater than twice the static load of the truck.

Figure 11: Debedding test setup and close up to the fixture and bolts.

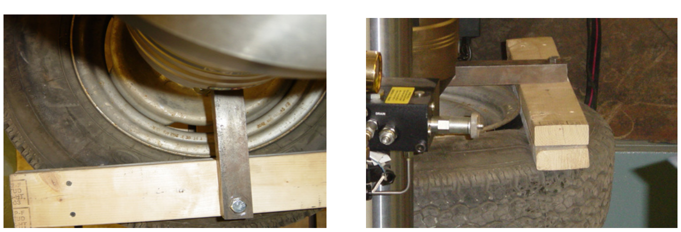


Figure 12: Vertical top view of the pusher and tire under testing.

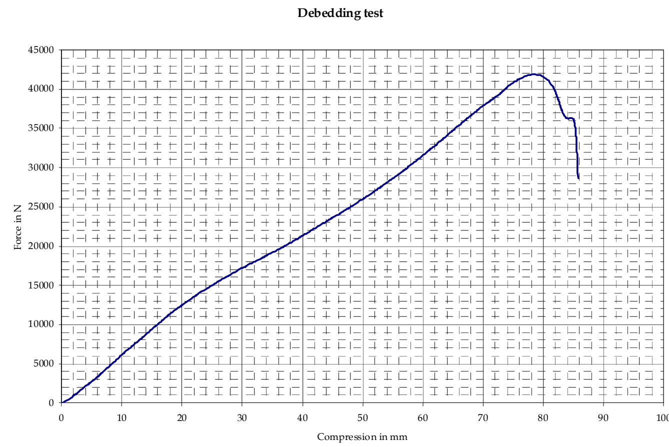


Figure 13: Force versus compression curve measured by the load cell of the Instron testing machine.

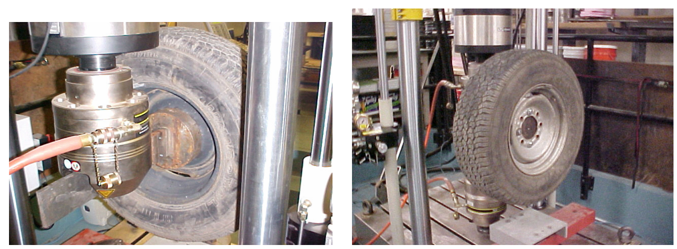


Figure 14: Steel hub and fixture used in the compression test, and test set-up.

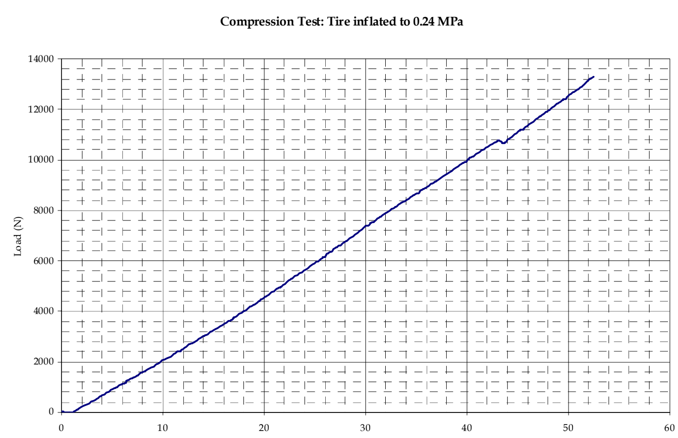


Figure 15: Load-deflection curve for the compression test.

COMPARISONS BETWEEN THE TESTS AND THE NUMERICAL SIMULATIONS

For the debedding test, the numerical model can be easily calibrated so the detection of the “blow-out” condition can be matched almost exactly with the experiment. The “blow-out” condition is based on the deflection of the tire bead coil with respect to the rim flanges and the center well.

Regarding the tire compression test, the simulation results are very close to the test result as shown in Figure 16 (for a deflection range between 0 and 32 mm), where the errors in the energy are negligible. Deflections of a correctly inflated tire rolling on a road surface are expected to be in that range.

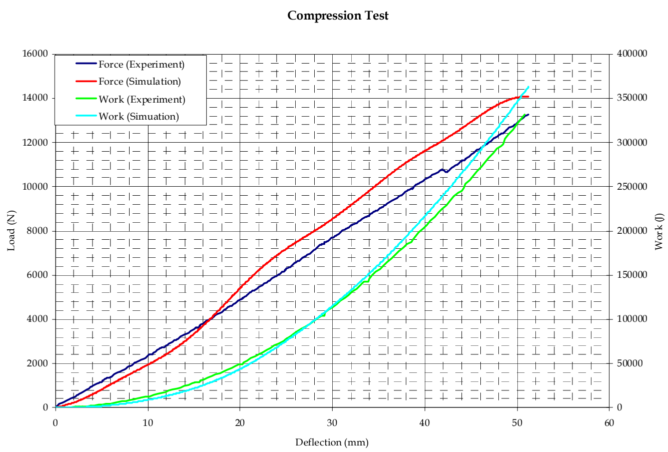


Figure 16: Comparison of the experimental results with the results obtained from the numerical simulation with LS-DYNA.

The deformed shape computed in the simulation compares very well to the deformation of the tire in the test as shown in Figure 18.

NUMERICAL STABILITY TEST

To test the numerical stability of the model, the tire model was "rolled" over a series of "pot-holes" made from a series of unequally spaced steps. The rim was loaded against the roadway with a vertical load equal to 7357.5 N and accelerated by a constant force of 9810 N. (Figure 19) This simple simulation is believed to be a severe testing simulation for any numerical instability since the tire undergoes large deformations as it compressed against the leading edges of the steps while the reference frame rotates with a continuously changing angular velocity.

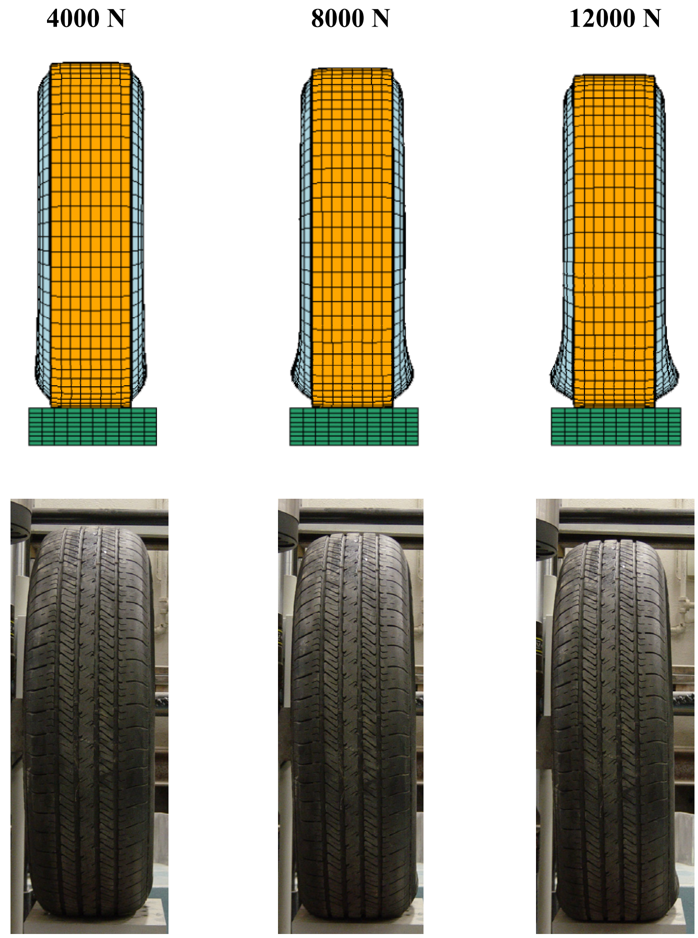


Figure 17: Comparison between the test and the simulation of the deformed shape at different loads.

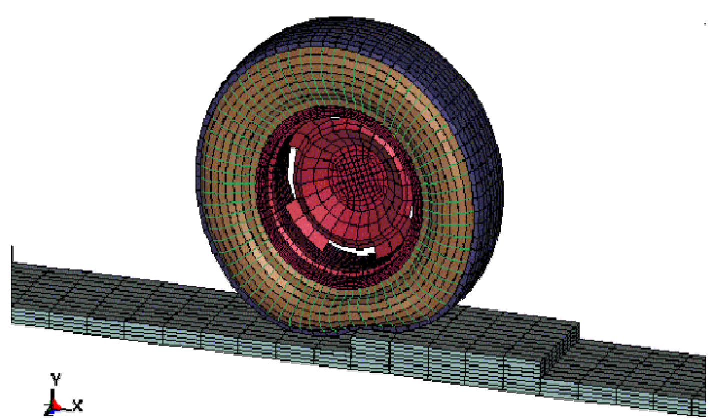
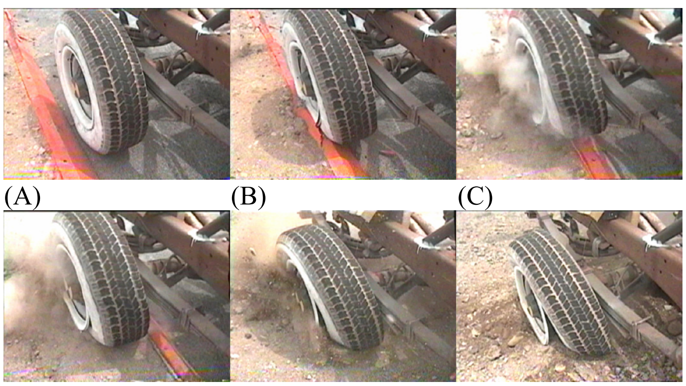


Figure 18: Image of the tire rolling over one of many steps.

FULL SCALE TESTS AND COMPARISON WITH LS-DYNA

A full-scale test program was conducted to study the interaction between tire and curb in non-tracking impact scenarios. The results of those tests indicated that the tire is most likely to fail due to the debedding of the bead coils rather than rupture of the tire structure. Of the sixteen tests that were conducted, four tests resulted in tire debedding and blow-out. The deflated tire in those cases did not suffer any major damage to the tire structure and the tires were simply reinflated and used in subsequent tests. Figure 19 shows a sequence of photographs of the tire failure event in one of the tests; frame C captures the “blow-out” of the tire and the tire’s sudden deflation. From the analysis of video frames it was estimated that the tire was completely deflated in less than 60 milliseconds after initial impact with the curb.



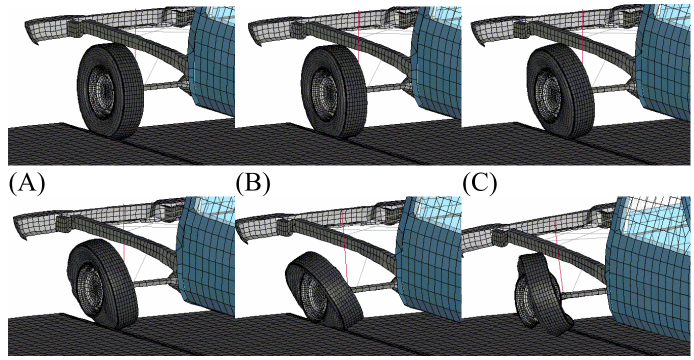
(A) (B) (C)

(D) (E) (F)

Figure 19: Sequence showing a tire debedding from full-scale test 603XD0135A.

The tire model developed and presented in this paper was implemented into the NCAC Chevrolet C2500 pickup model version 9 [4] [5] including the subsequent modification made on the suspension by Tiso [6]. The vehicle model was then used in analyses of non-tracking impacts into various roadside curbs to study the curb-tire interaction and vehicle stability [7]. In this type of analysis, the tire model plays a critical role in the overall kinematics of the vehicle and therefore the behavior of the tire must be properly accounted for.

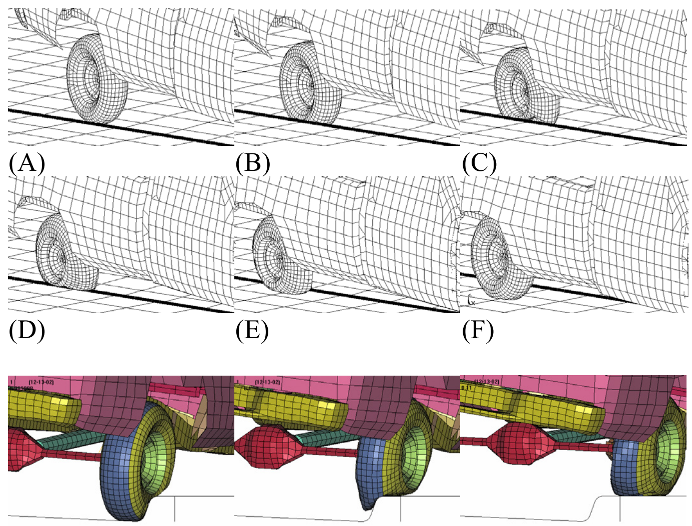
Figure 20 shows the results of an LS-DYNA simulation of the truck model impacting a four-inch sloped curve (i.e. very similar to the test shown in Figure 19) which illustrate the failure sequence of the tire during impact. Frame C captures the “blow out” of the tire and the following frames show the behavior of the deflated tire as it interacts with the curb and the ground surface. The behavior of the tire in the simulation (Figure 20) compares very well to the behavior of the tire in the physical test (Figure 19).



(A) (B) (C)

(D) (E) (F)

Figure 20: Sequence showing an LS-DYNA simulation result of a tire debedding with the new tire model.



(A) (B) (C)

(D) (E) (F)

(G) (H) (I)

Figure 21: Sequence showing the tire finite element model performances in non-tracking impacts used in the original and WPI-modified NCAC C2500 Version 9 (reduced).

For comparative purposes, Figure 21 illustrates the behavior of the tires modeled with thin isotropic shell elements (i.e., as is typical in many reduced-element vehicle models) for the case of the pickup model impacting a six-inch sloped curb. In this particular model tire deflation is not accounted for. As the tire compresses against the curb, the mesh of the tire forms to the shape of the curb. Then, as the tire proceeds to traverse the backfill area behind the curb, it springs back resuming its original shape resulting in a roll displacement of the vehicle that counters any initial adverse roll angles caused by the initial impact with the curb. Consequently, the model erroneously predicts that rollover is highly unlikely. Frames (G), (H) and (I) clearly show the unrealistic behavior discussed above.

FURTHER IMPROVEMENTS

From the computer analyses it was determined that the pressure inside the tire did not vary significantly during normal rolling. Therefore a simpler approach to modeling the air pressure inside the tire was later adopted which involved removing the air bag definition and all the "virtual parts" (i.e. parts needed to define a closed volume for the air bag) and simply applying a constant pressure to the inside surface of the tire elements. This approach led to a reduction in analysis time and it also provided a means for the analyst to control the deflation rate of the tire since the pressure is defined using a pressure-versus-time curve in LS-DYNA.

The computational performance of the pneumatic tire model was strongly affected by the contact algorithms used. In a preliminary analysis the required computation time was considered unacceptable for general use of the model. After careful debugging of the model, it was determined that the contact algorithm that was being used to compute contact forces between the tire's bead coils and the wheel rim was requiring over 65% of the total CPU time in the analysis. This contact was originally defined using the AUTOMATIC_GENERAL contact option in LS-DYNA and was subsequently replaced with the AUTOMATIC_SINGLE_SURFACE contact option with the parameters SOFT=2 and EDGE=1 in order to activate the shell edge-to-edge contact algorithm. This simple change reduced the computation time by approximately one-third compared to the initial run and did not degrade the performance of the model. It is believed that the model's efficiency could be further improved by conducting a contact optimization study.

Two other important failure modes of pneumatic tire are possible during vehicle impact against roadside safety hardware (e.g., guardrails and median barriers) and should be included in future models: 1) the tire pinching against the flange of the rim and 2) rupture of the tire due to impact with an object such as a guardrail post.

CONCLUSIONS

The generic tire modeling methodology developed in this research is an effective means of modeling pneumatic tires for use in impact analyses with roadside hardware simulations. The simplicity of the tire model makes it relatively easy to maintain and to implement into existing vehicle models while not compromising the computational efficiency of the reduced-element models that are widely used in roadside safety research. However, further improvements to the model may be necessary if rupture of the tire structure is likely (e.g., tire snagging on guardrail posts during impact with guardrail system).

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