

Pirelli Formula 1 tyre modeling application with Abaqus

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Pirelli tyres spa – Formula1

Abstract: As the sole tyre supplier for Formula1 Championship, Pirelli Tyre provides the teams with a virtual tyre model to help simulate racing conditions. The highly sophisticated body shape of a F1 car is driven by aerodynamic efficiency and tyre deformation plays an important role in this context. Tyre shape prediction at speeds up 300kph has been achieved by using a combination of Abaqus/Standard and Abaqus/Explicit. The numerical results have been verified using indoor test bench results. Tyre shape is also the key factor for wind tunnel analysis. The same modeling technique has been applied to wind tunnel FE tyre model.

*Keywords: High Speed, Tyre, Rubber, Viscoelasticity,*SST*

1. Introduction

1.1 Tyre performance and integrity

High speed tyre simulation of racing condition required a strong development of our FE modeling technique. All the material non-linearity and contact properties have been taken into account to predict tyre performance.

From a structural point of view the most critical design factors are: high speed, high vertical load (aerodynamic downforce), high camber angle and very low inflation pressure. During the race the tyre is constantly subjected to severe working condition.

Accurate description of footprint contact patch and local stress concentration inside the structure is crucial to have a high performance and safe product.

Temperature field is not currently included in the model primary to hold the CPU time down. Anyway temperature effect on material property variation is included in the material coefficients.

1.2 Tyre external shape and wind tunnel tyre

Another crucial consequence of such high stress levels is the high deformation tyres are subjected to. FE model is then requested to predict the tyre external shape within the whole load range. The F1 car aerodynamics is it strongly influenced by tyre shape than an extreme accuracy is requested in sidewall shape prediction.

1.3 Equivalent Structure

Due to confidentiality reason Pirelli cannot disclose the real tyre internal structure.

Both geometry and mechanical properties of all the materials are sensible intellectual property and cannot be disclosed.

For this reason we have developed an equivalent structural model able to reproduce real tyre characteristic having a complete different internal material distribution and properties.

Practically we scramble the internal reinforcement packaging in terms of stack sequence, angle values and material stiffness. The optimal solution is a material data sets which is agreement to experimental test results measured on our indoor test bench.

In principle it could exist several optimum materials data sets, and the calibration process would results too long compared to the very short time scale of Formula 1 car development. For this reason we chose as a reference structure a very simple and robust racing tyre specification (fig.).

The optimization process or, calibration, as we call it, is mainly driven by experience on tyre behavior. The calibration stops when the desired accuracy is obtained for all the experimental test results.

2. High speed tyre modeling with Abaqus

Modeling tyre with Abaqus has been widely described in literature (xx,xx). Simulation of passenger car tyre service condition is it part of standard design and development process at Pirelli, see (Donatellis, 2009). Simulation of high speed racing tyre required an enhancement in modeling technique because of the high frequency tread-road impact in addition to high vertical load and low pressure.

2.1 Model Set up

Tyre cross section and material properties are defined in the axisymmetric model. A 2D mesh of CGAX4R and CGAX3 element is used in for all the rubber part. To model the textile reinforcement the *RABAR LAYER option is used and the *EMBEDDED ELEMENT option is create tie the fiber and the rubber matrix.

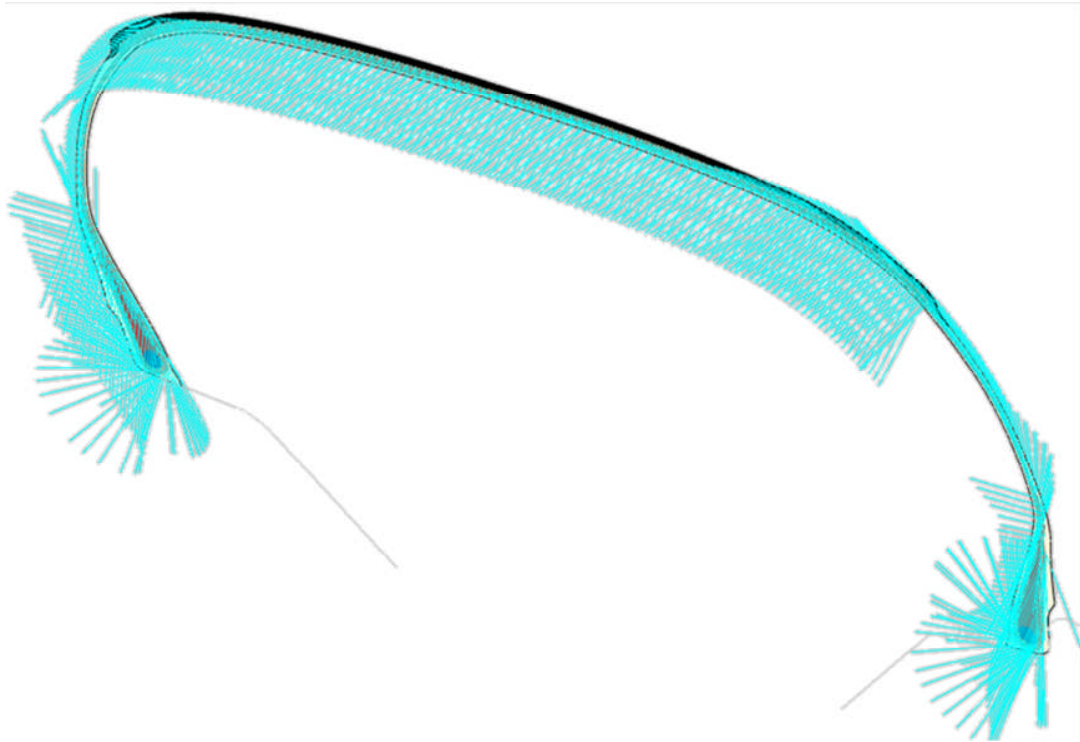


Figure 1. Tyre cross section

Axisymmetric analysis is used to simulate rim mounting and air inflation. The results are used as starting condition for 3D analysis using the *SYMMETRIC MODEL GENERATION feature.

2.1.1 Abaqus/Standard (*Steady State Transport):

Hybrid elements are specifically suited for incompressible material like rubber while reduced integrated element can be used for any application (Abaqus documentation for detail).

The Abaqus routine *Steady State Transport is well suited for C3D8H for tyre analysis. A solution can be obtained on a relatively short time because only the final stationary state is calculated (no transitory calculation). Moreover the 3D tyre mesh can be biased toward the contact patch area, saving element out of there. Finally the hybrid elements give a smooth solution for stress-strain field output and the contact force distribution.

2.1.2 Abaqus/Explicit:

Formula 1 tyre works under extreme load conditions which imply high speed and high deformation. Steady State solution is no longer applicable for such problems and Abaqus/Explicit is the only way to properly describe tyre deformation. Based on our experience we found 150kph as speed crossover, above which we have to run full explicit simulation to achieve desired results. Drawback of this approach is the massive increment in cpu time.

Special attention must be paid to mesh quality together with material properties defines the maximum allowable time increment (Dt) for explicit integration algorithm.

3D circumferential mesh must be uniform. To balance cpu time and accuracy, we used for high speed tyre 180slices. Compared with the typical meshing strategy, where the mesh is finer close the footprint but coarsen outside, we see about 40% more degree of freedom. The contact patch length could be underestimated.

For sake of time saving (see Figure 2) the *SST is used to speed up the tyre imported into Abaqus/Explicit using the *IMPORT capabilities.

Note on element type:

Abaqus/Explicit do not include hybrid element in his library than reduced integration C3D8R are used. The use of fully integrated element C3D8, are not currently applied because they are about 2-3 time more computationally expensive than the reduced counterpart.

Compound Properties

The entire rubber compound has been defined combining long-term hyperelastic property and linear time domain viscoelasticity law.

```
*MATERIAL,NAME=MAT_001
*HYPERELASTIC,N=1,MODULI=LONG TERM
C01, C10, D
*VISCOELASTIC, TIME=PRONY
a1, 0.,  $\tau_1$ 
a2, 0.,  $\tau_2$ 
```

Hyperelastic material parameters (C_{10} , C_{01} and D) are identified using the well-known data fitting procedure based on static experimental test.

Prony series coefficient (a_1 , a_2 , τ_1 , τ_2) are calculated fitting relaxation test data. The number of Prony series terms is not the same for all the compounds.

Analysis workflow is depicted in Figure 2.

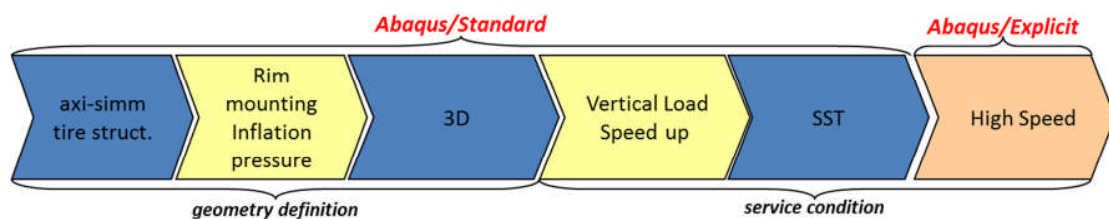


Figure 2. Analysis workflow

2.1.3 Simulation performance

High speed tyre simulation requires ultimate performance in terms of HPC efficiency and scalability. We rely on a Linux multicore cluster system to run our simulation. To improve HPC efficiency we paid great attention to find the optimal setup between hardware resources and Abaqus/Explicit features.

Stable time increment for our typical analysis is around $5.e-7$ which results in extremely large number of increments. In this case it is mandatory to run in double precision. All the Explicit analysis use general contact algorithm for rim and road contact.

Figure 3 shows how release 6.12 improves scalability for tyre analysis pushing the limit up to 128cores.

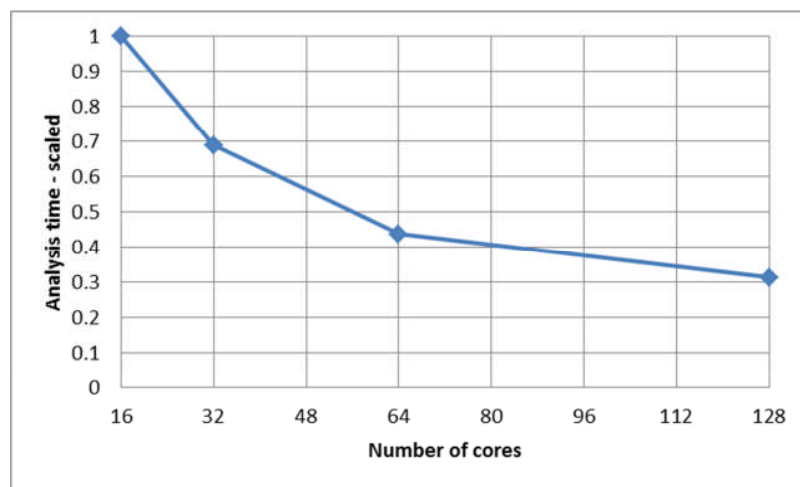


Figure 3 – Abaqus 6.12 scalability

2.2 Indoor test verification – Static

Tyre model is first checked for static dimension and stiffness. Laser scan cross section profile can be easily compared with 2D axi-symmetric model result. Figure 4 shows a front tyre cross section profile comparison. The analysis simulates the rim mounting at the nominal inflation pressure. Maximum allowed distance is 2mm for each mesh node. The verification continues on static results in terms of vertical stiffness and contact patch.

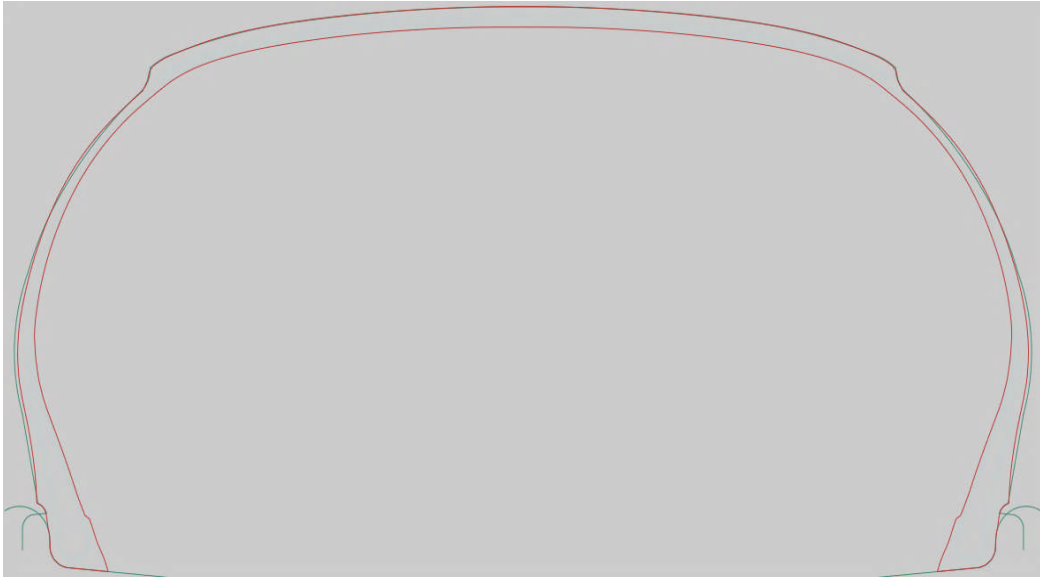


Figure 4 - 2D profiles comparison - rim mounting and inflation pressure

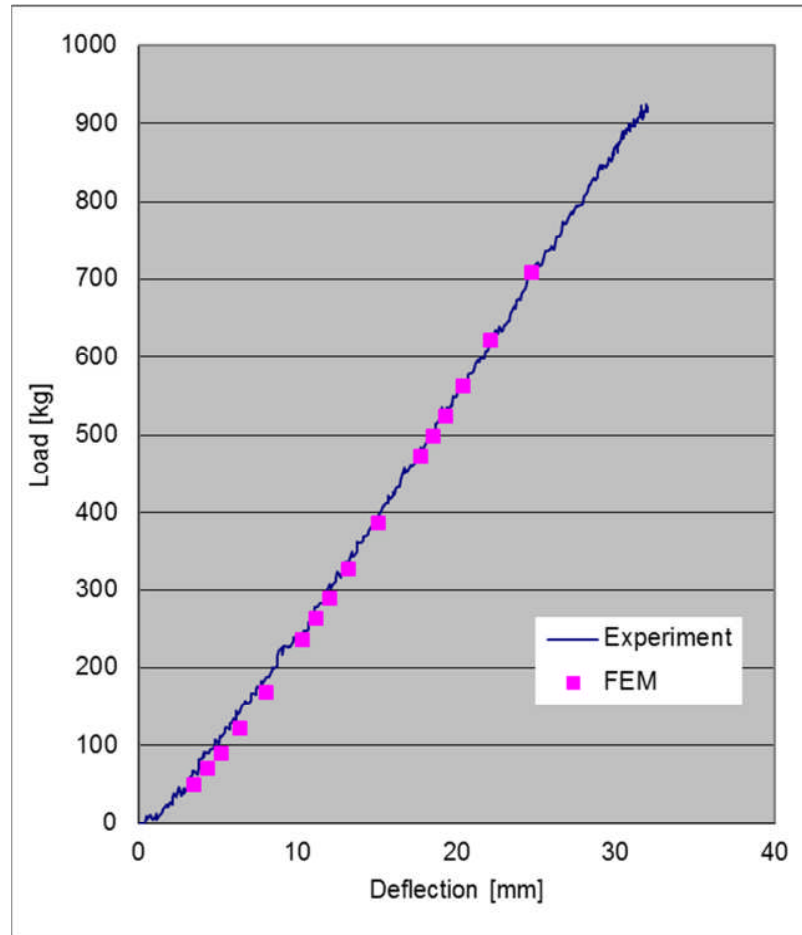


Figure 5 – Vertical load deflection curve – FEM vs Experiment

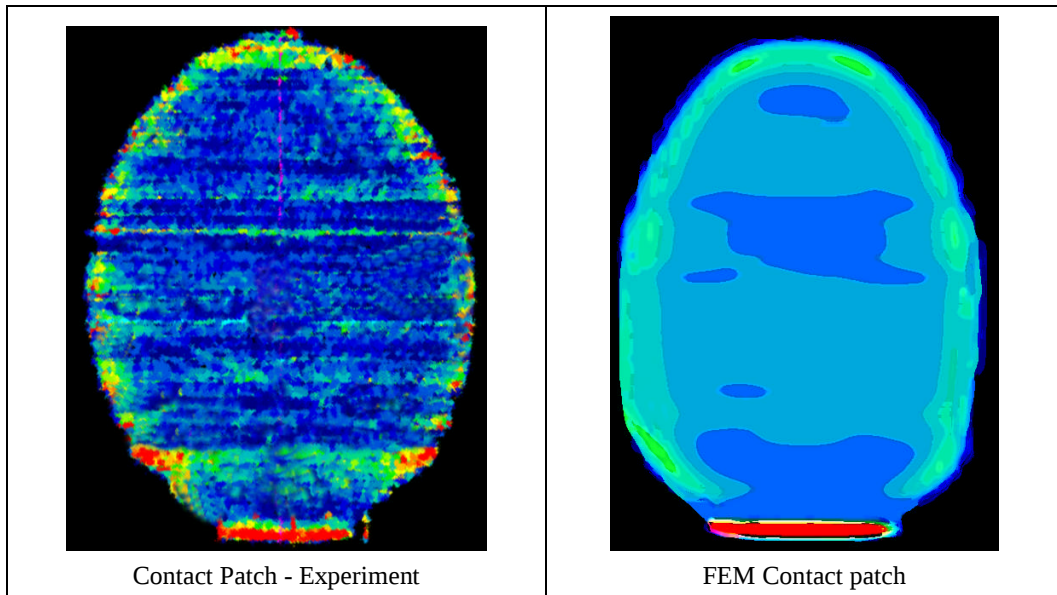


Figure 6 – Footprint pressure distribution

2.3 Indoor test verification – dynamic

Measure the tyre deformation in service condition rise several applied problem to be solved. Hold tight a scan system to a running car is an objective limitation for the measurement quality. Scan system dimension is another limiting aspect.

To properly take the external tyre shape in several conditions Pirelli commonly use high speed indoor test bench; for the specific case of FE model calibration we used drum-road set-up. During the test we keep constant the vertical load leaving the wheel hub free to lift as a consequence of spinning velocity. The scan system has been applied to measure the sidewall profiles at different speed up to 300kph. Figure 7 shows the scan pointing toward the contact patch center, the region where we expect to have the highest sidewall deformation.

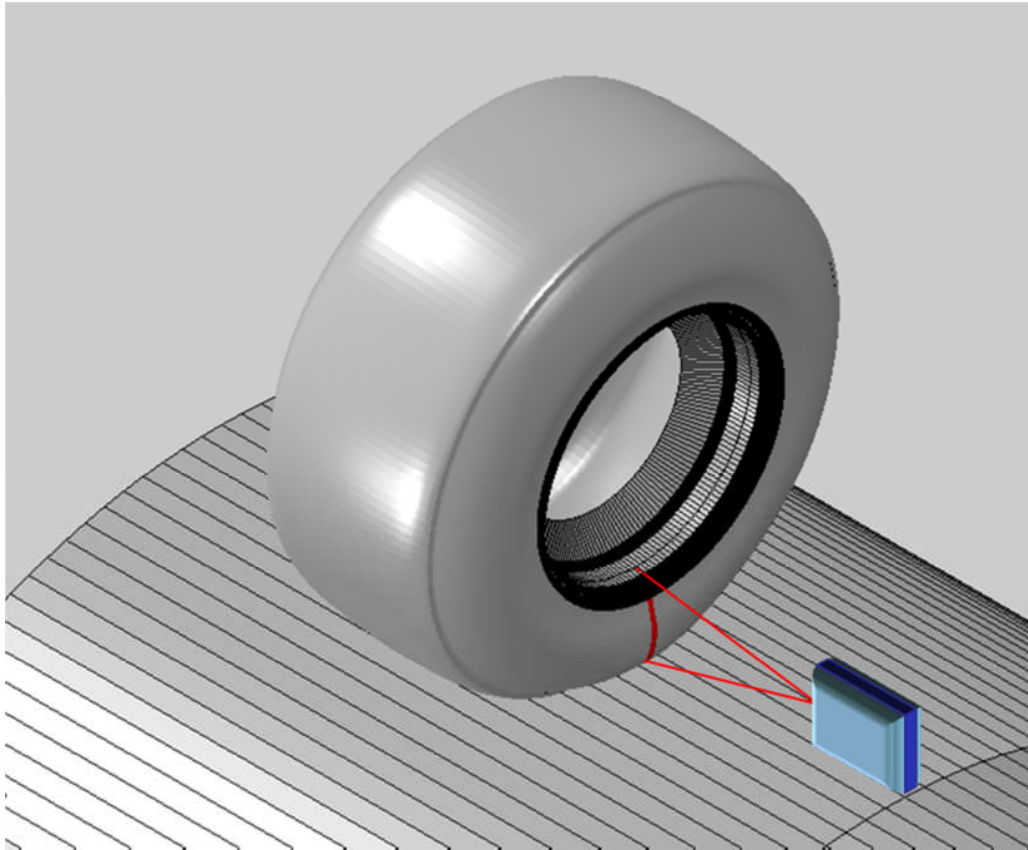


Figure 7. Laser scan profile measurement

The laser scan is able to extract the rolling tyre profile, providing the deformed geometry in a 2D CAD format. To compare this experimental data we used the Plug-in utility for extracting two-dimensional parts from meshes in Abaqus/CAE (Abaqus answer ID 2414).

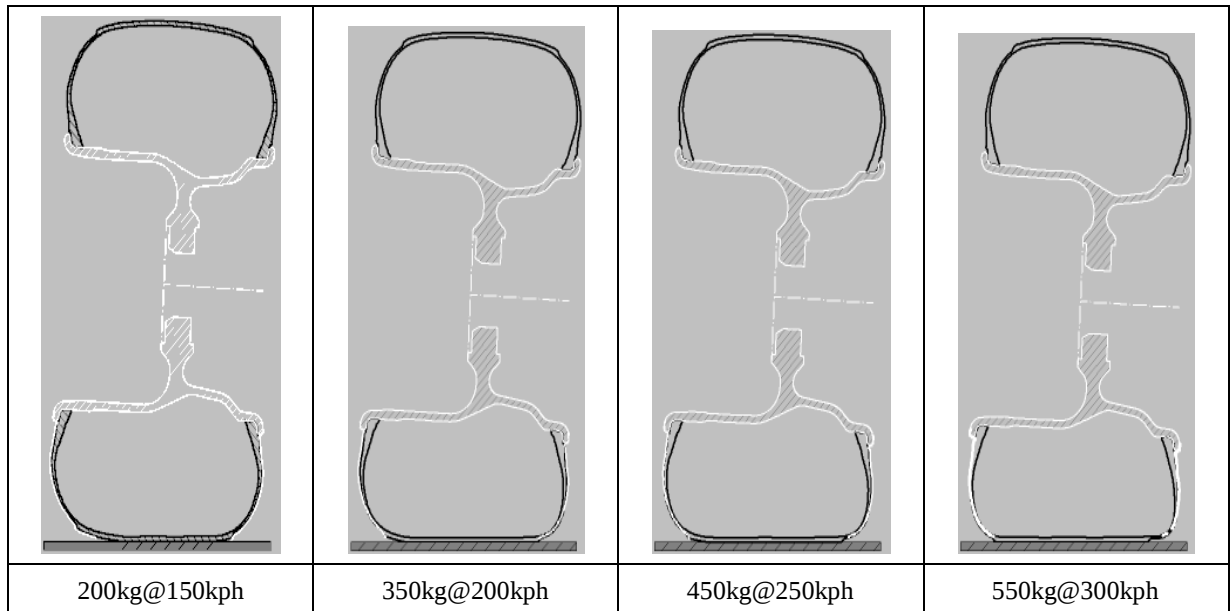


Figure 8 – Front tyre cross-section comparison (18psi, CA=3°)

Figure 8 shows Abaqus/Explicit results comparison with experiment at four different load conditions. Bottom tyre profile is used as reference (white line in pictures). The rim cross-section is included to emphasize the hub deflection. For this tyre the hub lift due to high spinning velocity is not enough to balance the increment of vertical load (downforce).

3. References

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