Making FEM Tire Model
And
Applying It For Durability Simulation

Masaki Shiraishi*, Hiroshi Yoshinaga*, Naoaki Iwasaki*
Kimihiro Hayashi+

* Sumitomo Rubber Industries, LTD.
1-1,2-chome,Tsutsui-cho,Chuo-ku,Kobe 651,Japan
+ The Japan Research Institute,Ltd.
16,Ichiban-cho,Chiyoda-ku,Tokyo 102-0082,Japan

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ABSTRACT

In recent years, CAE (Computer Aided Engineering) has become very popular for effective development of many industrial products. In the development of automobile, CAE has been applied in many fields. About endurance and fatigue analyses of automobile, it is necessary to simulate the force by road input, and accurate tire model is necessary for this. But the construction of tire is very complicated and its model is so complicated that large calculation resource is necessary. Such a simulation is not useful for actual automobile development. Then we tried making simplified tire simulation model that express the tire properties of minimum requirement. After developing tire model, we applied the model to curb striking simulation to confirm the availability of the model.

INTRODUCTION

With the progress of CAE-related technology there has been a rapid expansion in it's areas of application. In the automotive industry the areas of application of CAE have expanded from strength and collision analysis even to areas such as durability analysis.

In automobile durability and fatigue life analyses it is necessary to accurately represent the load input from the road surface. Hence it is necessary to have an accurate tire model. However, a tire is made from composite materials, and an FEM model capable of taking into account the detailed design factors would have to be very large. Because of this large computing resources would be needed, and it is not practical to use such tire models in a model of the complete automobile. Therefore an effort was made to develop a simplified tire model which is sufficiently accurate, convenient to use and which is correlated with tests.

APPROACH

Structure of an Automotive Radial Tire

Figure 1 shows a radial tire for an automobile. A tire is fitted to a wheel, inflated, the wheel is then fitted to an automobile and used. The part where a tire connects to the wheel is called the bead, and the force in the bead is mainly taken by the beadwire. The carcass (or casing) and belt are made of fibrous materials and have the function of maintaining the shape of the tire when it is inflated. The casing is fixed by wrapping around the beadwire on both sides, and the orientation of the fibers is almost radial. With only the casing the tread portion which touches the ground would expand when inflated, but the belt has the function of restraining this expansion so that the tire contacts the ground evenly. The belt is normally provided in two layers with the orientation of the fibers alternately at 20 degrees to the circumferential direction. The carcass is made from polyester and other organic fibers, the belt from steel cord composed of steel wires twisted together, and both are provided with a topping of rubber. In addition to the carcass and belt there is a bead reinforcing filler provided to stiffen the bead and a band made of fibers provided to restrain the expansion of the tread during high speed running.

The tire is formed by adding rubber to these fibrous materials. The main rubber parts are the tread, the sidewall, the bead rubber and the chafer. The tread rubber is in contact with the road surface and it transmits various forces, so it contributes greatly to the performance of the tire. Also for running on wet, unpaved, or icy road surfaces different patterns are provided as appropriate to its use. The sidewall protects the tire from bending when turning, from stones by the roadside, etc. The bead rubber stiffens the area where the tire connects with the wheel. The chafer rubber is used where the tire connects with the wheel, to prevent leakage of air and wear due to friction with the wheel flange.

From this it can be seen that including the tread pattern a tire is very complex in shape, and as it is a composite of fibrous and rubber materials simulation is difficult.

Tire Performance and it's Simulation

A tire has four fundamental functions, each of which has related performance requirements as follows:

Function	Related Performance Requirement
1. Load support function	Durability
2. Driving and controlling force transmission function	Traction and braking performance on various types of road surface
3. Shock absorbing function	Ride comfort performance
4. Course maintenance function	Cornering, etc., performance on various types of road surface

In addition to the above functions, vibration, noise, wear, rolling resistance and other performance criteria can be added.

Simulation of these functions is done using the finite element method (FEM). However, as stated above, because of the complexity of the construction of a tire these are nearly all very large simulations. An example of a tire model used in such simulations is shown in Figure 2. This model faithfully reproduces the tread pattern, and the internal structure is reproduced by means of solid elements for the rubber and membrane elements for the fiber material, so that the number of elements is around 80,000. For a dynamic analysis using this model, a time step of around 1 microsecond is necessary, and many such time steps are needed to carry out a simulation of one revolution of the tire travelling at say 50 km/h, an event which lasts approximately 0.2 seconds. Due to the recent progress of hardware an analysis of this scale consisting of only the tire has become practical. On an NEC-SX4 supercomputer this analysis would take approximately 30 hours.

Automobile Road Test Simulation

In order to reduce the development time and cost of a new car design CAE has been widely used. Crashworthiness simulation for example is an indispensable part of the development process. In order to carry out durability or fatigue lifetime analysis it is necessary to consider what the force input from the road surface is. For this purpose it is necessary to have an accurate tire model. Then it is possible to fit this tire model to the car body model, carry out a running simulation and obtain the stresses and strains in each part of the car.

However, as stated above, as the structure of as tire is complex a simulation requires a large model and large computing resources. To carry out a simulation with a model consisting of four such tire models fitted to a body model, with detailed modeling of the parts of the body which are of interest would not be practical in terms of model size and computing time. Therefore we attempted to simplify the tire model as much as possible in order that it could be used in a practical road test simulation of a car.

Simplified Tire Model

The original detailed model is shown in Figure 3 and the simplified is shown in Figure 4. Neither model includes the tread pattern. The differences between the two models are described below.

- *Tire Shape:*The shape of the original tire model is that of a tire before it is fitted to the wheel, so the first step in a simulation is to set the width of the beads to that of the wheel. This is done by means of constraints on the nodes comprising the beads, however these constraints become troublesome when simulating the movement of a wheel. The stresses arising in the tire as a result of fitting to the wheel are reasonably small. Therefore the shape of the simplified model was taken to be the same as that of the tire after it is fitted to the wheel, as shown in Figure 5.

- *Fiber Materials:*The main complexity in the original tire model arises from the layering of fibrous and rubber materials. In the original model each layer is individually modeled. Figure 6 shows how the modeling of the fibrous materials was modified from the original model to obtain the simplified model. In the original model the fiber material layers are represented by membrane elements with orthotropic stiffness properties, and rubber modeled using solid elements. However in the simplified model these layers are all represented by a single layer of shell elements. These shell elements have two Gauss points through their thickness. The element stiffness matrix of each layer was added in the thickness direction in order to obtain a single averaged element stiffness matrix. If the sum of the thickness of the individual layers is used as the shell thickness then the bending stiffness would be greatly overestimated. Therefore it was necessary to adjust the thickness and stiffness of the shell element so that it's bending stiffness was the same as that of the original model. Also, looking at a cross-section of the tire model, a large number of distinct materials is used (in this case 24) and this is difficult to deal with, so it was simplified to three different materials having virtually the same stiffness. Furthermore, in order to make the stiffness the same as that obtained from measurements the model stiffness was adjusted by trial and error.
- The number of nodes and elements in each of the models is as shown in the table below. The size of the simplified model has been considerably reduced, and the computing time has been reduced by a factor of about 25.

	Original Model	Simplified Model
Number of elements	22801	2642
Number of Nodes	16803	2648
Computing time (index)	100	4

DISCUSSION OF RESULTS

Simplified Tire Model Simulation Results and Validation

In order to verify that the simplified tire model could accurately represent the force input from the road, analysis of the deformation characteristics and of a tire passing over an obstacle were carried out, and the results were compared with those of a physical test. Note that the purpose of the detailed model is to examine the design features of the tire, but that of the simplified model is to be able to reproduce actual phenomena, for which purpose it's stiffness and damping factor has been adjusted. Therefore it is not possible to compare the results of the detailed and simplified tire models, as to do so would just invite misunderstanding.

Deformation Characteristics

A simulation of the deformation characteristics of the tire under load was carried out, and the results were compared with those of a test. The boundary conditions are shown in Figure 7. There were two types of target for the tire, a plane surface and a step at 45° to the direction of motion of the tire, and these were modeled using rigid shell elements. Figure 8 shows the simulation results and a photograph of the test. The simulation results agree very well with the deformed shape obtained in the test. Also, the load-deformation curve for both simulation and test is shown in Figure 9. It can be seen that the two agree very well. Therefore it may be considered that the simplified model is capable of representing the real tire stiffness very well.

Characteristics of Tire Passing over a Projection

A simulation was carried out of the tire passing over a projection or cleat while in motion, and the results were compared with those of a test. The boundary conditions are shown in Figure 10. The size of projection was 20×20 mm and the tire speed was 35 km/h. For a vibration simulation it is necessary to define damping. In order to get agreement with test it is convenient to use system damping, however if this is used it will restrict the movement of the tire. Also it is possible to define material damping, but this does not necessarily give good agreement with test results. Therefore, as shown in Figure 11, a method of damping was adopted in which motions other than those rigid body motions expressing the rolling of the tire were damped. The rolling motion of the tire is defined by the movement of the rigid body representing the axle of the vehicle, so the tire motions associated with this were not damped, but the velocity components of vibrations in the radial and lateral directions and other directions unconnected with the movement of the vehicle were damped. The simulation results and a photo obtained from a high-speed camera are shown in Figure 12. The deformed shape obtained from the simulation is very similar to that of the test. Also, Figure 13 shows the comparison between the reaction force at the axle from both the test and the analysis. It can be seen that the agreement between them is very good. Therefore it can be considered that the simplified tire model is capable of reproducing the characteristics of a tire passing over a projection.

Application of the tire model to curb strike

The simplified tire model was checked through the tests used tire only. Our object to develop tire model is durability simulation using exact tire model. Then it is necessary to apply the tire model on durability simulation. At first we picked up curb strike simulation of compact sized car because of easy to analyze using LS-DYNA.

Tire Model

The tire models used in the analysis are shown in Figures 14 and 15. The tire sizes are 195/60R15 and 205/50R16, standard tires for mid-range cars. The internal pressure was 200kPa (2 atmospheres), and this value was attained gradually after the start of the analysis. The wheel was modeled using rigid elements, and extra nodes were provided in the region where the tire and wheel connect. In the physical test, load-measuring apparatus was attached to the wheel, so in the analysis the mass of this apparatus was added to the mass of the wheel.

Analysis Model

Two models were used, one with the tire alone, and the other with the tire attached to the car.

*Tire-only Model.*The analysis model is shown in Figure 16. Both 15 inch and 16 inch finite element tire models were used. The tire axle was modeled with rigid beam elements, and was connected to the wheel by means of a constrained joint with the extra nodes on the wheel. This rigid axle was put in motion by applying horizontal and vertical velocities which were equal to those obtained for the axle in the test.

The road surface was modeled using rigid shell elements, and a contact surface was defined between it and the tire. The vertical force (self-weight) was produced by making this road surface move vertically.

*Tire fitted to the Body Model.*The full model is shown in Figure 17. The body-in-white was modeled as a network of rigid beam elements, which was not allowed to deform. The sub-frame, suspension and steering rod were modeled as elastic bodies, so the effect of deformation could be taken into account. Also, the shock tower top panel was modeled using elastic-plastic shell elements, so elastic-plastic deformations could be considered. The bush was modeled using a spring element, so that the suspension response would not be too hard.

Unlike the test vehicle this model was provided with strut suspensions. Also the body shape differed from the test model, but by adjusting the mass of the rigid beams the position of the center of gravity and the mass were the same as in the test vehicle.

The 15 inch tire model was used. The axle of the tire was modeled with rigid beams, and was connected to the wheel by means of a constrained joint with the extra nodes on the wheel. Also, these rigid beams were merged with the brake hub and became part of the suspension. On the other hand, damper elements which could only deform in the vertical direction were attached to the extra nodes on the wheel, the lower end of which moved horizontally together with the rigid axle of the tire. These damper elements removed the vertical vibrations arising upon initial loading with self-weight.

In this model the road surface does not move but is fixed.

The road surface was modeled using rigid shell elements. The height of the step was 100 mm, and the shape was as measured. A contact surface was defined between the tire and road surface, and a friction coefficient of 1.0 was used.

*Analysis Conditions.*The analysis conditions differed for the tire only model and the tire fitted to the car model. Both of them were driven over the step at 15 km/h.

Tire only Model.

- Apply internal tire pressure (200 kPa)
- Apply the automobile's self weight (4,000N)
- Roll the tire at the specified speed (15 km/h)
- Move the tire's axle according to the velocity constraints
- For damping, the newly-developed DAMPING_RELATIVE capability was used. Using this capability all vibrations apart from the regular rotational components were damped.

Tire fitted to the Body Model.

- Apply internal tire pressure (200kPa)
- Load the entire body
- Roll the tires at the specified speed (15 km/h)
- At the same time as rolling the tires the whole body is given an initial velocity of 15 km/h
- Vibrations occurring upon loading with self-weight are removed using the damper pre-tensioning capability.

Simulation Results

*Tire only Model.*The comparison of the axle force obtained from the analysis and test was carried out. The results for the 205 tire are shown in Figures 18 to 20, and for the 195 tire in Figures 21 to 23. The load arising in the tire axle is greatly influenced by the velocity constraint conditions applied to it. The results shown here are those obtained after modifying the velocity constraints several times. There is still scope for improvement, however the results are satisfactory and it indicates the practical usefulness of the tire model.

*Car Body + Tire Model.*The body + tire model was not only examined for it's axle loading, but also the behavior of the center of gravity of the body was investigated and compared with test results. Firstly the overall body behavior is shown in Figure 24. When the tire rises up on the step initially the tire and suspension absorb the deformation, and the front of the body does not rise up. Afterwards the front of the body rises due to the recovery of the tire and the suspension deformation. The body + tire model is capable of reproducing this type of behavior. Comparing the axle force with test results (Figures 25 and 26) it can be seen that the accuracy is improved over the tire only model. In particular the peak force and time are both in good agreement with test. However, in the direction of travel the axle force has only one peak in the test result, whereas in the simulation results two peaks are obtained. This double peak is found in the tire only model also, and it is necessary to investigate the reasons for this in the future.

For the behavior of the center of gravity a comparison of acceleration and angular velocity was carried out. The comparison of acceleration is shown in Figures 27 to 29. As the simulation was carried out with the body considered to be rigid it is not possible to compare the high frequency vibrations of the body, so the test results were filtered. The angular velocity of the center of gravity of the body, shown in Figures 30 to 32, also shows the same tendency. It is considered that adequate analysis results were obtained.

CONCLUSIONS

A simplified tire model which is capable of being used in analyses of automobile durability and fatigue, which can accurately reproduce the input force from the road surface, and which does not require long run times has been developed. The simulation results obtained using this model agree well with test results for tire deformation and a tire passing oven a projection.A simulation of a vehicle rising up a step was carried out using the FEM tire model developed in the FEM Tire Project. The practicality and robustness of the tire model was checked by means of a tire only analysis, and the feasibility of carrying out a simulation using a full model consisting of the car body (BIW + suspension) and tires was investigated.

The body + tire FEM model differed from the test vehicle with respect to suspensions and wheelbase etc., however good agreement between test and analysis was obtained. This demonstrated that if an accurate tire model is used it is possible to carry out simulations of the body behavior and the force input to the body from the road.

We would like to develop this work further by concentrating more on the body, to carry out a practical vehicle running simulation.

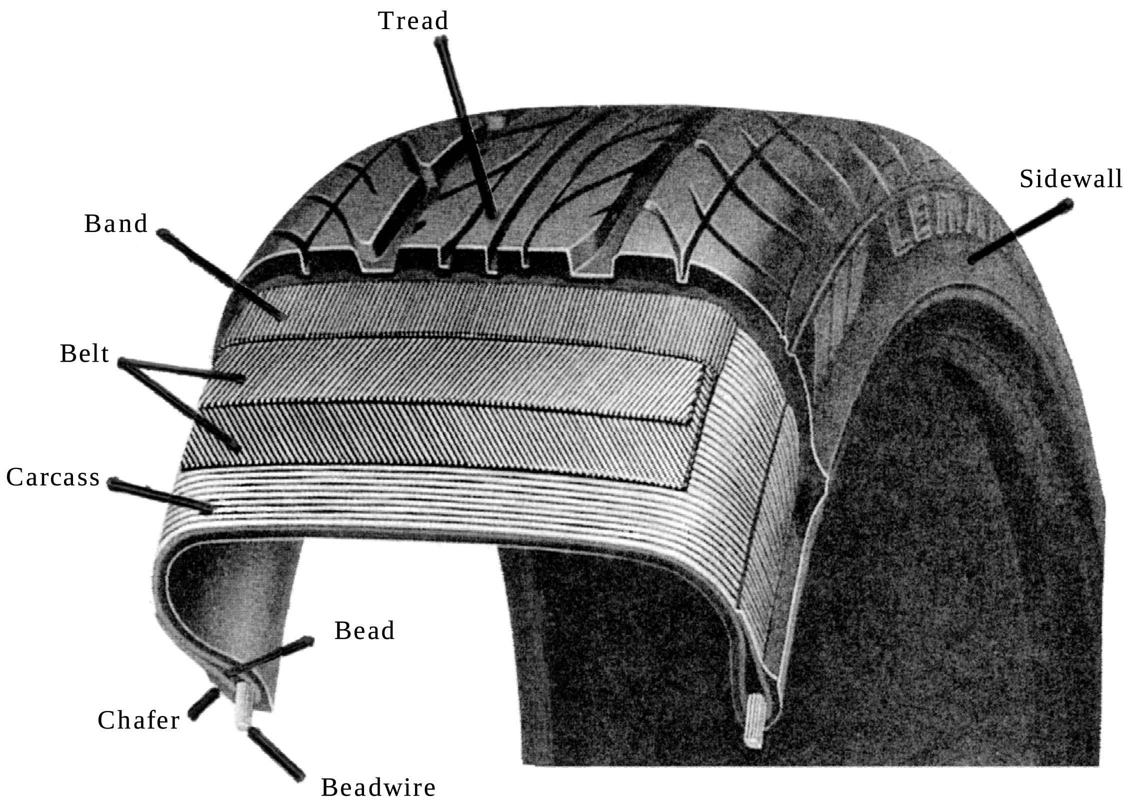


Fig.1 : Tire construction

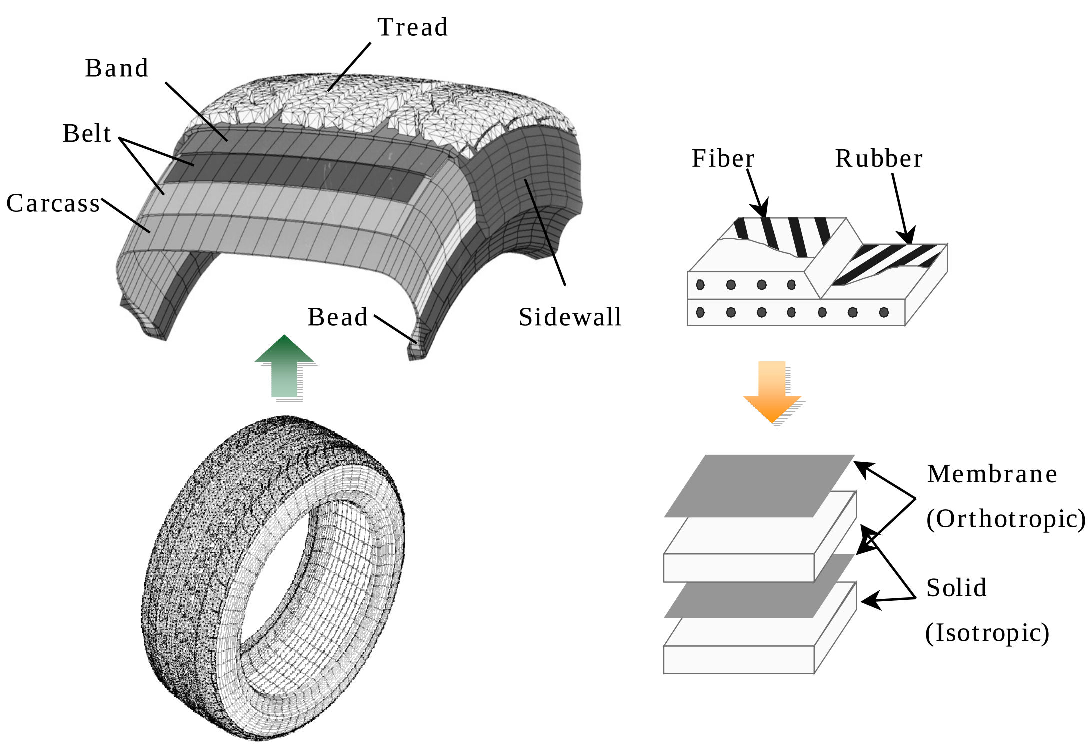


Fig.2 : Tire simulation model

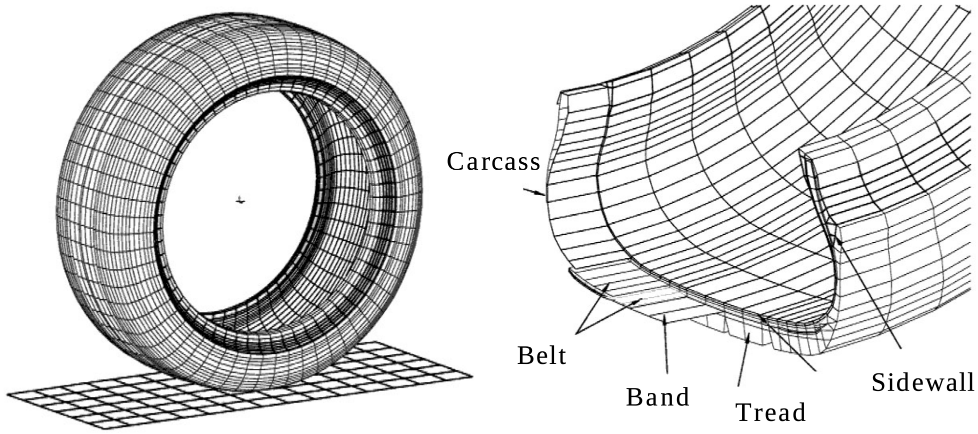


Fig.3 : Original model

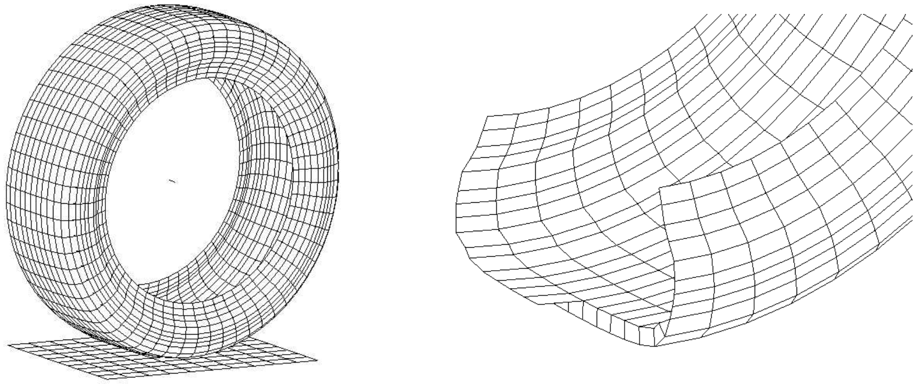


Fig.4 : Simplified tire model

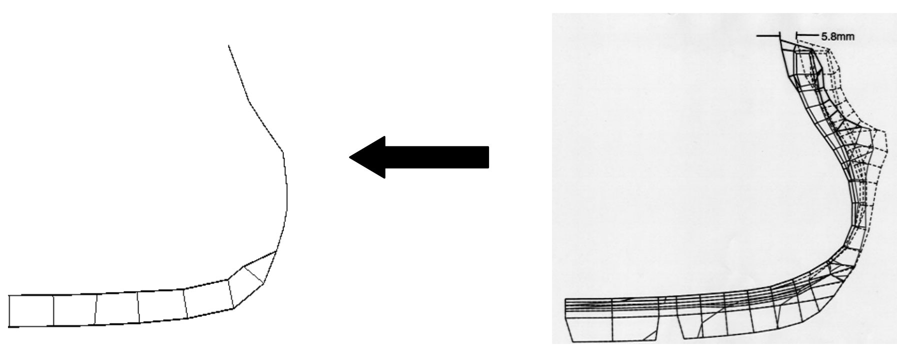


Fig.5 : model of wheel set shape

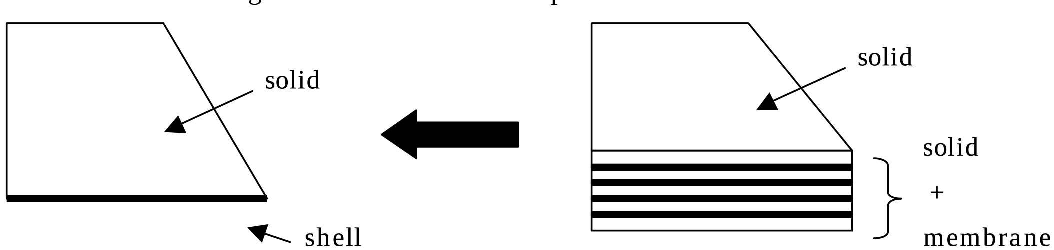


Fig.6 : modeling method of fiber reinforced rubber

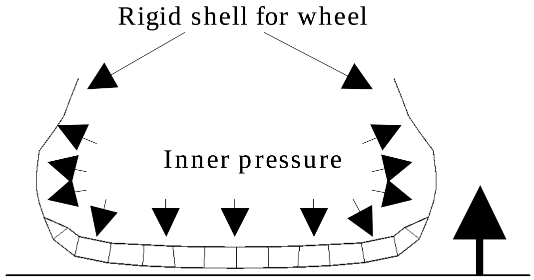
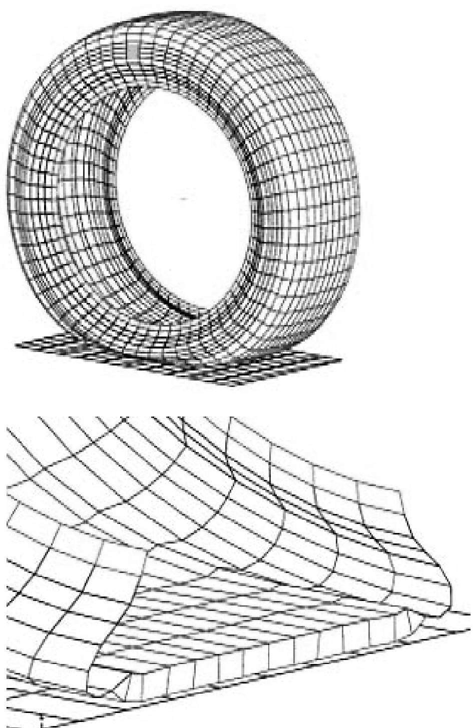
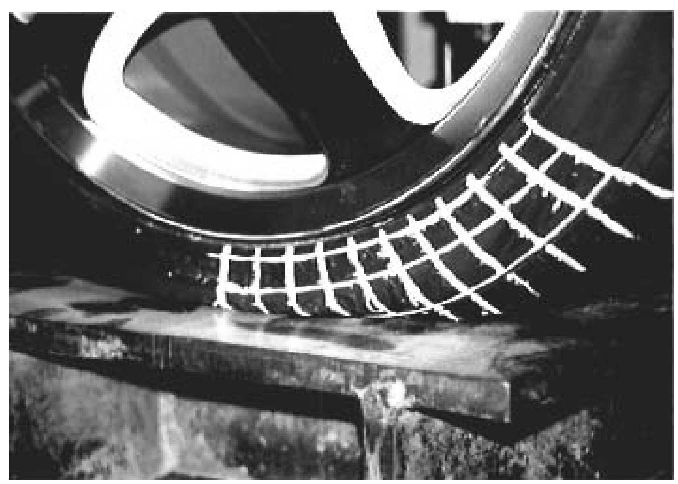


Plate is moved by velocity constrained condition.

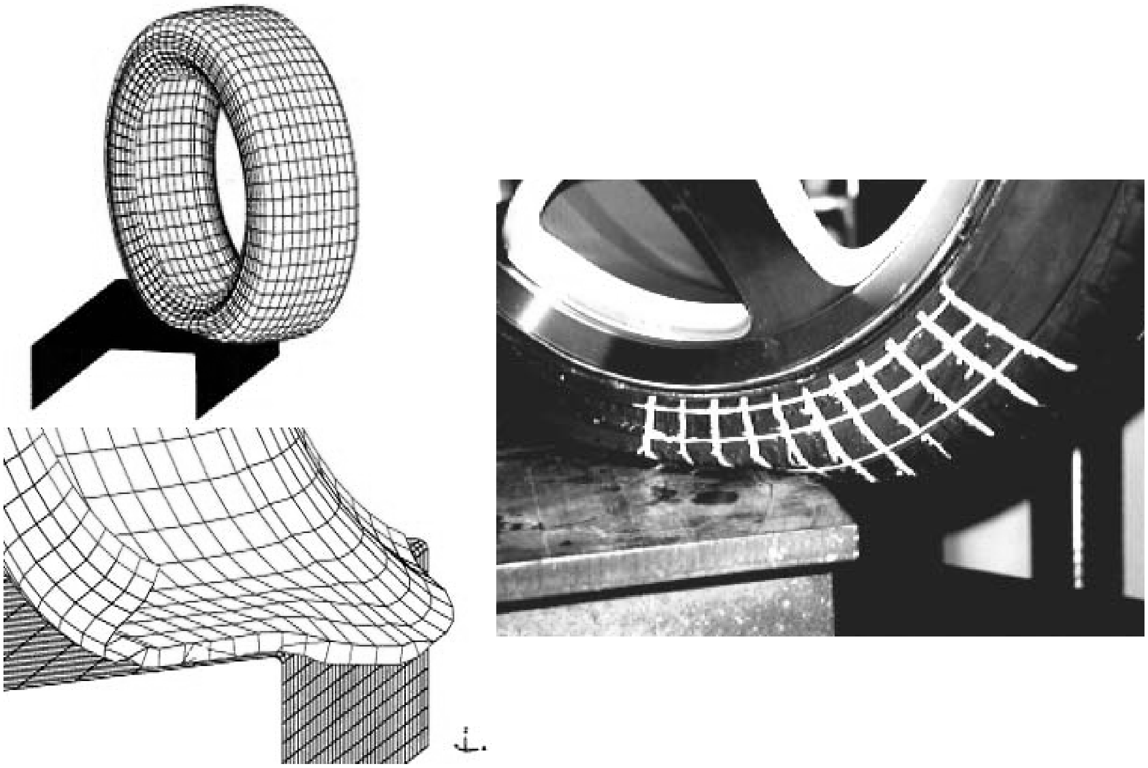
Fig.7 : Boundary condition for loading





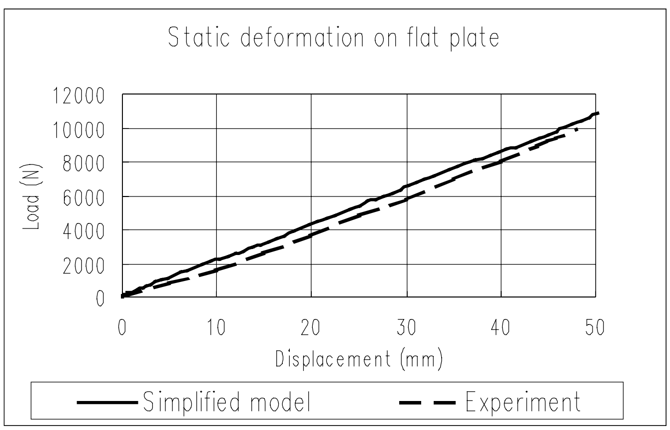
(Flat plate : Left : Simulation Right : Experiment)

Fig.8-1 : Static loading shape (FLAT PLATE)



(45 degree step plate : Left : Simulation Right : Experiment)

Fig.8-2 : Static loading shape (STEP PLATE)



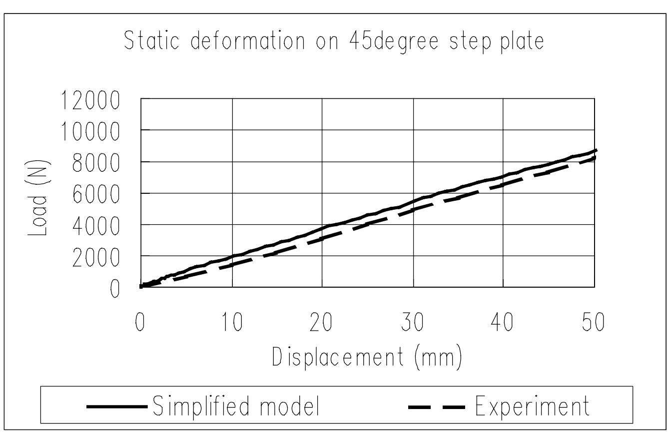


Fig.9 : Static deformation with loading

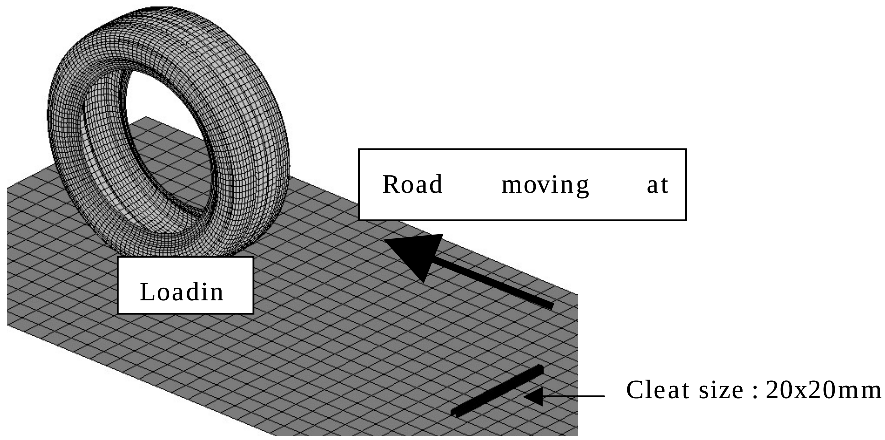


Fig.10 : Boundary condition for cleat impacting simulation

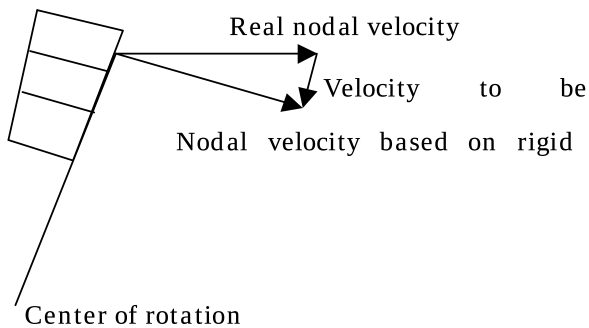


Fig.11 : Method of damping definition

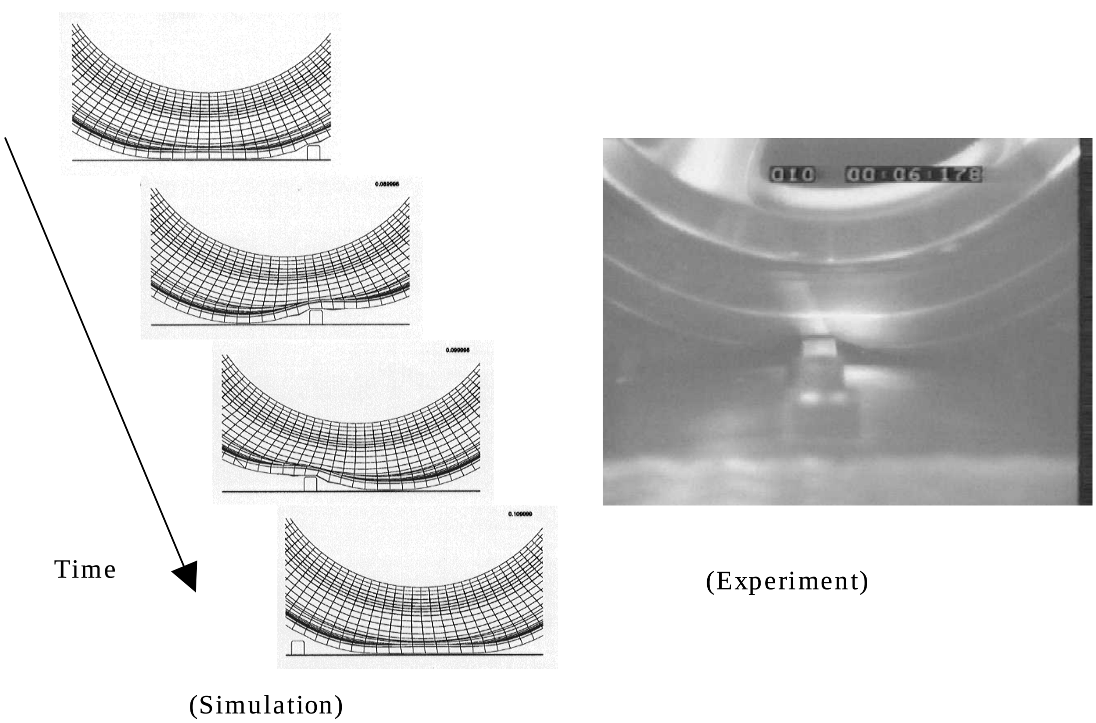


Fig.12 : Cleat impacting shape

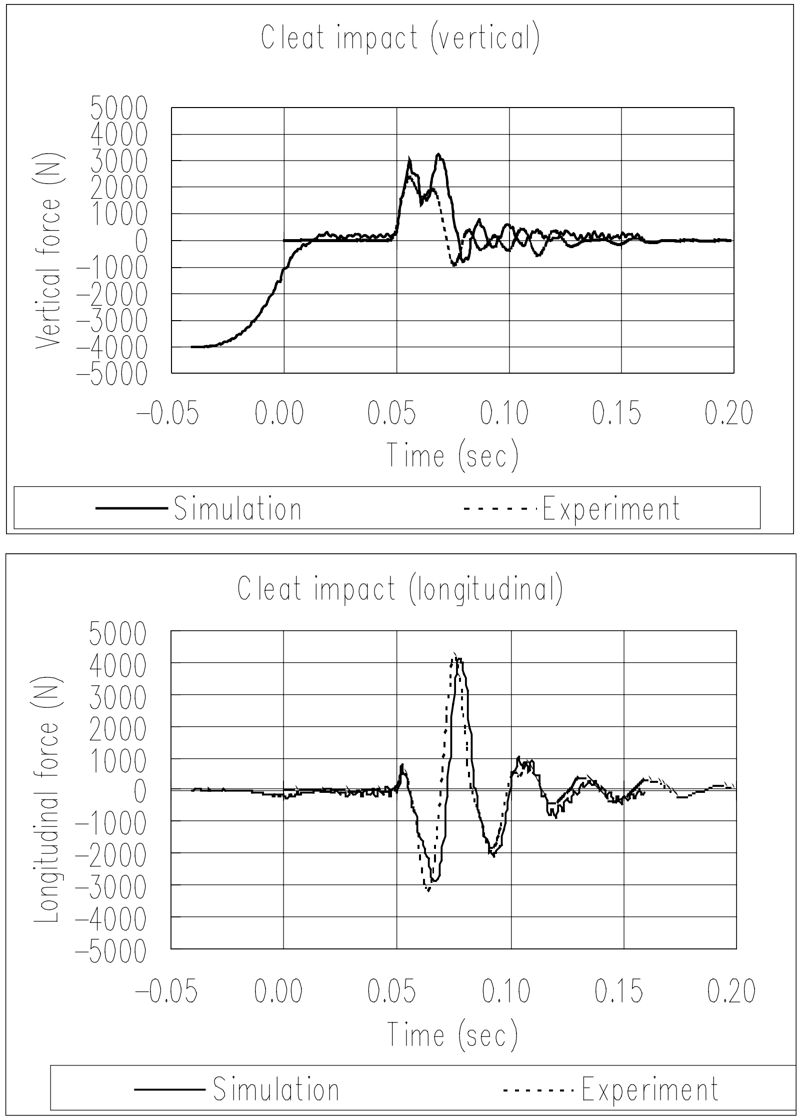


Fig.13 : Cleat impacting force

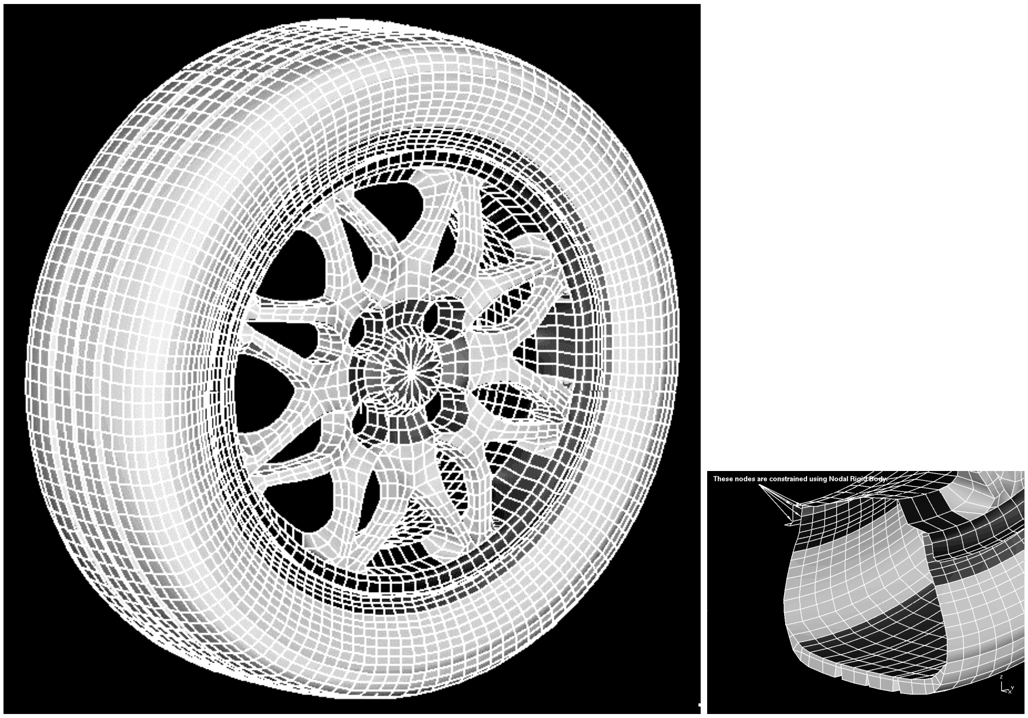


Fig.14 195/60R15 Tire Model

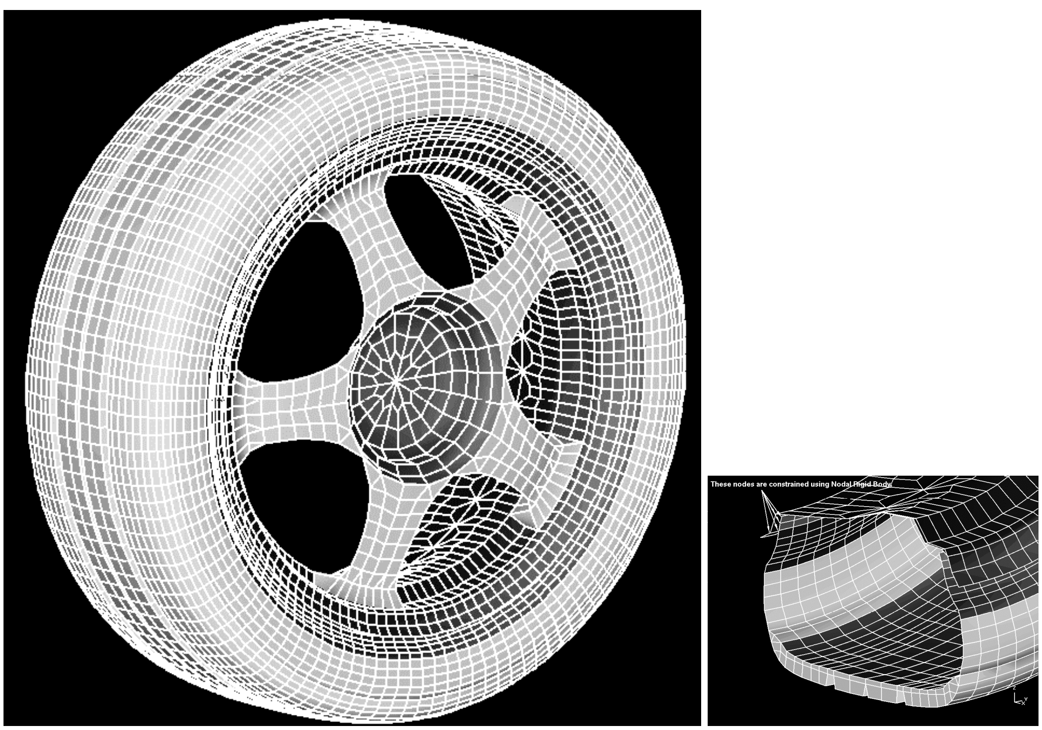


Fig. 15 205/50R16 Tire Model

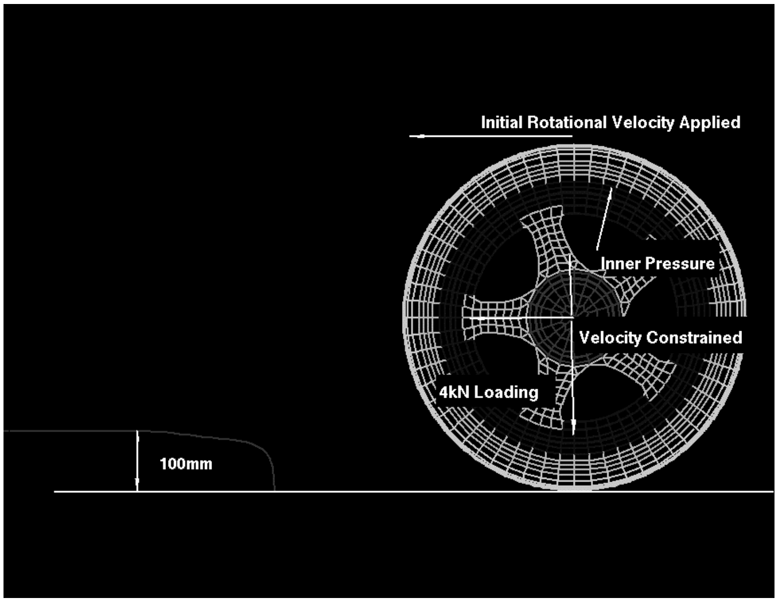


Fig. 16 Curb Strike Model Using Tire Only 205 Tire

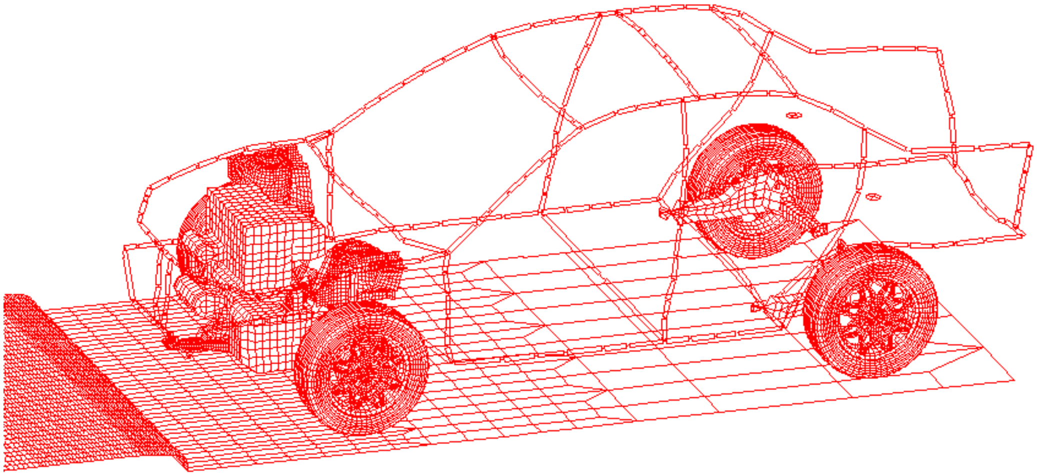
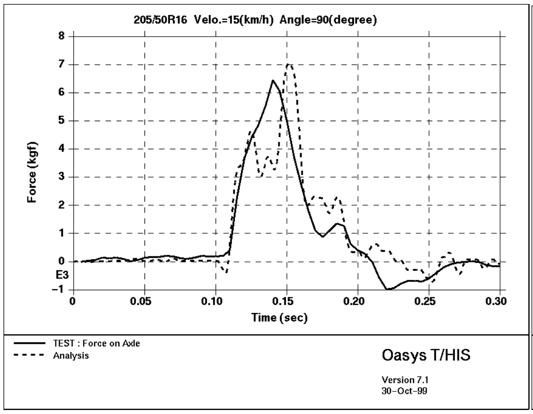


Fig.17 Curb Strike Model With Body + FE Tire 195/60R15 Tire



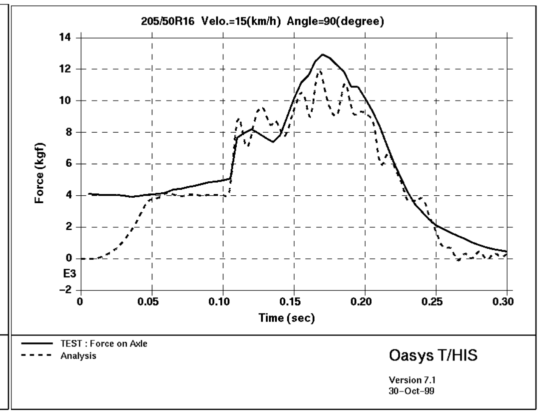


Fig.18 : Longitudinal Axle Force (205 Tire) Fg,19 : Vertical Axle Force (205 Tire)

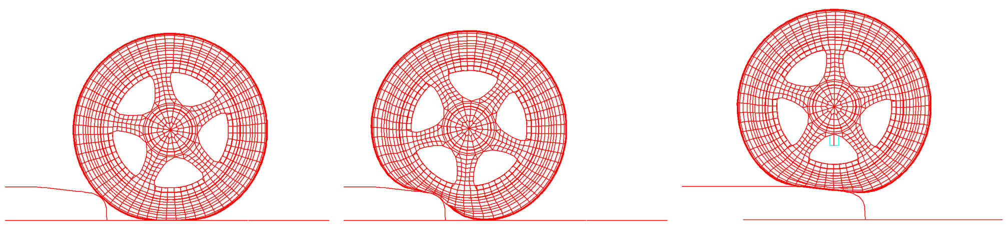
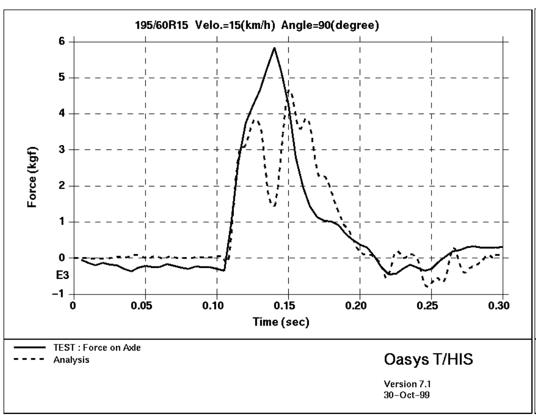


Fig.20 : Tire Deformation (205 Tire)



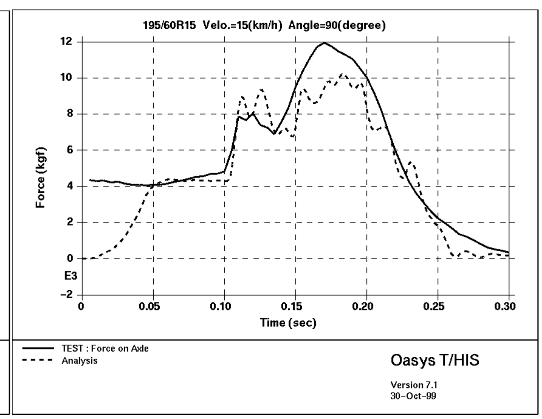


Fig.21 : Longitudinal Axle Force (195 Tire) Fg,22 : Vertical Axle Force (195 Tire)

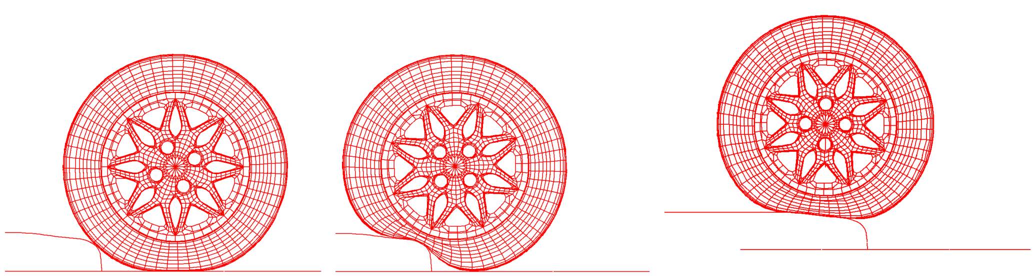


Fig.23 : Tire Deformation (195 Tire)

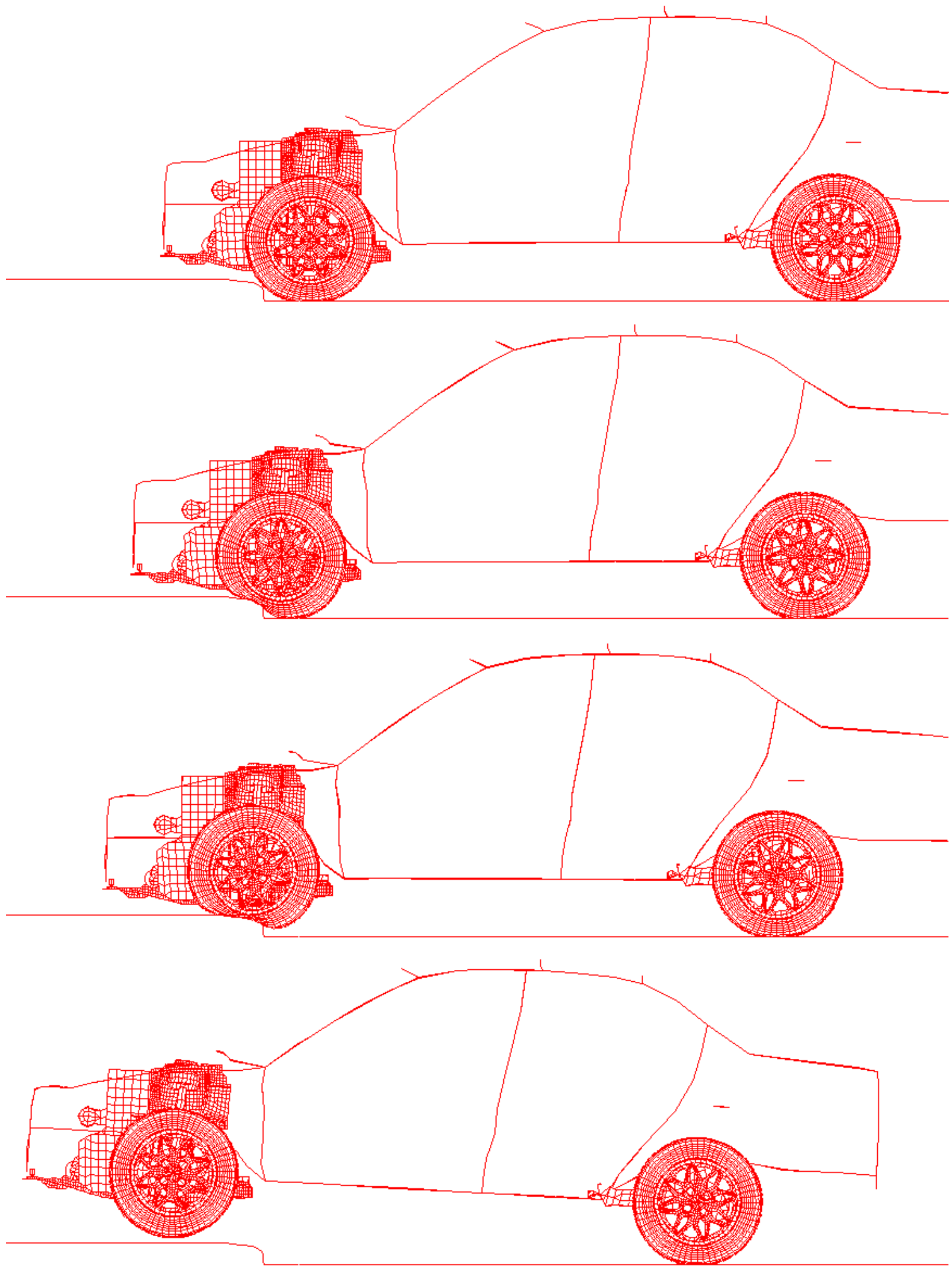


Fig. 24 : Deformation (195 Tire Used)

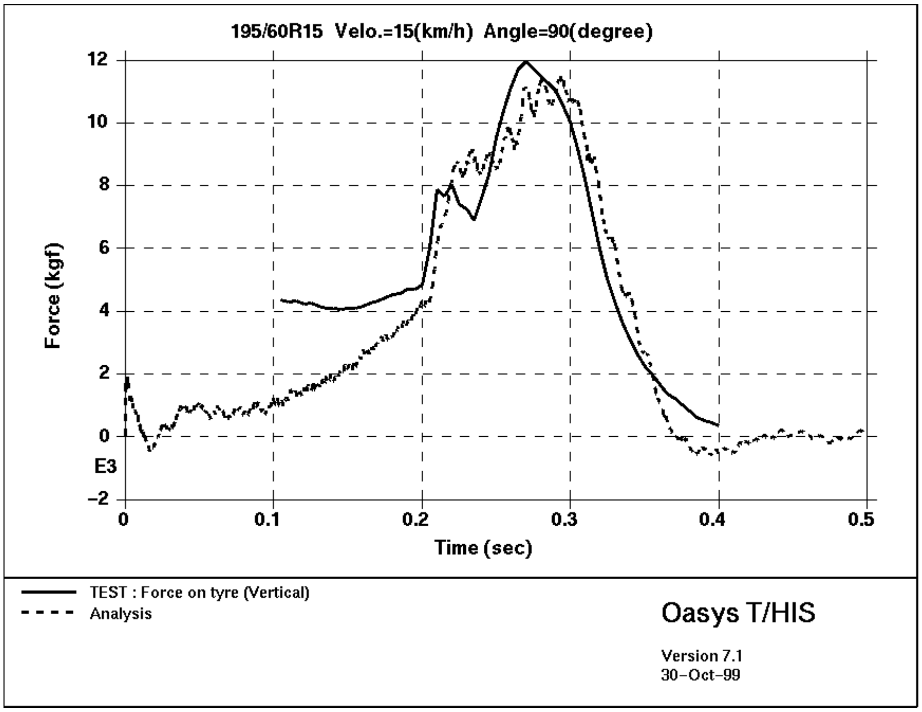


Fig. 25 : Vertical Axle Force BiW + FE Tire Model

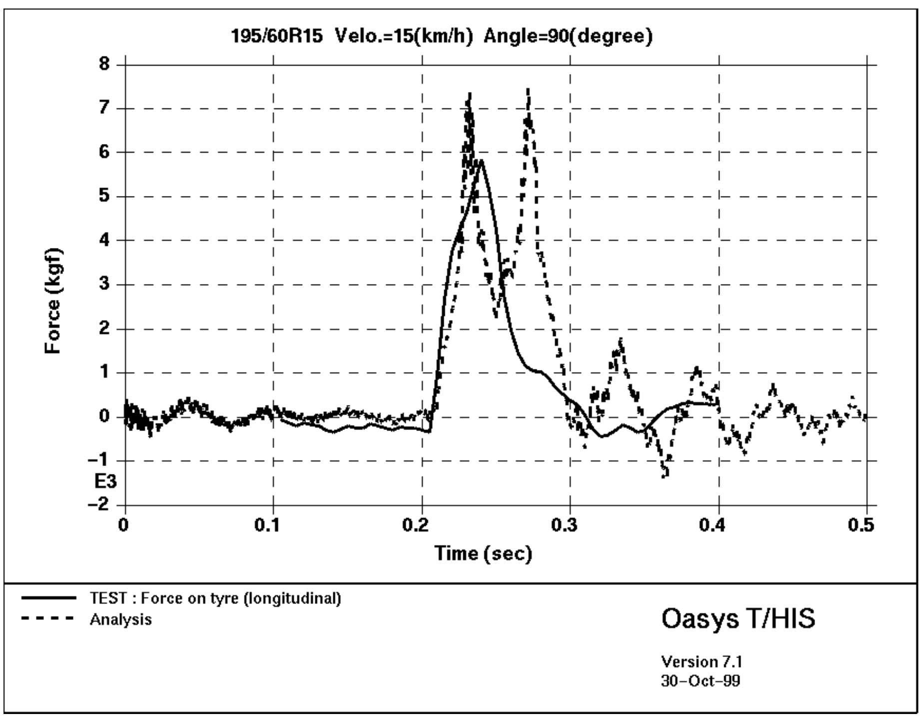


Fig. 26 : Longitudinal Axle Force BiW + FE Tire Model

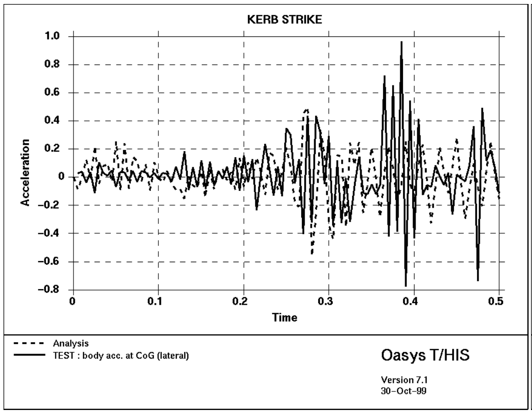


Fig.27: Accel. At Center of Gravity(Lateral)

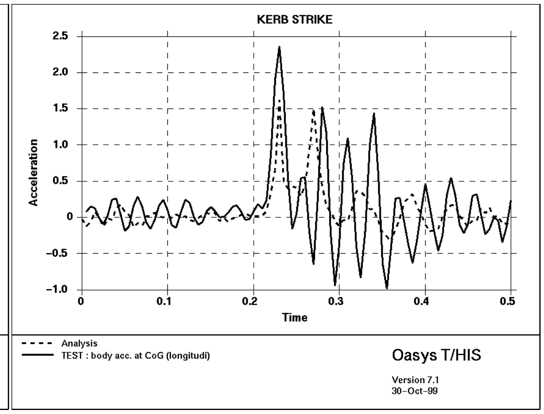


Fig.28: Accel. At Center of Gravity(Longitudinal)

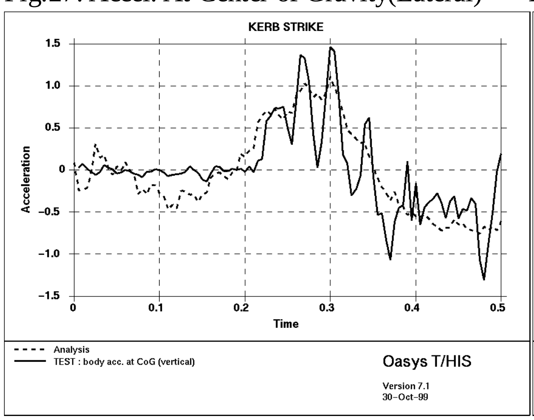


Fig.29: Accel. At Center of Gravity(Vertical)

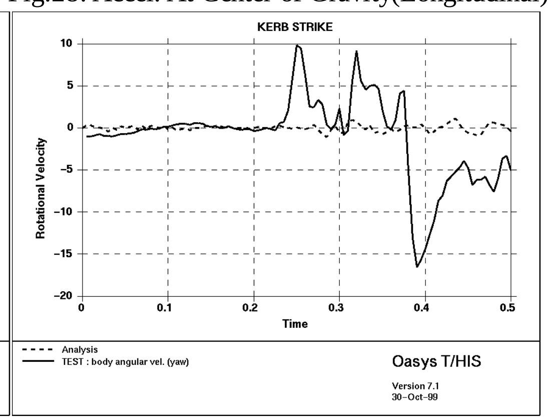


Fig.30: Yaw Rate At Center of Gravity

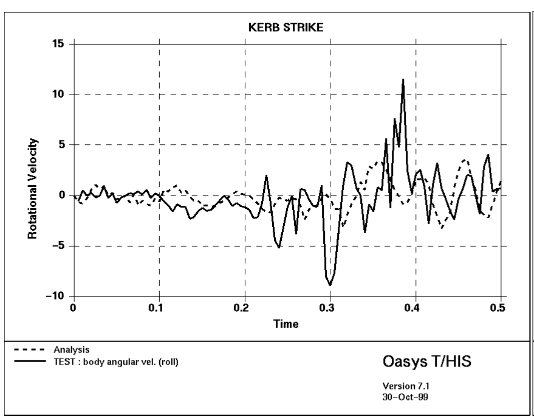


Fig.31: Roll Velo. At Center of Gravity

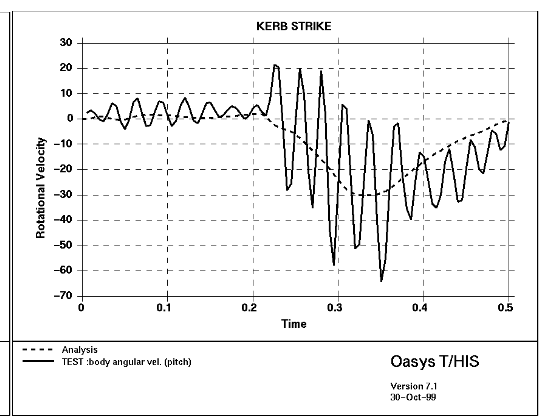


Fig.32: Pitch Velo. At Center of Gravity