

# Role of Abaqus in the Development of the Michelin Tweel<sup>®</sup> Tire

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*Abstract: Abaqus simulation tools have been a critical part of the development of the Michelin Tweel tire structure. A design process has been built around Abaqus 2D and 3D simulations using both Abaqus/Standard and Abaqus/Explicit solvers. This process has allowed Michelin Tweel tire designers to quickly optimize new Tweel tire dimensions for stiffness, contact pressure, durability, and rolling dynamics. The available Python Scripting Interface and Fox Toolkit have allowed for elements of the process to be simplified into easy-to-use tools that help reduce the burden of building ready-to-run models and post processing results. This paper will outline this design process with emphasis on modeling techniques and the Python based tools.*

*Keywords: tweel, tire, non-pneumatic, Fox Toolkit, Python*

## 1. Introduction

### 1.1 Motivation

The Michelin Tweel tire has been under development for several years and has matured to the point where it has been extensively field tested on low speed applications like the skidsteer loader. Current efforts are focused on advancing the technology to higher speed applications.

Tweel tires are similar to pneumatic tires in that they carry significant loads at large deformations but are quite different in that they carry these loads without the benefit of inflation pressure. Whereas all pneumatic tires of a given size, inflated to a particular pressure, will have nearly identical vertical stiffness and ground contact pressure, a Tweel tire has its stiffness and contact pressure governed by a host of geometric and material parameters. While certain simple expressions have been developed to estimate some Tweel tire characteristics such as contact pressure, most characteristics do not lend themselves to simple analytical expressions.

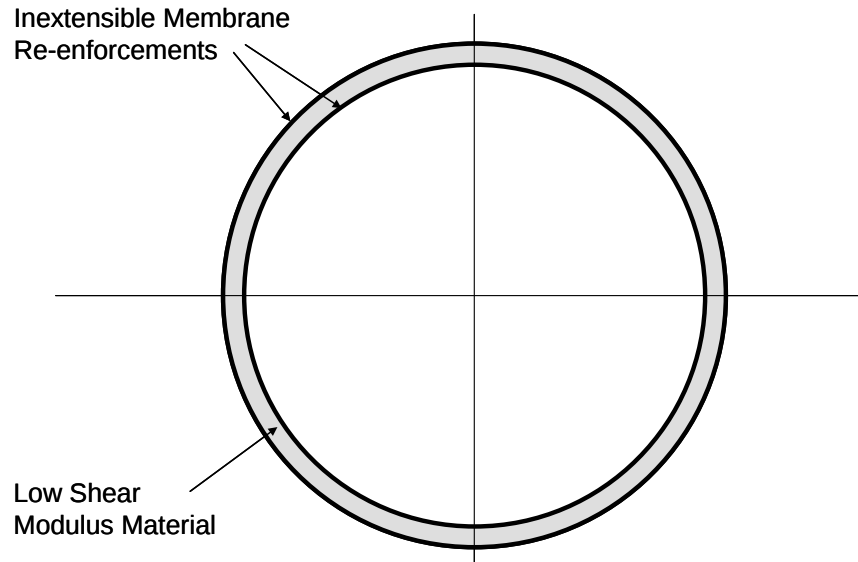
As a result, Michelin has found it essential to have finite element based analytical tools that can, at a minimum, quickly and easily predict the stiffness, contact pressure and stress state of a new Tweel tire design. This paper will describe the tools and the design process used to define a Tweel tire using the Abaqus simulation environment.

### 1.2 Tweel Tire Mechanics

While the purpose of this paper is not to describe the mechanics of the Tweel tire, it is necessary to outline some of the basics of Tweel tire mechanics. The Tweel tire is a structure designed to mimic the critical characteristics of the pneumatic tire without the requirement of inflation pressure (Rhyne, 2006).

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In the Tweel tire, the inflation pressure is replaced by a circular beam that deforms almost entirely in shear. It consists of two inextensible membranes separated by a relatively low shear modulus elastic material and is called a “shear beam”. A schematic drawing of the Tweel tire shear beam is shown in Figure 1. This ring can be made from typical “tire” materials like rubber and steel cable reinforcements or it can be made from relatively low modulus polyurethane and reinforced with steel cable or other reinforcing materials.



**Figure 1. Schematic of Tweel Tire Shear Beam.**

When this ring is forced to conform to a flat surface it will generate nearly uniform contact pressure where the average contact pressure is given by

$$p \cong \frac{Gh}{R} \quad (1)$$

where

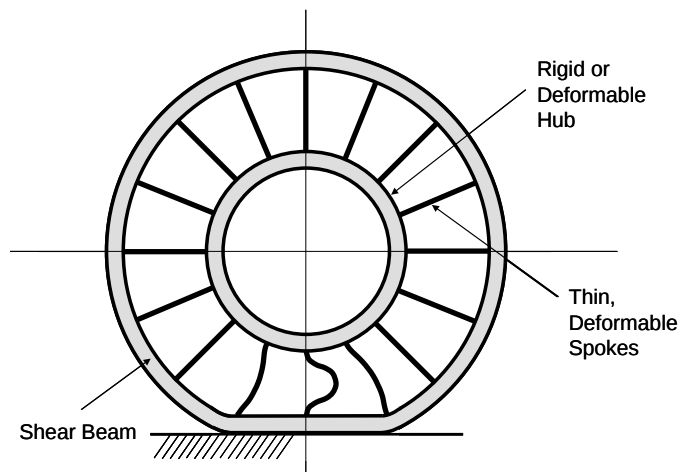
$p$  is the contact pressure,

$G$  is the shear modulus of the elastic material between the inelastic membranes,

$h$  is the nominal thickness of the shear beam, and

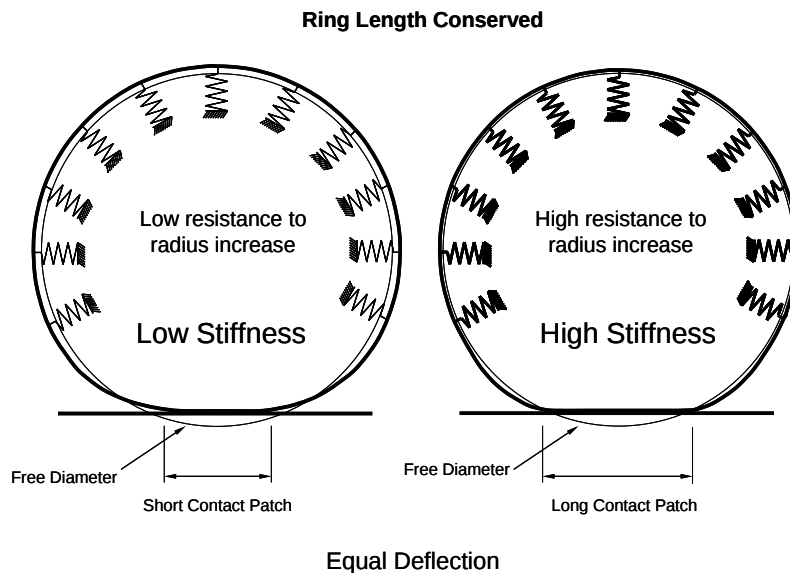
$R$  is the nominal radius of the shear beam.

The shear beam is connected to a hub with flexible spokes which buckle when compressed as shown in Figure 2. These spokes are normally made of polyurethane.



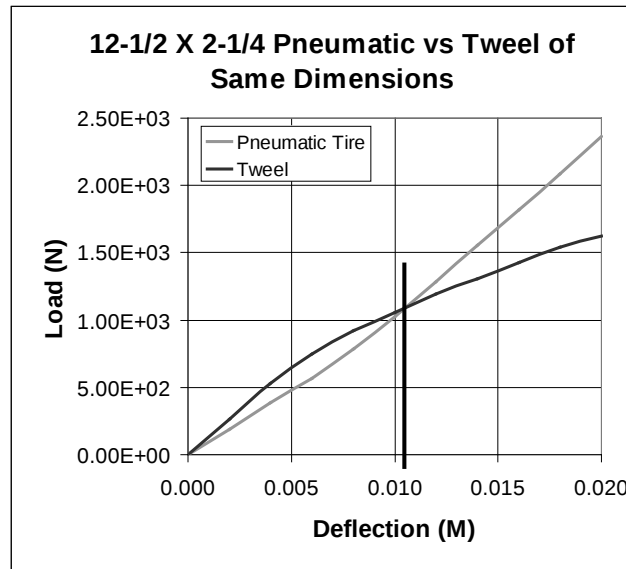
**Figure 2. Schematic of Complete Tweel Tire with Spokes.**

The overall vertical stiffness of the Tweel tire is controlled by the bending and extensional stiffnesses of the ring combined with the radial stiffness of the spokes. If the spokes act as weak springs, the upper portion of the inextensible ring can easily increase in diameter and the contact patch can be short. This represents the low stiffness case. If the spokes act as stiff springs, it is difficult for the ring to increase in diameter and the contact length must be greater. This is the high stiffness case. Figure 3 gives a schematic representation of these two cases. Note that the contact pressure is independent of this mechanism. Thus the contact pressure and the stiffness of the Tweel tire are uncoupled.



**Figure 3. Effect of High and Low Stiffness Spokes.**

A comparison of the load deflection behavior of a pneumatic tire and a Tweel tire of the same dimension are shown in Figure 4. While the pneumatic tire acts as a hardening spring, the Tweel tire acts as a softening spring. Note that the two tires have the same load at a deflection of about 0.011 M. Looking at the 0.011 M point where the secant stiffness of both tires is the same, we can see that the tangent stiffness of the Tweel tire is about half that of the pneumatic tire. We have the paradoxical situation of low deflection and low stiffness.



**Figure 4. Load Deflection of a Tweel Tire Compared to a Pneumatic Tire.**

## 2. The Tweel Tire Design Process

Once an application has been identified for a new Tweel tire design, the first step in the design process is to define the technical targets against which the design iterations can be measured. The following list is typical of the technical characteristics that might be specified for a new design:

- Overall Tweel tire Geometry (Diameter, Width)
- Hub Geometry (Diameter, Width)
- Mass
- Stiffness (Vertical, Lateral, and Longitudinal)
- Ground Contact Pressure (Average and Peak)
- Rolling Resistance
- Durability
- Maximum Speed
- Impact Resistance

With a well defined set of targets in mind the next challenge for the Tweel tire designer is to begin to flesh out a definition of the geometry and materials that will satisfy the targets without exceeding the limitations of the materials chosen.

At a minimum, the designer must define the following parameters:

- Ring Shear Layer Material modulus
- Ring Shear Layer Thickness
- Spoke Modulus
- Spoke Thickness
- Spoke Count
- Spoke Curvature
- Spoke Length

Typically what the designer will do initially is choose a material for the ring shear layer and then calculate a shear layer thickness using Equation 1. This assumes that the nominal diameter of the Tweel tire can be determined from the application. With the ring thus defined it is now a question of how to define the spokes. To accomplish this, a fast, simple-to-use finite element tool is very helpful.

### **3. Two Dimensional Static Analysis**

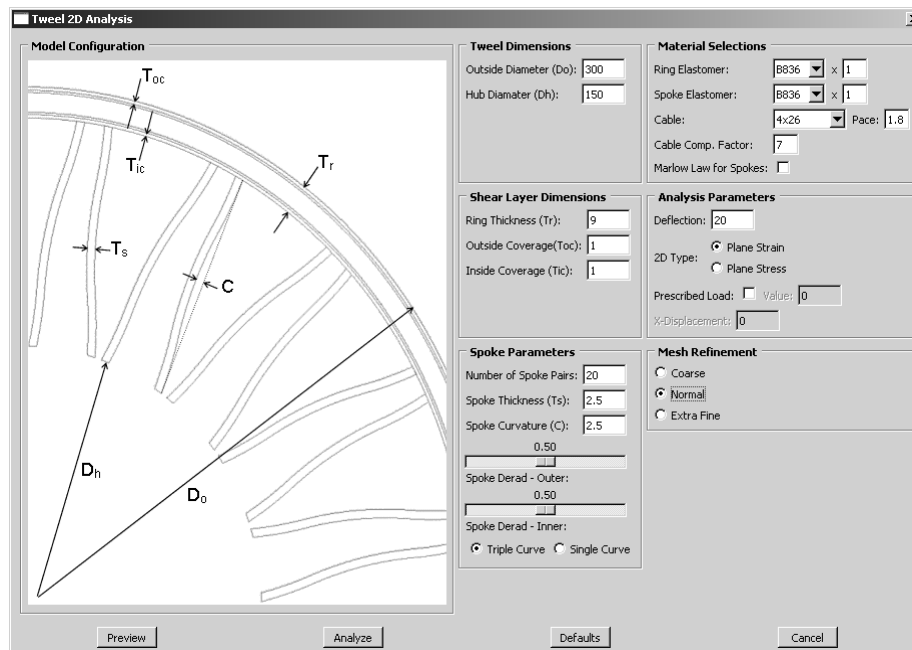
#### **3.1 2D GUI Design and Analysis Tool**

While the Tweel tire geometry is relatively simple to describe, building even two dimensional (2D) models over a wide range of geometric and material variations can be extremely tedious and time consuming. This is where the ability to automate the process of defining the basic elements of a Tweel tire design become crucial to the Tweel tire designer.

To this end, Michelin has developed a simple GUI based tool to define complete ready-to-run Tweel tire models using the Abaqus GUI Toolkit. The Abaqus GUI Toolkit is an extension of the FOX GUI Toolkit. FOX, which stands for Free Objects for X, is a modern, object-oriented, platform-independent GUI toolkit. Since the Abaqus GUI Toolkit is platform-independent, once you write an application for one platform, you can run that application on all supported platforms (Abaqus, 2008).

Not being expert GUI programmers, we started by looking at the Bolt Application Example available on the Abaqus Process Automation Portal. This example gave us a place from which to start that was actually quite close, in terms of basic functionality, to what we desired for our Tweel Tire Design application. The final result is a plug-in that appears as a menu item under the “Tools” menu in ABAQUS/CAE.

The 2D Tweel Tire Design GUI interface form is shown in Figure 5.



**Figure 5. 2D Tweel Tire Design GUI Interface Form.**

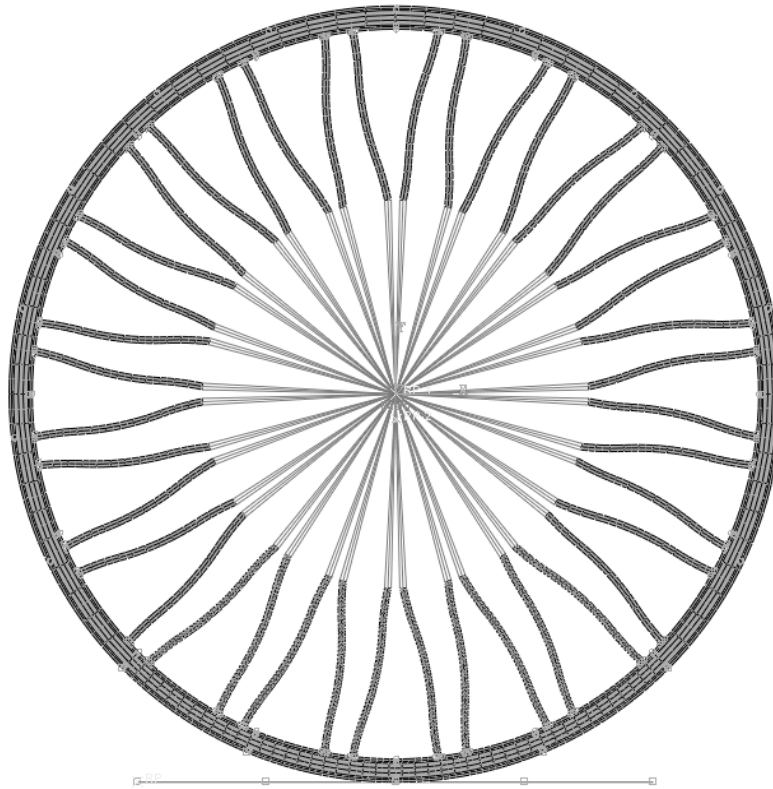
This form describes the most basic definition of a Tweel tire structure. The left hand column specifies the geometric dimensions which are defined in the inset graphic. Next, the two sliders allow the user to define the degree to which the spoke ends do not fall on radial lines. The final geometric choice the user can make is whether the spokes will have their curvature defined by a single circle or by three tangent circles as shown in the inset graphic.

The top block in the right hand column allows the user to choose spoke and ring materials, cable type and pace, and cable compression factor. The compression factor defines the ratio of tensile to compressive modulus of the reinforcing cables in the circumferential direction. Finally, this block allows the user to select Marlow law properties for the spokes. This simplifies dynamic simulation that might be done later in Abaqus/Explicit.

The next block allows the user to choose the ground deflection to be applied and whether the 2D elements will be assumed to be plane strain or plane stress. This block also has the option to allow the user to define two additional simulation steps with a prescribed vertical load and prescribed longitudinal deflection of the contact patch at the prescribed load. These steps are made optional since in the early stages of design a simple load vs. deflection curve is usually sufficient. Later the Tweel tire designer might want to know the deflection at a specific load and, with the prescribed longitudinal displacement, the overall longitudinal stiffness of the Tweel tire.

The final block in the right column allows the user to select the degree of mesh refinement in the model. All of the elements used in the model are quadratic.

Once the user has completely filled out the form, he can select the Preview button to build the complete meshed model and display the resulting assembly. A typical model is shown in Figure 6.



**Figure 6. 2D Tweel Tire Generated by the GUI Tool.**

If at this point he sees something that he would like to change he can easily do so by simply modifying his selections in the GUI form.

### **3.2 Model Definition**

The 2D model that is created by the GUI is an assembly of instances of six unique parts. The ring is comprised of one part defining the elastomeric portion of the ring and two parts defining the circumferential reinforcements. The reinforcement parts are constrained as embedded elements in the elastomeric portion of the ring.

Multiple instances of two parts are used to define the spoke array. The only difference between these two parts is the mesh refinement used on the spokes that appear near the lower portion of the Tweel tire where the load is applied. The spokes are connected to the ring using a tied constraint and are connected to the center of rotation by a coupling constraint.

The final part is the ground part which is defined as an analytical rigid surface. Initially, frictionless contact is defined between the outer portion of the ring and the ground. If the user

specifies an “X-Displacement” in the GUI form, the contact is changed to rough for the last analysis step.

Once the designer is satisfied with the model definition he can simply press “Analyze” to begin execution of the simulation job. On a well equipped Windows desktop workstation, the solution will be completed in a couple of minutes depending on convergence progress.

The minimum analysis steps defined by the GUI tool are the following:

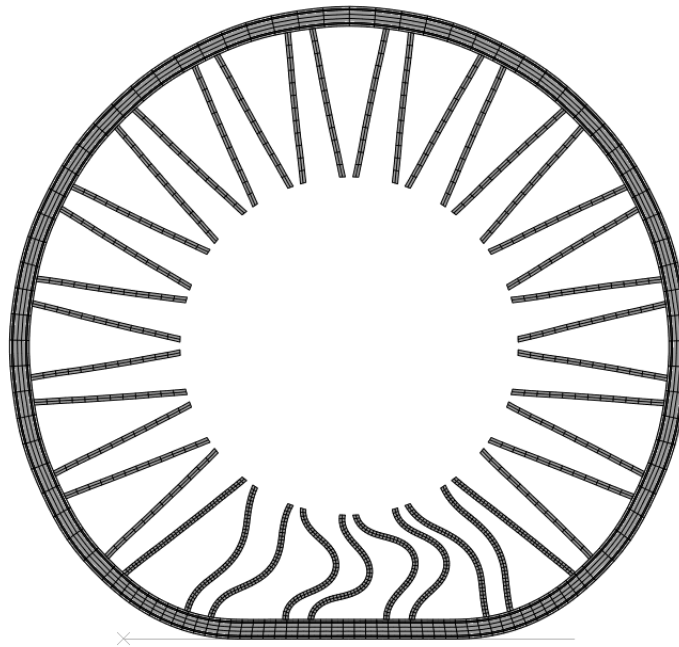
1. Cool the entire structure from 125°C to 25°C. This generates the correct pre-stresses in the spokes caused by cooling.
2. Move the ground up a specified amount while holding the center coupling point fixed.

Two additional analysis steps are generated if the user chooses the prescribed load option:

3. Replace the prescribed ground displacement with a prescribed load.
4. Change the contact friction to rough and move the ground a prescribed distance in the X-direction.

### 3.3 Typical Results

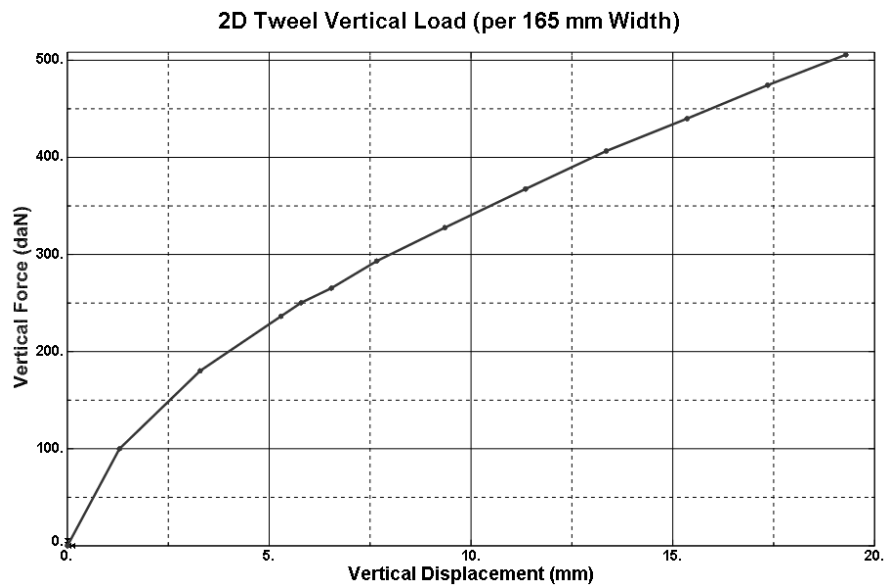
Once a converged solution is obtained, the designer is finished using the GUI tool. At some point in the future we might choose to develop a GUI based post-processing tool but for now all post-processing automation is done using Python scripts. An important point to make here is that, by comparison, Python scripts are far easier to build than robust GUI based tools and as such are a very efficient means of adding a maximum amount of automation with minimum effort.



**Figure 7. Deformed View of a 2D Tweek Tire Generated by the GUI Tool.**

Figure 7 shows a typical deformed Tweel tire model. Normally, one of the first responses the designer would like to display for a new design is the vertical load versus deflection, as shown in Figure 8. To accomplish this task a Python script was written that completes the following steps:

1. Locate the node that is at the bottom of the structure at the end of the Cooling Step and extract the vertical displacement data for that node.
2. Determine the distance from the ground to the bottom node at the end of the Cooling step and subtract that offset value from the vertical displacement data for that node.
3. Extract the vertical reaction force on the ground part reference node.
4. Query the user for the assumed width of the Tweel tire being analyzed.
5. Plot the vertical reaction force on the ground versus the offset vertical displacement data for the bottom node.
6. Dress up the plot as desired.



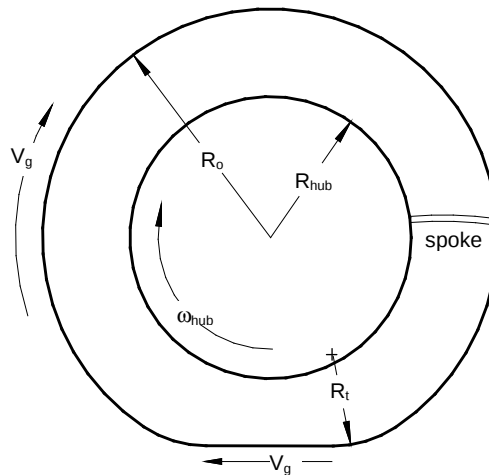
**Figure 8. 2D Vertical Load vs Deflection Plot Generated Using Python Script.**

Another handy use for Python scripts in post processing is the generation of custom field values from existing field values. One example might be to compute the maximum shear strain from the difference of the first and third principal strains. Another example would be to generate a custom field of an existing field value in a particular set of units. For instance, we normally generate all of our model data in pseudo-SI units (daN, mm, sec) but often want to view and communicate strain energy density values in PSI. A simple script can be run to generate a new field value of strain energy in units of PSI for every integration point in some or all steps.

## 4. Two Dimensional Dynamic Analysis

In the case of developing a Tweel tire for a high speed application, a check of the dynamic spoke response is made once the 2D static behavior of the new Tweel tire design is acceptable. Further details of this analysis method are given in a paper the author presented at the 2004 Abaqus conference (Cron, 2004).

In summary, the procedure involves using beam connectors to prescribe idealized paths corresponding to the paths taken by the inner and outer ends of a spoke as it travels around a rotating Tweel tire. In an actual Tweel tire, the inner ends of the spokes are connected to a circular hub and as such follow a simple circular path with constant rotational velocity at a constant radius. The outer ends of the spokes, however, follow a more complicated path idealized as three tangent circles and a tangent horizontal line and are constrained to a constant tangential velocity. The idealized configuration is shown in Figure 9.



**Figure 9. Idealized Geometry for 2D Spoke Dynamics Simulation.**

The challenge is to precisely define the geometry of the idealized paths and the timing required to transition from one portion of the path to the next. The assumption is made that the static shape of the ring determined from the 2D static calculation will define the shape of the path of the spokes in the 2D spoke dynamic simulation. The challenge is to quickly extract the idealized shape from a given static solution and set up the dynamic model. Left to be completed by hand, this is an arduous task. Again the Python scripting language allows us to write code that can access the deformed geometry and extract all of the information necessary to define the dynamic analysis. The steps taken by the script are the following:

1. Determine the best fit circle describing the position of the interior nodes of the upper half of the ring. This will determine the radius of the upper circular portion of the path.
2. Identify all of the nodes in contact with the ground and from them determine the contact patch length. This will define the length and position of the line defining the contact region.

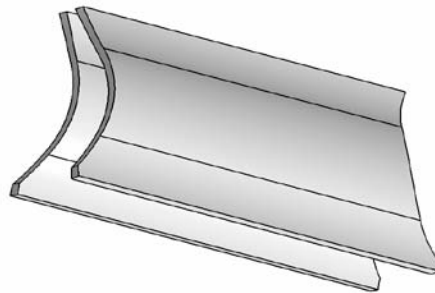
3. Compute diameter and center of a circle that connects the upper circle to the ground contact line.
4. Extract a finely meshed spoke pair from the static solution model.
5. Apply static boundary conditions to the single spoke pair and cool the structure with a coupled temperature-displacement calculation.
6. Import the cooled structure into an ABAQUS/Explicit model.
7. Create beam connectors that will attach the spoke ends to the center of rotation. Note that for the outer spoke end the center of rotation will change depending on where the spoke is positioned at a given time. This implies that the outer spoke end will actually have two beam connectors attached to it. One of length  $R_o$  and another of length  $R_i$ .
8. Query the user for the ground speed. This speed establishes the tangential velocity of the outer spoke end. The tangential velocity along with the total outer path length defines the time for one revolution and, thus, establishes  $\omega_{hub}$ .
9. Define boundary conditions and step times. The step times are computed from the outer path lengths and the tangential velocity. The boundary conditions on the beam connectors are simply a rotational velocity that enforces  $\omega_{hub}$  and the tangential velocity of the outer spoke ends.

The user can then run the simulation by hand. This simulation is fairly light and the computation time for two revolutions of the spoke (one revolution is used to ramp the spoke to full speed) is around 20 minutes on a well equipped Windows desktop workstation.

## 5. Three Dimensional Static Analysis

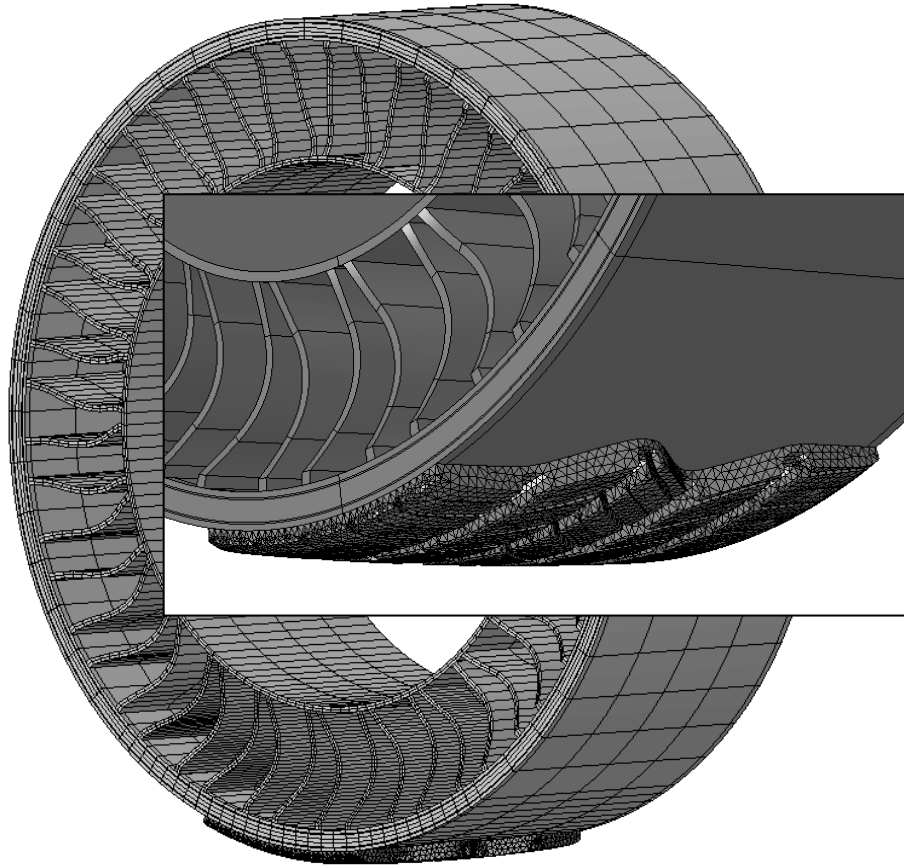
### 5.1 Model Definition

Once satisfied with the 2D static and dynamic results, the Tweel tire designer is ready to extend the analysis to three dimensions (3D). The first step in accomplishing this is to take the simple spoke geometry defined in the 2D model and use it as a basis to build geometry for the 3D spoke. Normally, 3D spoke geometry is generated using Catia though Abaqus/CAE could also be used. The primary additional definition in the 3D spoke is the lateral profiling or “scalloping” on the edges of the spokes. Typical spoke geometry for a 3D Tweel tire design is shown in Figure 10.



**Figure 10. Typical Spoke Geometry for a 3D Tweel Tire.**

The remainder of the geometry would normally be generated in Abaqus/CAE. The exception would be if a complicated tread geometry was to be included in the analysis. In that case the tread geometry would also be generated in Catia. Typical geometry for a complete 3D static Tweel tire model is shown in Figure 11 with the mesh.

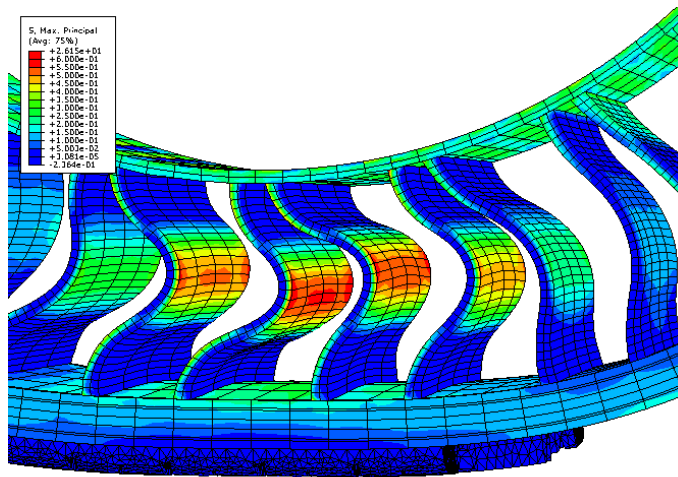


**Figure 11. Complete Geometry for a 3D Tweel Tire With Orphan Mesh Tread.**

This model is constructed in a manner similar to the 2D model described earlier. That is, the spokes are instanced and then tied to the neighboring structures. The internal reinforcements are modeled as solid cylinders that are then embedded into the “host” ring structure. The tread might be represented by axisymmetric geometry included directly in the ring definition. In the structure shown in Figure 11, the tread is actually defined as a detailed orphan mesh that is tied to the outer ring cylindrical surface.

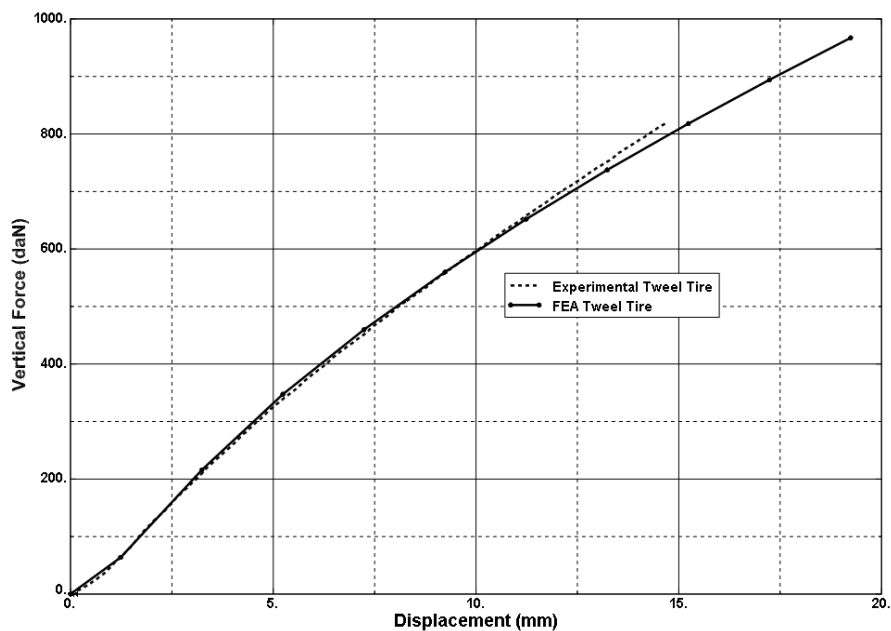
## **5.2 Typical Results**

The deformed view of the contact region of a typical 3D Tweel tire is shown in Figure 12. Here we can see that the most important stresses in the spokes occur in the contact region.



**Figure 12. Deformed View of the Contact Region of a Typical Tweel Tire.**

Again, for the 3D Tweel tire, the designer is interested in the vertical load versus deflection. Figure 13 shows the plot of load versus deflection for the FEA model along with the results from an experimental Tweel tire. This plot is generated by a Python script that is essentially the same as the script described earlier for the 2D case.



**Figure 13. 3D Tweel Tire Vertical Load vs Deflection.**

## 6. Three Dimensional Dynamic Analysis – Rolling

One of the challenges in Tweel tire development has been the noise and vibration caused by the Tweel tire rolling at speeds typical of an automobile. We have found a fairly simple technique for evaluating Tweel tire vibrations for a complete 3D Tweel tire using Abaqus/Explicit.

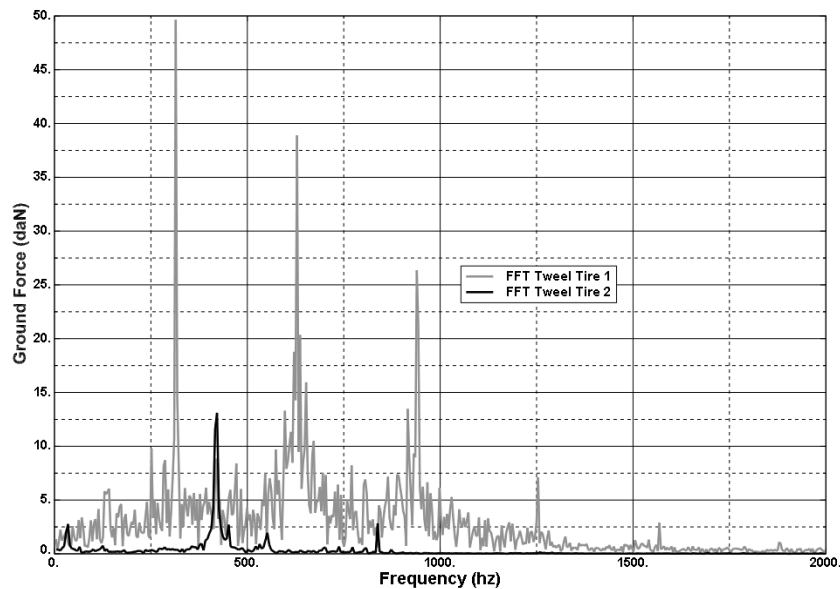
The method involves first modifying the static model described above to make it suitable for simulations with Abaqus/Explicit. The modifications normally include changing the element type from quadratic to linear, changing the ring mesh so that it is axisymmetric, simplifying the tread into axisymmetric ribs and grooves, and making the mesh the same on all of the spokes. In our static models we often employ user-defined hyperelastic material definitions which we normally convert to a Marlow definition in the dynamic model.

The simulation then proceeds as follow:

1. Begin the simulation with an initial condition of rotation applied to the entire Tweel tire corresponding to the speed of interest. At this point the Tweel tire is assumed to be at its molding temperature.
2. Over a period of 0.1 seconds, simultaneously cool the structure and move the ground up to the desired final deflection position. Note that contact between the Tweel tire and the ground is assumed to be frictionless.
3. Hold the conditions constant for ~0.5 seconds and record the vertical reaction force on the ground as History data.

Once the simulation is completed, a Fast Fourier Transform is applied to the ground force signal. Our experience has been that this ground force signal will be very sensitive to vibrations present in the rolling Tweel tire. In fact, this simulation appears to be more sensitive under the assumption of frictionless contact than it is if we roll the Tweel tire with friction and actually translate the ground (or the Tweel tire).

Figure 14 shows the results from two Tweel tires of similar design with very different ground force signals. Experimental objective and subjective noise results confirmed in this and other cases that the reduced ground force signal did in fact correspond to a greatly reduced level of noise and vibration.



**Figure 14. Simulated Ground Force Spectra Comparison of Two Tweel Tires.**

## 7. Summary

Abaqus simulation tools have been a critical part of the development of the Michelin Tweel tire structure. A design process has been built around Abaqus 2D and 3D simulations using both Abaqus/Standard and Abaqus/Explicit solvers. This process has allowed Michelin Tweel tire designers to quickly optimize new Tweel tire dimensions for stiffness, contact pressure, durability, and rolling dynamics. The available Python scripting and Fox Toolkit have allowed for elements of the process to be simplified into easy-to-use tools that ease the burden of building ready-to-run models and post processing results.

## 8. Acknowledgements

Mike Shubert of the Dallas support office was extremely helpful in developing the GUI tool and other Python scripts referred to in this paper. Without his assistance our progress would have been greatly reduced.

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