Abaqus Technology Brief

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An Integrated Approach for Transient Rolling of Tires

Summary

A wide range of loading conditions must be considered in the design of a tire. Computational simulations of a quasi-static, steady-state dynamic and nonlinear transient dynamic nature must be completed. In addition, the complexity and size of typical tire models highlight the need for efficient solution techniques.

Abaqus/Standard, which uses an implicit solution method, can be used to simulate rim mounting, inflation, and footprint loading. The footprint loading step is typically followed by a rolling analysis. The Abaqus/Standard steady-state transport capability provides an efficient solution method for the steady rolling case, as the cost of the analysis is independent of the rolling speed of the tire. With this feature Abaqus/Standard can model the tire rolling on a flat road or a drum, as is frequently performed experimentally.

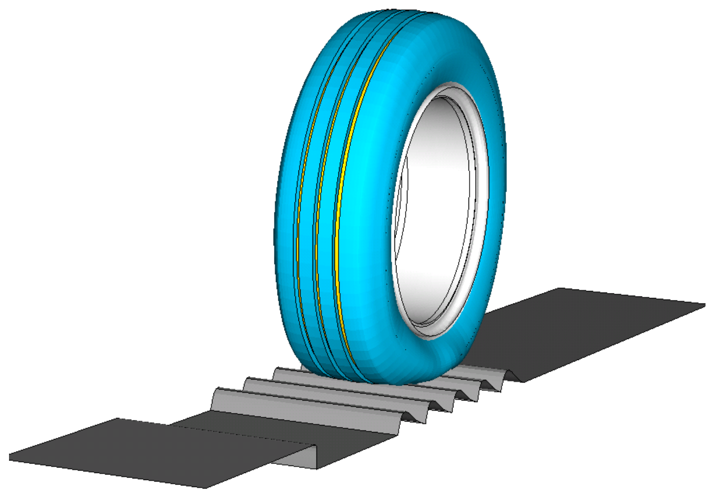
Adverse road conditions may cause transient dynamic loading events. Abaqus/Explicit is ideally suited for simulating rapid loading situations such as collision with obstacles, traversal of holes or bumps, effects of vehicle acceleration, etc. The solution from the steady-state transport analysis obtained in Abaqus/Standard can be used as the initial condition for the Abaqus/Explicit analysis. The long run times that would be required using explicit time integration to apply the quasi-static preloading and to accelerate the tire to the desired traveling velocity are, thus, avoided.

Close integration between Abaqus/Standard and Abaqus/Explicit facilitates a streamlined total analysis approach, one in which the analysis proceeds progressively in stages. Each loading stage examines an important design load while also serving to provide the base state for the next loading stage.

Introduction and Analysis Approach

Tire analysis is a challenging task. The geometry and modeling requirements are complex, the loading conditions involve complicated contact conditions, and the nature of the loading ranges from quasi-static to highly dynamic.

Accurate modeling of tires requires the use of hyperelastic material models for the rubber matrix and precisely positioned and defined reinforcement. Users may choose to characterize the strain energy potential of the hyperelastic material with one of several well-known mathematical forms or directly from available test data.



Key ABAQUS Features

- Ability to choose from wide selection of hyperelastic constitutive models.
- Ability to define reinforcement independent of tire geometry, significantly reducing meshing efforts.
- Ability to transfer geometry and analysis results from an axisymmetric model to a three-dimensional model.
- Ability to efficiently compute the steady-state rolling response at a given speed.
- Ability to import results from the steady-state rolling analysis into ABAQUS/Explicit to serve as the initial or base state for the transient rolling analysis.
- Ability to efficiently model transient dynamics for large models using ABAQUS/Explicit.

The definition of reinforcing cords is simplified by allowing the geometry of the reinforcement to be independent of the material carrying the reinforcement. The meshing of the cords is, thus, independent of the meshing of the rubber matrix. Abaqus offers surface elements to carry the reinforcement. Surface elements do not have any structural properties and are used only to define the geometry for the cords. The surface elements are embedded in the solid elements used to model the rubber matrix. Abaqus will create the appropriate constraints between the nodes of the matrix material mesh and the nodes of the surface element mesh. Using embedded elements can prevent potential meshing problems such as very small elements between layers of reinforcement.

The transient rolling analysis is conducted as a sequence of loading steps. The analysis sequence is progressive in that the current step requires completion of the previous step. The loading sequence begins by mounting the tire on the rim. It is inflated in the second stage and loaded by the weight of the vehicle in the third, with the tire in contact with the road to determine the static footprint. The fourth stage determines the state of the tire when rolling at a steady speed; force and moment results at the axle can also be determined. The steady-state rolling condition is then used as the initial state of the fifth stage, in which the target transient rolling analysis is completed. While the fifth stage is the final objective of the analysis sequence, each stage provides valuable information to the tire designer.

Structural symmetry is used where possible to reduce model size and, hence, maximize computational efficiency. During the mounting and inflation stages, a half-symmetric axisymmetric model is used. The symmetric model generation capability is used to generate a partial three-dimensional model for the footprint analysis and a full three-dimensional model for the steady-state and transient rolling stages.

The rim mounting, inflation, and footprint analyses are inherently quasi-static. As such they are most efficiently solved using the implicit solution technique available in Abaqus/Standard. The steady-state rolling analysis is conducted using a mixed Eulerian/Lagrangian approach in Abaqus/Standard. This capability allows the steady-state solution to be determined without the computational expense associated with an explicit solution procedure. In addition, the computational effort is independent of the steady rolling speed. The results of this fourth modeling stage are used as the base state for the final, transient rolling simulation. In this stage the tire will traverse a series of bumps while rolling at speed. The fifth stage, which involves nonlinear transient dynamics, will be analyzed using Abaqus/Explicit.

The following sections describe the details of each loading stage and present some representative results. Figure 1 diagrams the overall approach to analyzing the transient rolling of tires in Abaqus.

Axisymmetric Rim Mounting and Inflation

The axisymmetric cross-section of the tire is used to perform the rim mounting and inflation analyses. At this stage the symmetry of the tire is exploited and only half the tire cross-section is modeled, as shown in Figure 2. Symmetry boundary conditions are applied at the midplane.

For the model under consideration the layers of the belt cords under the tread are used in pairs, with the orientation of the cords symmetrical about the direction of travel. That is, if one ply of the pair is oriented at θ° with respect to the direction of travel, the other member of the pair is oriented at −θ°. The cord plies must be offset through the thickness of the tire; they cannot occupy the same space. Therefore, coupling is introduced between the extensional and in-plane shear deformation of the structure. When the tire is deformed, some amount of twist or relative rotation of the belt plies about the axle occurs. Special axisymmetric elements that allow twist about the circumferential direction as an independent degree of freedom must be used.

The cord reinforcement is characterized completely by the cross-sectional area of each fiber, the spacing between the fibers, and the material properties and orientations of the fibers. Figure 3 and Figure 4 display three- and two-dimensional views of the reinforcement configuration, respectively.

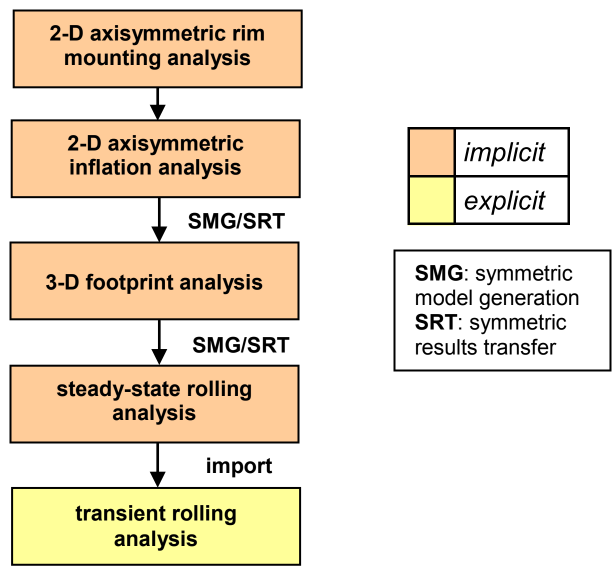


Figure 1: Stages in the analysis pipeline.

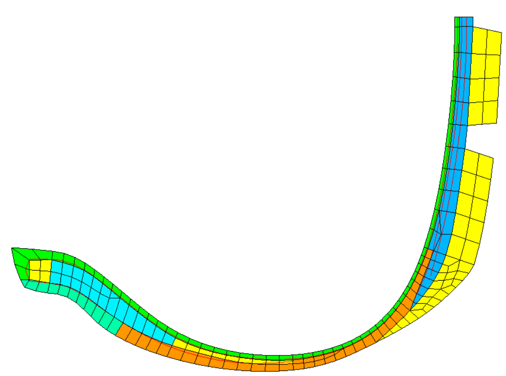


Figure 2: Axisymmetric cross-section of the tire. The color coding identifies regions with different material properties.

The cord reinforcement is characterized completely by the cross-sectional area of each fiber, the spacing between the fibers, and the material properties and orientations of the fibers. Figure 3 and Figure 4 display three- and two-dimensional views of the reinforcement configuration, respectively.

The rim is typically modeled as a rigid surface, reducing the cost of and simplifying the analysis. Contact is modeled between the rim and the tire; frictional effects are normally included. The rim is moved to the desired position against the tire before the inflation pressure is applied.

Three-Dimensional Footprint Analysis

The loading during the footprint analysis is no longer axisymmetric; a three-dimensional model is, thus, required. The symmetric model generation capability is used to create the model by revolving the cross-section around an axis. The axis of revolution is parallel to the rolling axis of the tire.

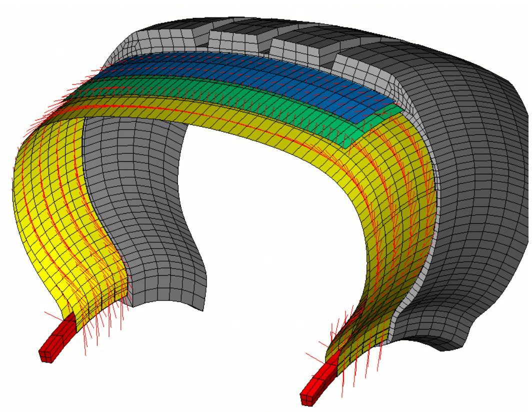


Figure 3: Reinforcement orientation in the belts and the carcass in three dimensions.

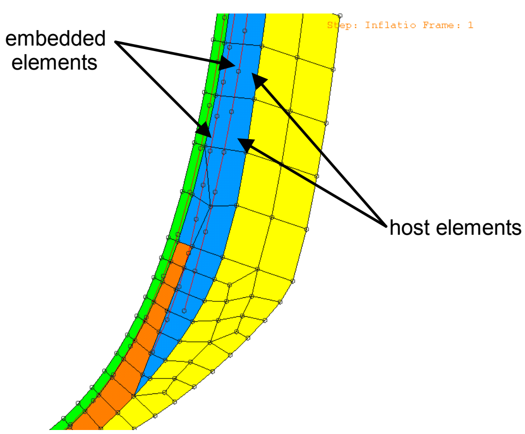


Figure 4: Embedded elements in the tire cross-section.

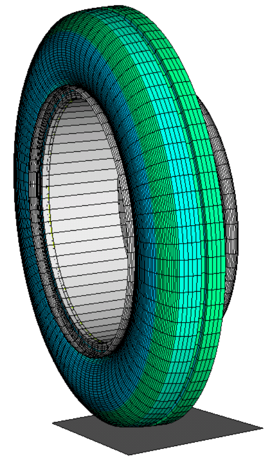


Figure 5: Partial three-dimensional model generated using symmetric model generation.

Since the final goal is to perform a transient Lagrangian dynamic rolling analysis, we use a uniform fine discretization around the circumference. The results from the end of the axisymmetric analysis are transferred to the newly generated three-dimensional model using the symmetric results transfer capability.

The footprint analysis is performed on a half-symmetric three-dimensional model (Figure 5) to reduce computation time. On the midplane of the tire perpendicular to the axle, antisymmetry conditions are applied using linear constraint equations. In the next stage the symmetric model generation capability can be used again to reflect the half-symmetric model about a line to generate the full three-dimensional model. The results from the end of the footprint analysis are transferred to the full three-dimensional model using the symmetric results transfer capability. The road is modeled as a rigid surface. Contact is modeled between the tire and the road.

In Figure 6 the deformed partial three-dimensional model is shown, while the deformed full three-dimensional model is shown in Figure 7. The footprint contact pressure results are shown in Figure 8.

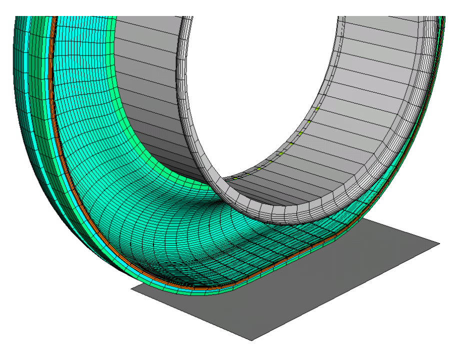


Figure 6: Partial three-dimensional model with footprint loading.

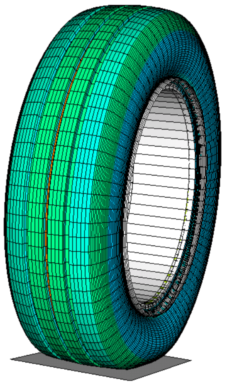


Figure 7: Full three-dimensional model generated using symmetric model generation.

Steady-State Rolling

Steady-state rolling is modeled most effectively by using a reference frame that is attached to the axle of the tire. The reference frame translates with the tire but does not rotate; the tire is, therefore, rotating through the reference frame. An observer in this frame sees the tire as points that are not moving, although the material of which the tire is made is moving through those points.

The finite element mesh describing the tire in this frame of reference remains stationary. This kinematic description can be viewed as a mixed Eulerian/Lagrangian formulation, where the rigid body rotation is described in an Eulerian manner and the deformation is measured in a Lagrangian manner.

Ideally, a fine mesh is needed only near the footprint region. If the purpose of the analysis is only to calculate the steady-state response, special elements designed to model cylindrical structures can be used. The advantage is that the model size is reduced significantly.

Here, the final simulation will be a transient dynamic analysis once steady-state rolling has been achieved. Such a Lagrangian analysis requires fine meshing around the circumference to accommodate changing contact conditions. While this loading stage considers only straight rolling, the steady-state transport capability can also be used to analyze cornering and camber. The footprint contact pressure and the in-plane shear stress in the circumferential direction due to friction are shown in Figure 9 and Figure 10, respectively. Figure 11 displays the distribution of force in the outermost reinforcing belt.

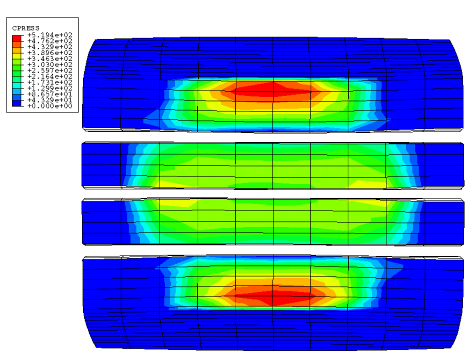


Figure 8: Contact pressure distribution at the footprint region in the footprint loading step.

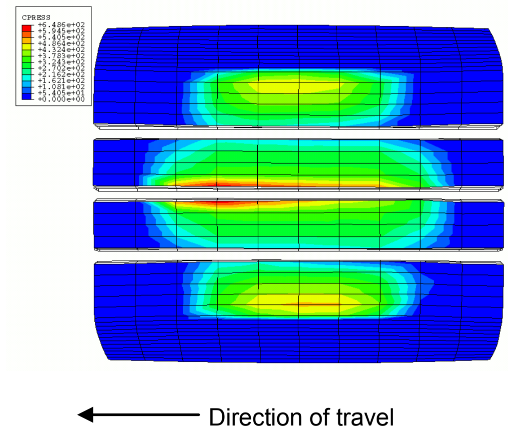


Figure 9: Contact pressure distribution at the footprint region in the steady-state transport step.

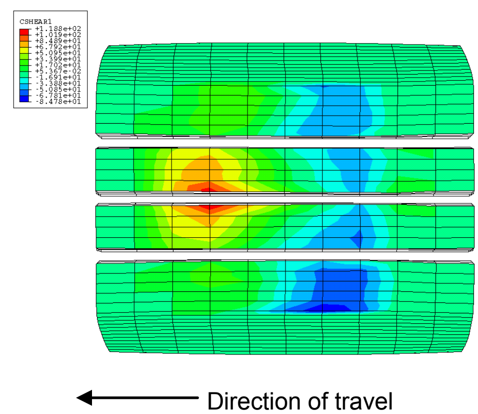


Figure 10: Shear stress due to friction in the direction of motion in the steady-state transport step.

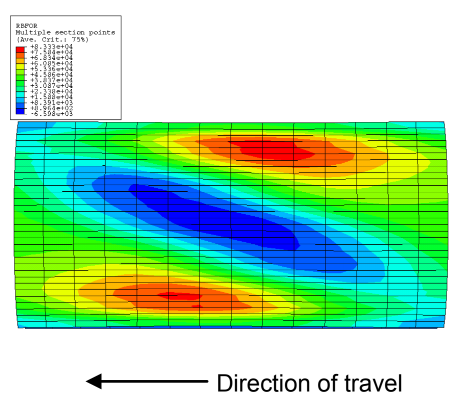


Figure 11: Reinforcing cord force in the outermost belt near the footprint region in the steady-state transport step.

Import and Transient Rolling

Model information and results from an Abaqus/Standard analysis can be transferred to an Abaqus/Explicit analysis and vice versa. The results from the end of the steady-state rolling analysis are imported into Abaqus/Explicit as the initial (base) state for the transient rolling analysis.

Figure 12 displays the initial configuration of the model used in the transient rolling analysis. The road and the rim are modeled as rigid bodies, and the coefficients of friction between the road and the tire and the rim and tire are 1.0. The height of the bumps is approximately 10% of the tire radius.

In this case the tire moves at a constant velocity of 60 mph along the direction of motion (the same velocity as used in the steady-state rolling step). The vehicle load is applied to the reference node of the rigid surface modeling the rim.

Typical results of interest—including deformation, contact pressure, and reinforcement stress—are shown in Figure 13, Figure 14, and Figure 15, respectively.

Since no suspension components were modeled, the vertical force at the reference point of the wheel is not available directly. A qualitative assessment can be inferred, however, from the reaction forces at the reference point of the road. Figure 16 shows the magnitude of the vertical reaction force at the road reference point. The curve has been generated using an SAE low-pass filter with a cutoff frequency of 1000 Hz.

Conclusions

Abaqus has an efficient, cost-effective methodology for the transient rolling analysis of tires. The streamlined, integrated approach uses the symmetric model generation, symmetric results transfer, and steady-state transport capabilities to minimize analysis time.

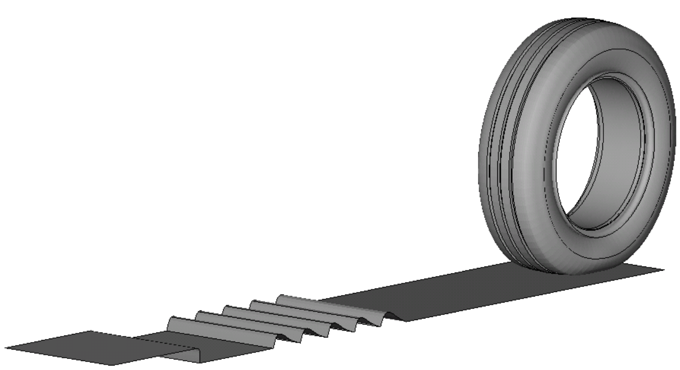


Figure 12: Tire model imported into Abaqus/Explicit from Abaqus/Standard.

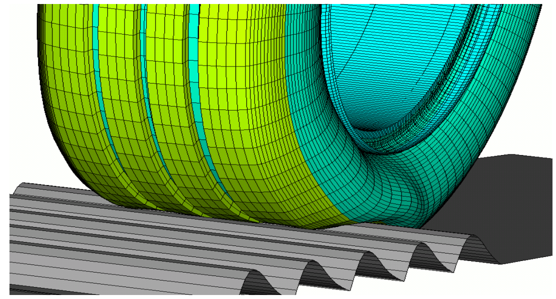


Figure 13: Deformation of the tire in the footprint area as it rolls over the first bump.

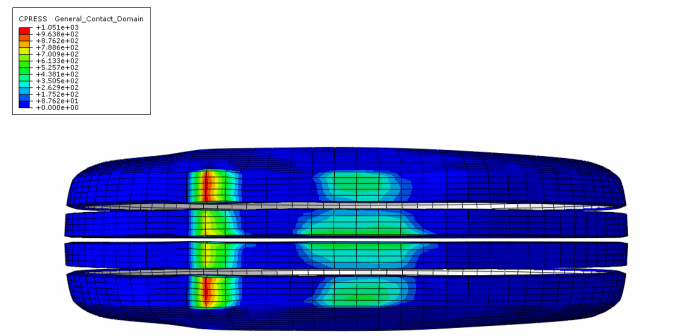


Figure 14: Contact pressure distribution during the initial impact with the first bump.

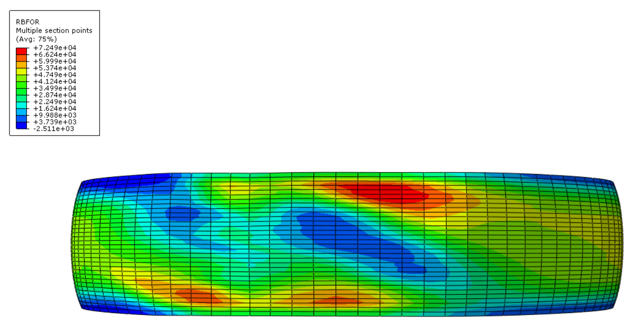


Figure 15: Reinforcing cord force in the outermost belt during the initial impact.

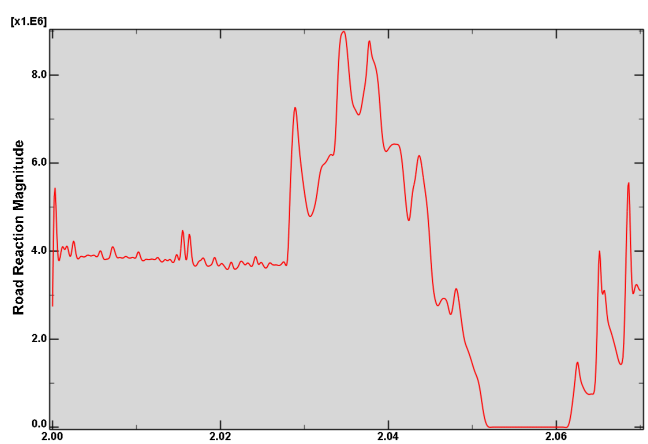


Figure 16: Vertical reaction force magnitude at road reference point.

Acknowledgements

Dassault Systèmes SIMULIA Corp. would like to acknowledge Hankook Tire Co. for supplying the tire model used in this study.

References

1. Kennedy, R., and J. Padovan, "Finite Element Analysis of a Steady and Transiently Moving/Rolling Nonlinear Viscoelastic Structure-II. Shell and Three-Dimensional Simulations," Computers & Structures, vol. 27, no. 2, pp. 259–273, 1987.
2. Oden, J. T., and T. L. Lin, "On the General Rolling Contact Problem for Finite Deformations of a Viscoelastic Cylinder," Computer Methods in Applied Mechanics and Engineering, vol. 57, pp. 297–367, 1986.

Abaqus References

For additional information on the Abaqus capabilities referred to in this brief, see the following Abaqus 6.11 documentation references:

- Analysis User's Manual
  - "Defining reinforcement," Section 2.2.3
  - "Steady-state transport analysis," Section 6.4.1
  - "Symmetric model generation," Section 10.4.1
  - "Hyperelastic behavior of rubberlike materials," Section 21.5.1
- Example Problems Manual
  - "Symmetric results transfer for a static tire analysis," Section 3.1.1
  - "Steady-state rolling analysis of a tire," Section 3.1.2
  - "Import of a steady-state rolling tire," Section 3.1.6