



# Development and Implementation of Large-Scale Numerical Models for Shape Memory Mars Spring Tires

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# **Development and Implementation of Large-Scale Numerical Models for Shape Memory Mars Spring Tires**

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## **Summary**

The current work focuses on implementation of the user-defined shape memory alloy (SMA) model in the finite element analysis program ABAQUS for large-scale simulations of the Spring Tires made of SMA developed at the NASA Glenn Research Center. The main objective of this study was to improve and optimize the structural design of the SMA tires through in-depth numerical analysis and sensitivity studies. Various design variables (wire diam., coil diam., pitch, spring length, and bead angle) were varied to study their influence on the global load-displacement response of the tire construct. A detailed investigation of the three-dimensional stress states was also carried out to enhance understanding of the local changes as the tire goes through global deformation. It was concluded that a robust numerical model with a good predictive capability, together with a thoughtfully crafted sensitivity study, can result in reduced design iterations required to reach a desired tire performance. This will, in turn, lead to significantly reduced manufacturing time, required labor, and testing expense.

## **1.0 Introduction**

Shape memory alloys (SMAs), otherwise known as memory metal or smart metal, are named as such because they can be deformed to very high strain levels and then return to their original shape via the application of thermal or mechanical energy, depending on the nature of the system employed in the application. Typically, SMAs are utilized in one of two fundamentally different ways. The first makes use of the superelasticity/pseudoelasticity (SE/PE) phenomena (Nemat-Nasser and Guo, 2006; Wang, Yue, and Baruj, 2005; Zhu et al., 2004), where the application of stress causes the material to undergo a metastable transformation, but the material returns to its original form when the applied stress is removed. The second makes use of the shape memory effect (SME) (Stebner et al., 2009; Jones and Dye, 2011; Benafan and Gaydos, 2017) where the material is deformed in the low-temperature phase, but the deformation remains until the material is heated above the transformation temperature, at which point the material returns to its original form. Because of their ability to act in such vastly different capacities, SMAs have played an important role in various innovative engineering and medical applications such as aerospace actuators, vibration damping devices, and coronary stents. Research

involving SMAs can be grouped into three main areas: (1) experimental work, (2) constitutive modeling efforts, and (3) analytical (computational) studies for boundary value problems involving structural components and/or SMA devices. A comprehensive literature review and a detailed list of previous studies in all three fields has been already presented in detail by Saleeb et al. (2013, 2015). In the area of constitutive modeling, some recent research efforts have been made over the past few years utilizing micromechanical and phenomenological approaches to model the SMA behavior. Some recent references in these subareas include Cisse et al. (2016), Chowdhury (2018), Scalet et al. (2019), Petrini and Bertini (2020), Simoes and Paneda (2020), Zhang and Baxevanis (2021), and Alsawahli and Landis (2022). Among all the recent numerical models, none has focused on large-scale simulations of SMA structures for aerospace or industry use, which is of great interest to application-based SMA research.

Rovers utilized in lunar and Martian terrains require tires that are capable of traversing rugged fields while withstanding extreme temperatures and atmospheric conditions. Inspired by the flexible wire-mesh tires used on three lunar roving vehicle (LRV) missions to the Moon during Apollo 15, 16, and 17 (see Figure 1(a)), a new compliant tire technology was developed in 2009 known as the Spring Tire (Benzing, Kish, and Asnani, 2015). Co-invented by the NASA Glenn Research Center and Goodyear Tire & Rubber Company, the Spring Tire (Figure 1(b)) consists of several hundred coiled springs woven into a flexible mesh and formed into the shape of a tire. Like the LRV wire-mesh tires, the Spring Tire conforms to the terrain to provide traction and reduce energy loss; however, the use of coiled wires versus straight wires provided major improvements in durability and load-carrying capacity. Like the LRV wire-mesh tires, the original Spring Tires were made from spring steel and were prone to permanent deformation when undergoing high localized loads. Subsequently, a new iteration of this technology was invented, known as the Superelastic Tire (Padula, Benzing, and Asnani, 2019) (Figure 1(c)). This new technology incorporated the use of superelastic SMA springs, which could effectively undergo approximately 30 times more reversible deformation than the steel springs. This new technology provided even greater durability and allowed for more flexibility in design, such as the use of other structural forms to reduce mass or increase load-carrying capacity.

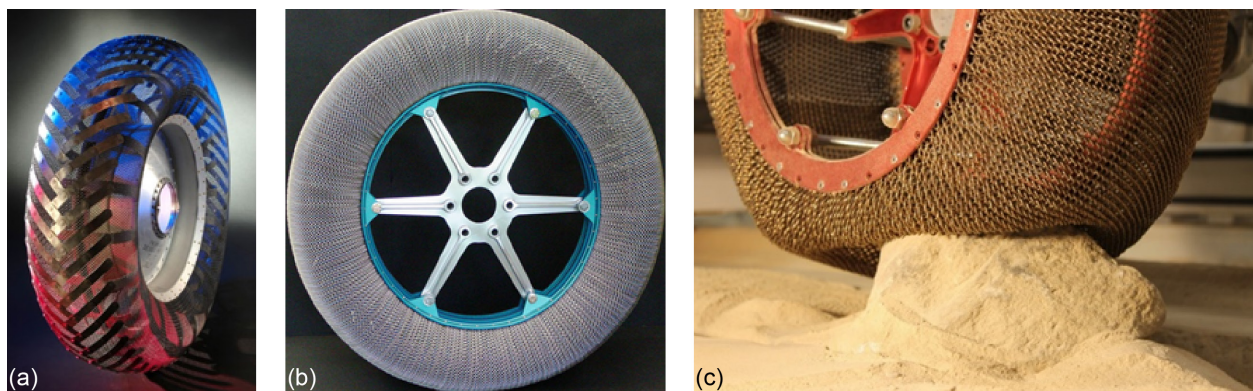


Figure 1.—Aerospace tire technologies (collectSPACE, 2023). (a) Apollo LRV wire mesh. (b) Original Spring Tire. (c) Superelastic Tire.

Because of the unique nature of both the SMA material and the complex interactions between the springs, designing Spring Tires for a specific application requires extensive effort. Historically, design decisions have relied on full-scale empirical testing; however, this is very expensive and time consuming, especially when multiple iterations are needed. Another challenge to Spring Tire design is that nearly all the design parameters are coupled. For example, if a designer wanted to increase tire stiffness by changing the spring pitch (the distance from the center of one coil to the center of the adjacent coil, refer to Sec. 4.1, SMA Tire Experiments), this would require changing the number of springs and ultimately affect performance properties such as mass and envelopment. Also, because the materials are temperature dependent, it is critical to design the tires so they will have sufficient performance at the full temperature range of a given mission, which is also difficult to do empirically. To address the aforementioned challenges, development and application of a comprehensive and reliable numerical model was deemed essential for reducing experimental costs and schedule time and also for guiding the experimental team through various stages of the design process.

Development of a large-scale, robust, and predictive finite element (FE) model for the Spring Tires made of SMAs is the main emphasis of this report. The novelty of this work lies in the thorough, detail-oriented, and computationally efficient FE analysis (FEA) of full-scale SMA tires. A well-thought-out material characterization plan followed by model validation and a systematic sensitivity study on SMA structures has never previously been reported in the literature. Developing a robust, validated numerical model entailing complex spring interactions within a tire construct is the first essential step towards organizing a reliable numerical sensitivity study for the current application. After validating the numerical model through comparison with available in-house experiments at the material level, one can change tire design variables in a systematic manner to examine the resultant load-displacement response and internal stress and strain states. Detailed analysis of the resultant tire stiffness and internal states can aid in determining tire configurations with an anticipated favorable performance, which will, in turn, substantially reduce the cost and schedule time of the tire build, manufacture, and assembly.

Following this introduction, a summary of the FE model construction is presented in Section 2.0. Section 3.0 includes a brief description of the user-defined SMA model followed by a detailed report of the characterization process. Experimental results and model validation are discussed in Section 4.0. Detailed numerical sensitivity study results are shown in Section 5.0, followed by strain and stress analysis in Section 6.0. Finally, main concluding remarks are summarized in Section 7.0.

## **2.0 Construction of Finite Element Model**

The FEA consists of a full Spring Tire constructed through an automated Python scripting algorithm in the FE software ABAQUS (Dassault Systèmes Simulia Corp.). After importing the tire geometry as a computer-aided design (CAD) solid model, proper element types, material properties, and boundary conditions are assigned to run the FE model. In a highly nonlinear analysis, one needs to pay special attention to individual element size and element types to ensure an accurate solution. Setting the element size to approximately 1 to 2 percent of the specimen size (in this case, an individual spring's wire diam.) and choosing three-dimensional (3D) quadratic elements instead of linear brick elements will provide a robust converged solution after a few iterations (Fish and Belytschko, 2007). The tire is fixed at the rim; the end elements of each individual spring are restricted at the rim area. The contact between the springs is defined through various contact controls. Node-to-surface contact algorithms, used here, are generally more stable with a given tangential and normal contact penalty definition. ABAQUS assumes by default that the interaction between contacting bodies is frictionless. Therefore, one should include a friction model to capture the interaction properly. Introducing penalty stiffness (tangential and normal), using a

higher friction coefficient, and not allowing surface separation post-contact, leads to a more stable solution. Quasi-static compressive loading is applied through a moving plate (Figure 2), where the velocity of the moving plate is ramped up using a smooth quasi-static step definition. As long as the kinetic energy of the system remains smaller than 1 percent of the internal energy, the velocity of the moving plate can be artificially increased to accommodate a reasonable simulation time. After going through these procedures and conducting a thorough mesh convergence study, a tire model with a fully elastic material was run to completion before shifting to the nonlinear SMA material. This step allows the user to ensure all FE model specifics are working properly before adding a more complex material (i.e., SMA) behavior. Once the functionality and accuracy of the elastic model was fully established, the nonlinear user-defined material routine for the SMA was implemented for the tire construct in ABAQUS. Next, the model was run to simulate the compressive loading of a tire made of SMA springs on a flat surface (see Sec. 3.0 for a summary of material model details). Please note, accurate and reliable results can be obtained with more than one methodology in ABAQUS. Hence, if the models are consistently built following the same methodology, the analysis will be robust with reliable and precise results.

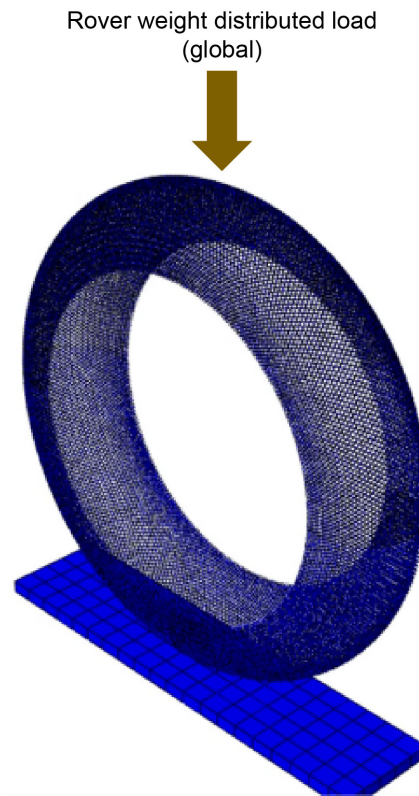


Figure 2.—Tire construct with compressive loading plate in ABAQUS FE model.

### 3.0 General, 3D Multimechanism SMA Material Model Summary

The SMA model used herein was initially developed as a generalized viscoplasticity with potential structure (GVIPS) model by Arnold, Saleeb, and Castelli (1994). It was later modified by Saleeb et al. (2013, 2015) to target the modeling of both ordinary and high-temperature SMAs. The modified framework, now termed SMA-GVIPS, is implemented as a user-defined material (UMAT) routine in the FE software ABAQUS (Dassault Systèmes Simulia Corp.). Recently, the UMAT has been modified by the authors to account for concurrent temperature dependency. For the detailed mathematical formulation involved in development and implementation of the user material routine, the authors refer the reader to Arnold, Saleeb, and Castelli (1994); Saleeb and Arnold (2001); and Saleeb et al. (2013, 2015). Meanwhile, a brief summary of the governing equations for the UMAT together with a simple illustration of the generalized constitutive formulation (Figure 3) is provided here. Viscoelastic behavior, governed by general laws of rate-dependent elasticity, followed by transformation—in the form of energy storage and dissipative mechanisms—constitute the essential energetics governing the SMA material behavior (Figure 3). SMA energy storage is driven by nonlinear hardening and saturation states defined by temperature-dependent thresholds, whereas SMA energy dissipation is associated with hysteretic behavior in SMA responses, transformation-induced strain, and static (thermal) recovery. Specific functional forms for reversible inelastic energy (stored energy)  $\Phi_{IR}$  and dissipation potentials  $\Omega$  are defined as

$$\Phi_{IR}(\sigma_{ij}, \alpha_{ij}^b) = \sigma_{ij} \varepsilon_{ij}^I + \sum_{b=1}^N H^b \quad (1)$$

$$\Omega((\sigma_{ij} - \alpha_{ij}), \alpha_{ij}^b) = \int \frac{K^2 F^N}{2\mu} dF \quad (2)$$

where

$\sigma_{ij}$  = material stress tensor

$\varepsilon_{ij}$  = material strain tensor

$I$  = reversible inelastic deformation

$H^b$  = hardening function

$b$  = number of active mechanisms in framework, ranging from 1 to  $N$

$K$  = critical transformation stress

$\mu$  = rate of dissipative mechanism

$F$  = transformation function

Stress-like internal variables  $\alpha_{kl}$  and conjugate strain-like internal variables  $\gamma_{ij}$  are denoted in evolutionary form as

$$\dot{\alpha}_{kl}^b = \left( \frac{d^2 \Phi_{IR}}{d\alpha_{ij}^b d\alpha_{kl}^b} \right)^{-1} \dot{\gamma}_{kl}^b \quad (3)$$

$$\dot{\gamma}_{ij}^b = - \frac{d\Omega}{d\alpha_{ij}^b} \quad (4)$$

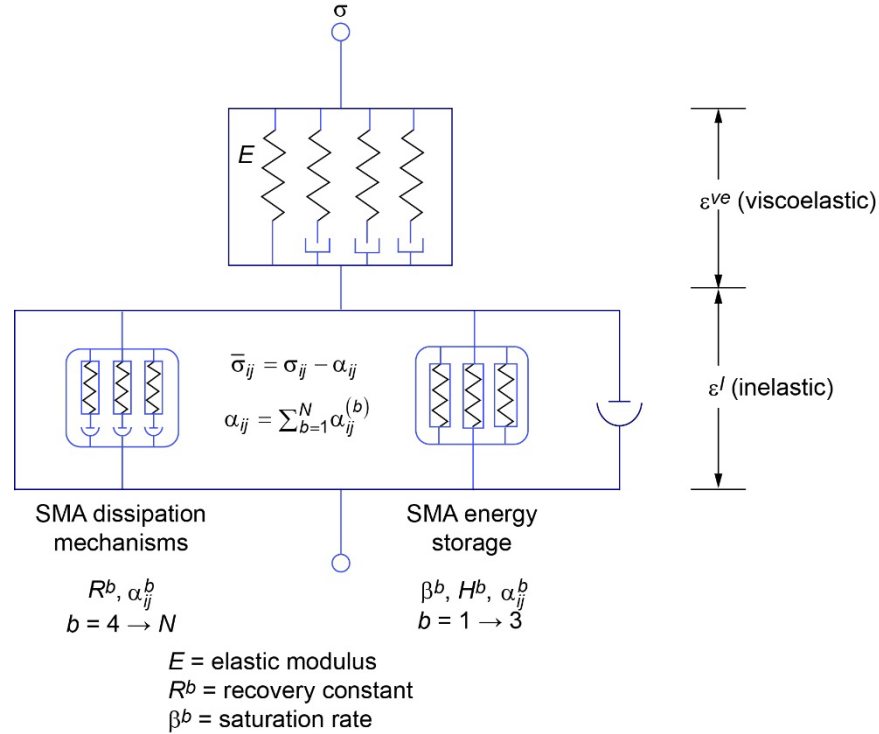


Figure 3.—Governing mechanisms within SMA UMAT (see Saleeb et al. (2013) for details).

The main model parameters that need to be defined as functions of temperature are stress-like variables in the evolution laws ( $\alpha_{ij}$ ) along with the temperature-dependent hardening functions  $H_b$ , which have recently been modified in the user-material routine to be fully temperature dependent. This allows the user to construct a temperature table with unique temperature lines and call in the corresponding variables' respective values for a given temperature during the analysis. Detailed definitions of all functions and variables can be found in Arnold, Saleeb, and Castelli (1994) and Saleeb et al. (2013).

Prior to implementing the UMAT for modeling the tire construct, the framework must be characterized using experimental data. To aid with material characterization, cyclic tensile tests were conducted on wire specimens to produce material-level stress-strain responses at different temperatures. In addition, the FE software ABAQUS was used to analyze the loading of a single material element in cyclic tension using the same two test temperatures (−90 and 25 °C). As previously stated, the main model parameters  $\alpha_{ij}$  and  $H_b$ , were defined as functions of temperature as an input for the UMAT to produce a numerical stress-strain response for the −90 and 25 °C cases. Next, the resulting numerical stress-strain responses were compared to the available experimental data. Based on the user's experience with the above-mentioned material model, most of the parameters can be approximated using the previous literature (Saleeb et al., 2013, 2015), but the parameters had to be fine-tuned until an acceptable match with the experiments was obtained for the material and processing being used in this work. Once a reasonably good agreement between the numerical and experimental data was obtained (see Figure 4), the set of numerical material properties could be reliably used to further model the tire behavior.

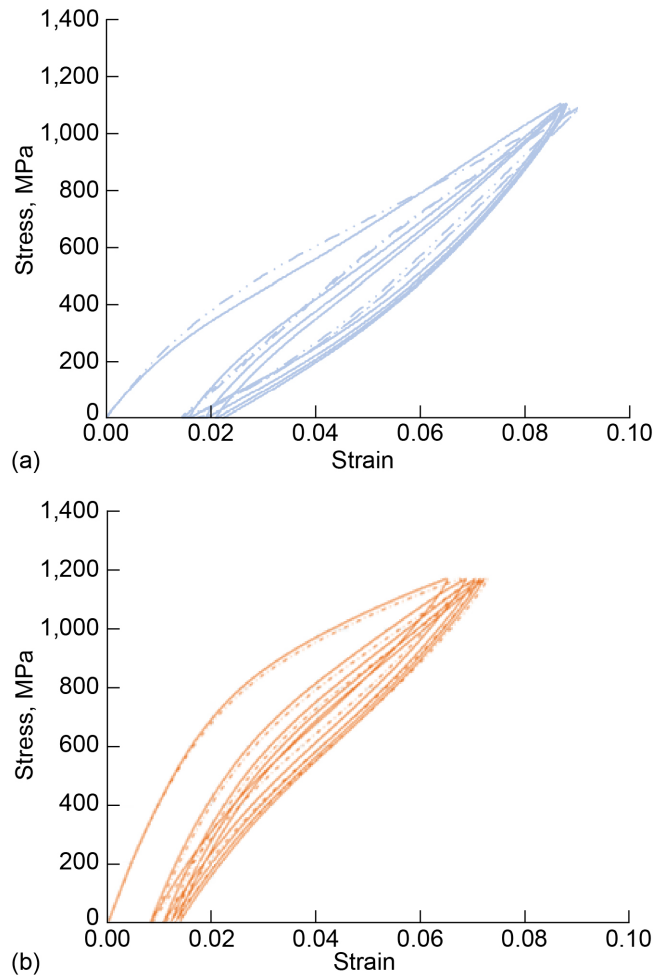


Figure 4.—Stress-strain response of SMA wire. (a) At  $-90^{\circ}\text{C}$ . (b) At  $25^{\circ}\text{C}$ . Solid lines represent experimental data; dotted lines represent model output.

## 4.0 SMA Tire Experiments and Model Validation

### 4.1 SMA Tire Experiments

Compressive plate-loading tests were conducted in-house (Figure 5) with the Spring Tire design parameters listed in Table I and spring design variables defined in Figure 6. The design variables listed in Table I were normalized with respect to an initial baseline SMA Spring Tire design (Baseline SFR 1.7) built at the NASA Glenn Research Center at the beginning of this experimental program. Spring design variables were varied experimentally to study their influence on the load-displacement response of the tires subjected to flat-plate compressive loading. The details of the experiments and the results are explained here. Each Spring Tire was compression tested in the radial direction at room temperature using an Instron 5584 electromechanically actuated load frame. Each tire was mounted at the wheel hub in the load frame as shown in Figure 5(a). A square aluminum plate, large enough to contact the entire tire footprint under load, was used to manually compress the tire to the load at which half of the average sidewall height deflection was achieved (Figure 5(b)). The load frame software control program was then set to compress the tire in displacement control to this predefined load for a total of five loading-unloading cycles. The displacement

rate was 16 cm/min. This process was repeated at six different index positions spaced at 60° intervals around the tire. The global load and displacement values were recorded with time for each compression test at each index position. The radial compression data were postprocessed to obtain a mean load versus displacement curve for each tire. To calculate these mean load-displacement curves, the load data for each index position were interpolated using a spline function. The resulting data sets, with displacement increments of 0.005 cm, were then averaged to determine the corresponding mean load values for each tire. The resulting mean compression curves are plotted in Figure 7 for the various SMA Spring Tire designs (TO#11-Springs A through F and a baseline design SFR 1.7).

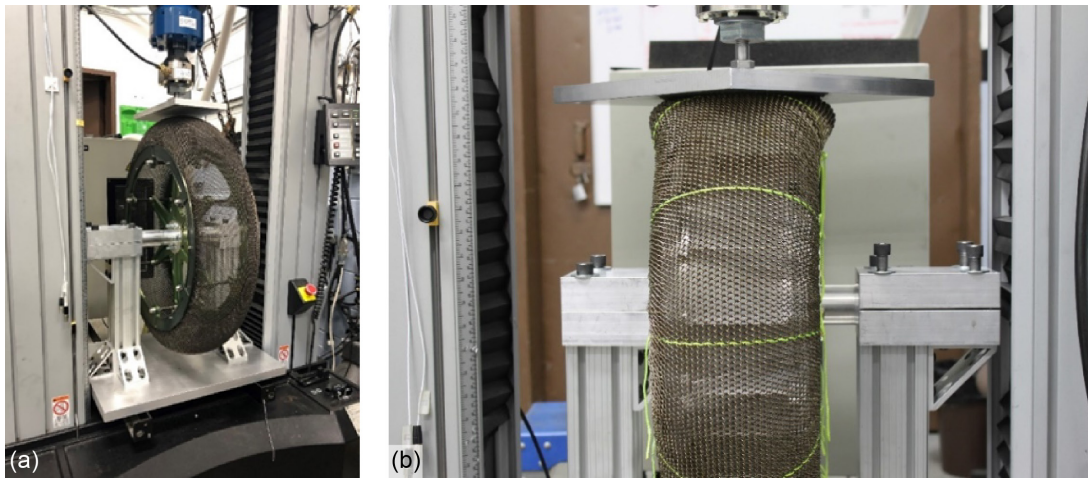


Figure 5.—Compressive plate-loading test for Spring Tire. (a) Spring Tire mounted in electromechanical load frame for compression testing against flat plate. (b) Spring Tire radially compressed to half of its average sidewall height.

TABLE I.—SPRING DESIGN PARAMETERS FOR SMA SPRING TIRES<sup>a,b</sup>

| Configuration    | Tire diameter, mm | Tire width, mm | Change with respect to baseline configuration |                          |          | Bead angle, deg |
|------------------|-------------------|----------------|-----------------------------------------------|--------------------------|----------|-----------------|
|                  |                   |                | Wire diameter                                 | Coil outer diameter (OD) | Pitch    |                 |
| Baseline SFR 1.7 | 550               | 168            | Baseline                                      | Baseline                 | Baseline | 85              |
| TO#11-Spring A   | 565               | 168            | None                                          | −14%                     | None     | 70              |
| TO#11-Spring B   | 565               | 168            | None                                          | −14%                     | +28%     | 70              |
| TO#11-Spring C   | 565               | 168            | None                                          | −14%                     | +56%     | 70              |
| TO#11-Spring D   | 565               | 168            | None                                          | −10%                     | +28%     | 70              |
| TO#11-Spring E   | 565               | 168            | −10%                                          | −24%                     | +28%     | 70              |
| TO#11-Spring F   | 565               | 168            | −10%                                          | −20%                     | 28%      | 70              |

<sup>a</sup>Normalized by values of Baseline SFR 1.7 configuration.

<sup>b</sup>Number of springs for each configuration was modified to produce same overall tire diameter, but springs counts are not listed here.

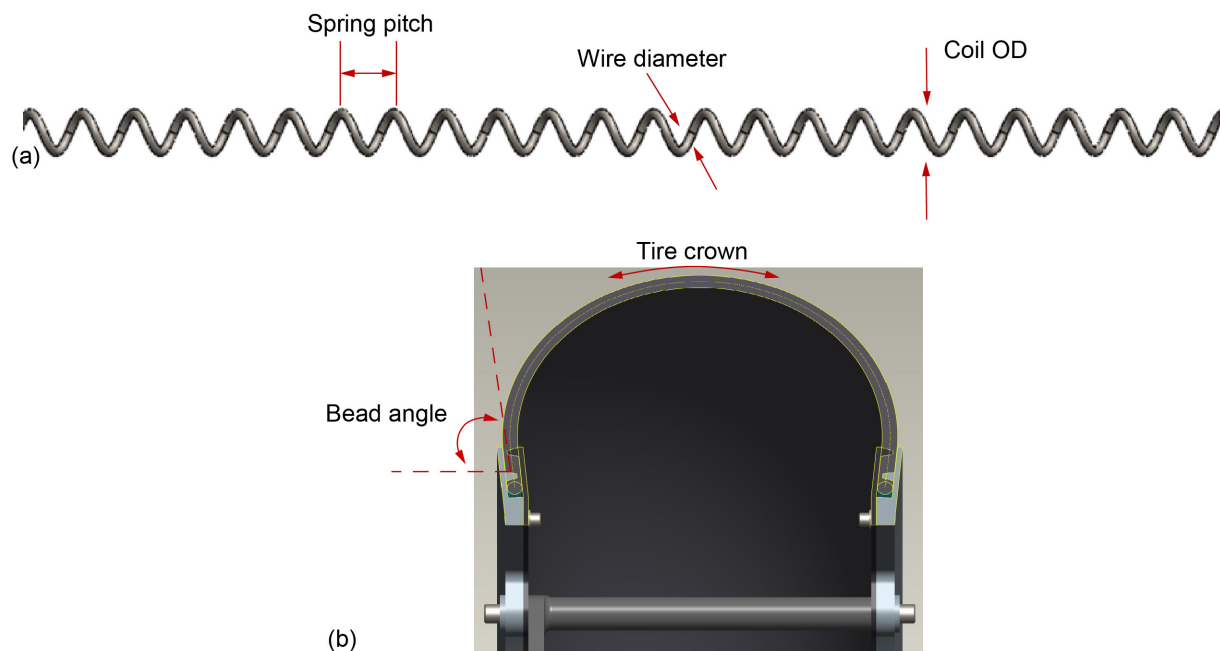


Figure 6.—Sample Spring Tire. (a) Spring design parameters. (b) Tire cross section, showing bead angle and tire crown.

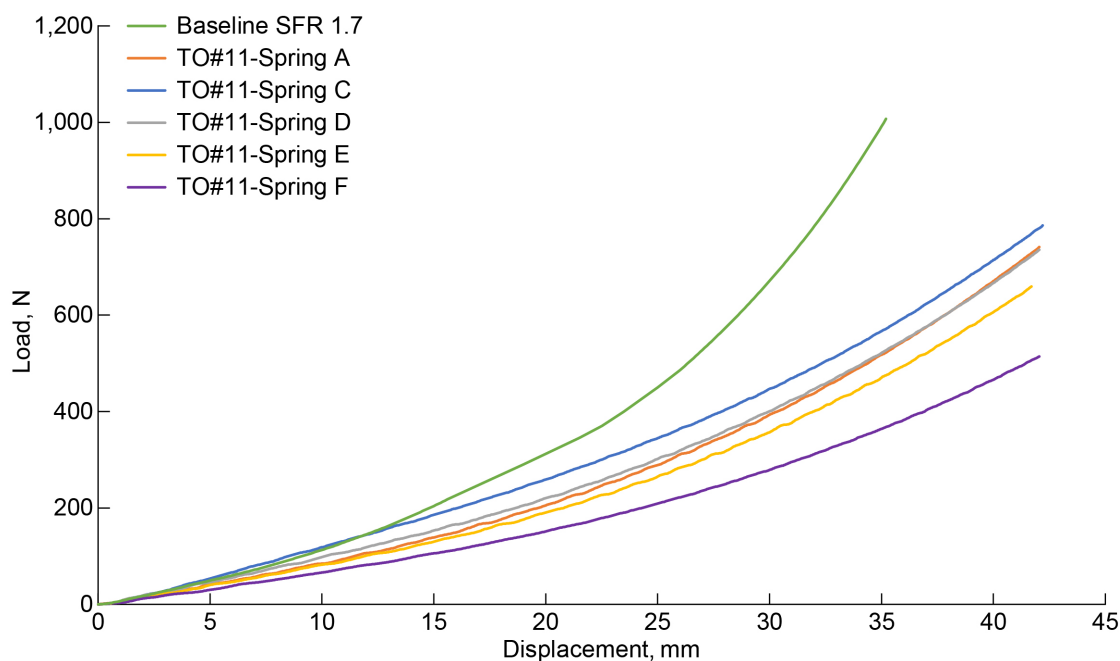


Figure 7.—Mean load-displacement curves for SMA Spring Tires radially compressed at room temperature with flat plate.

## 4.2 SMA Spring Tire Model Validation

After the SMA material model was successfully characterized, it was incorporated into the Spring Tire FE model (Figure 2) for large-scale simulations of the tire construct subjected to compressive flat-plate loading. FE model specifics are described in detail in Section 2.0. It is worthwhile to remember the SMA

material model is parameterized and characterized from material-level tests conducted on the SMA wires (as explained in detail in Sec. 3.0). These characterized material properties remain unchanged throughout all tire designs made from this material. Each tested tire configuration not only has a different spring geometry, but also a different number of springs to produce a desired overall tire diameter. Despite these geometric and configuration differences, a properly characterized material model can accurately predict the performance of the complicated structure even when multiple design variables are altered simultaneously. Here, the numerical model is validated at room temperature by comparing the load-displacement analyses for SMA Spring Tire configurations shown in Figure 8 with their empirical counterparts. The numerical results are in good agreement with the corresponding experimental data (Figure 8), capturing complicated loading and interactions occurring concurrently when the tire goes through the specified deformation range. The predictive capability of the model is very promising given the model was not precalibrated based on any full-scale tire experiments, and all predictions were fully blind.

One source of discrepancy between the numerical and empirical analyses might be lack of prestrain definition in the model. Currently, there are no empirical methods to predict the amount of tension in the springs at the tire crown after assembly prior to loading. The tire CAD model used herein did not include any prestresses, which definitely exist to differing degrees in the as-fabricated tire assemblies. To address this, user-defined constraints, such as modified contact definitions and contact boundaries in the model, can be utilized to account for the prestrain tension effect. However, the true contact definition can vary between tire constructs as it is dependent on many factors such as spring geometry, spring count, and overall tire shape. In retrospect, it was concluded that the best approach to include the appropriate prestrain tension would be through modeling the tire build process. The authors are currently working on modeling the tire assembly and forming process, which will more accurately account for the prestrain that exists within the as-built tires prior to compressive plate loading. This will also help with setting a more accurate contact model to represent interactions between the springs at the crown. Results from this ongoing work will be presented in future publications.

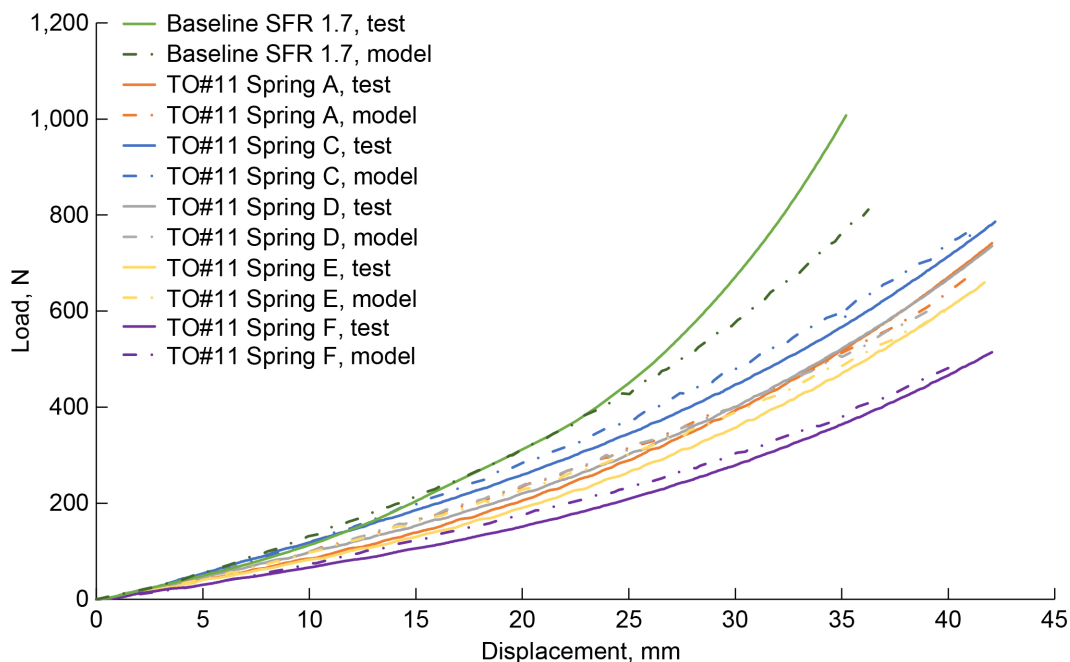


Figure 8.—Comparison of load-displacement curves (numerical and experimental) for SMA Spring Tires radially compressed with a flat plate at room temperature.

It is also important to note that at the time this report was written, the full-tire model had only been validated at room temperature (Figure 8). This is because of the test capabilities that were available. However, new test capabilities are being developed at the NASA Glenn Research Center, which will allow for full-tire compression testing at temperatures ranging from  $-196$  to  $+150$  °C. This new capability will then allow for the model to be validated and tuned across an extremely wide operating temperature range.

## 5.0 SMA Tire: Sensitivity Studies

Designing Spring Tires for extraterrestrial applications is extremely complicated because of the need to balance many, often competing, mission-level requirements. For instance, certain changes that would otherwise be made to increase the tire stiffness to allow for higher load-carrying capability are in direct conflict with the changes that are needed to allow for larger footprint area and thus better traction and climbing. Other competing tire attributes, such as mass or durability, lead to similar design trades, making defining an optimum geometry extremely difficult. As a result, having the ability to model different architectures to evaluate design choices and their respective tradeoffs helps to minimize the number of articles that need to be tested. Additionally, a detailed numerical model is the only way to determine other important design attributes (e.g., internal states of stress and strain) that cannot be measured directly in a laboratory setting, but significantly impact life considerations. Another difficulty in the design of Spring Tires is the coupled design space. Altering even one parameter can lead to required changes in other parameters to maintain specific global performance metrics (e.g., tire stiffness, tire size, etc.) important to mission requirements. Given the complexity of these structures, optimizing the design through build-and-test strategies is not an option because of the number of iterations, cost, and time that would be required to do so. By leveraging the material model described herein, an extensive design parameter sensitivity study was conducted to help determine the appropriate tire geometries that would strike a good balance between tire performance and adhering to mission requirements.

For the purposes of the sensitivity study, spring parameters including pitch, coil diameter, wire diameter, and bead angle were varied over preselected ranges (see Table II). Each of these ranges were, in part, restricted to known limits related to the large-scale manufacturing limitations inherent to the material. Despite the narrowed ranges for each of the parameters, the number of geometric configurations needing to be assessed would have made a build-and-test approach infeasible. It should also be noted that the number of springs and the spring length also change throughout the configurations driven by the four main parameters mentioned above. Table II lists the various tire configurations and the corresponding design variables (normalized with respect to the baseline design (SFR 1.7)) for each of the investigated configurations.

To simulate a real test scenario, the SMA tire model was loaded radially with a flat plate up to approximately half of its mean sidewall height (see Sec. 2.0 for details of the FE model). Virtual load-displacement data together with stress-strain profiles were generated for each configuration to help the team investigate the effect of each design parameter on the global tire performance. Results are discussed here and in Section 6.0, SMA Tire Stress-Strain Analysis.

TABLE II.—EXTENDED SPRING DESIGN PARAMETERS FOR  
SMA SPRING TIRE SENSITIVITY STUDY<sup>a,b</sup>

| Configuration    | Tire diameter, mm | Tire width, mm | Change with respect to baseline configuration |          |          | Bead angle, deg |
|------------------|-------------------|----------------|-----------------------------------------------|----------|----------|-----------------|
|                  |                   |                | Wire diameter                                 | Coil OD  | Pitch    |                 |
| Baseline SFR 1.7 | 550               | 168            | Baseline                                      | Baseline | Baseline | 85              |
| Config1          | 550               | 158            | None                                          | None     | +29%     | 85              |
| Config2          | 550               | 158            | None                                          | None     | +100%    | 85              |
| Config3          | 550               | 158            | None                                          | None     | +50%     | 85              |
| Config4          | 550               | 158            | None                                          | None     | +79%     | 85              |
| Config5          | 550               | 158            | None                                          | None     | +186%    | 85              |
| Config6          | 550               | 158            | None                                          | None     | None     | 70              |
| Config7          | 550               | 158            | None                                          | −5%      | None     | 70              |
| Config8          | 550               | 158            | None                                          | −10%     | None     | 70              |
| Config9          | 550               | 158            | None                                          | −14%     | None     | 70              |
| Config10         | 550               | 158            | −10%                                          | −20%     | None     | 70              |
| Config11         | 550               | 158            | −10%                                          | −24%     | None     | 70              |
| Config12         | 550               | 158            | None                                          | −16%     | None     | 70              |
| Config13         | 550               | 158            | −10%                                          | −22%     | None     | 70              |
| Config14         | 550               | 158            | −10%                                          | −29%     | None     | 70              |

<sup>a</sup>Normalized by values of Baseline SFR 1.7 configuration.

<sup>b</sup>Number of springs for each configuration was modified to produce same overall tire diameter, but springs counts are not listed here.

## 5.1 Pitch Effect

Compared with some of the other design parameters such as coil diameter and wire diameter, there was a fairly large range of pitch values that could be produced reliably without requiring added processing steps. It was also believed that changes in pitch would be relatively easy to implement and result in significant changes to overall tire stiffness and mass. For these reasons, pitch was used as one of the primary “design knobs” that could be adjusted to help meet requirements. For this sensitivity study, the range that was considered was limited by the maximum manufacturable pitch and the smallest pitch that would not cause spring packing issues at the rim, for the given wire diameter and coil diameter. As can be seen in Figure 9, the increase in the spring pitch has a very evident effect on increasing overall structural stiffness. The rise in stiffness with increasing spring pitch demonstrates a nonlinear trend, which makes simplistic load-displacement data extrapolations erroneous. Load-displacement data extrapolations for SMA Spring Tires in general is never a trivial matter, as there are inherent material and boundary nonlinearities in the tire construct, rendering any simple data extrapolations invalid. Thus, the value of a robust, reliable, and computationally efficient numerical model is clearly evident. Numerical simulations with varying pitch intervals can be analyzed in much shorter times—and at a far lower cost—compared to a build-and-test approach. These analyses are able to produce a virtual data map, helping designers pick spring attributes that provide the most favorable performance based on the driving needs of the tire with respect to mission requirements.

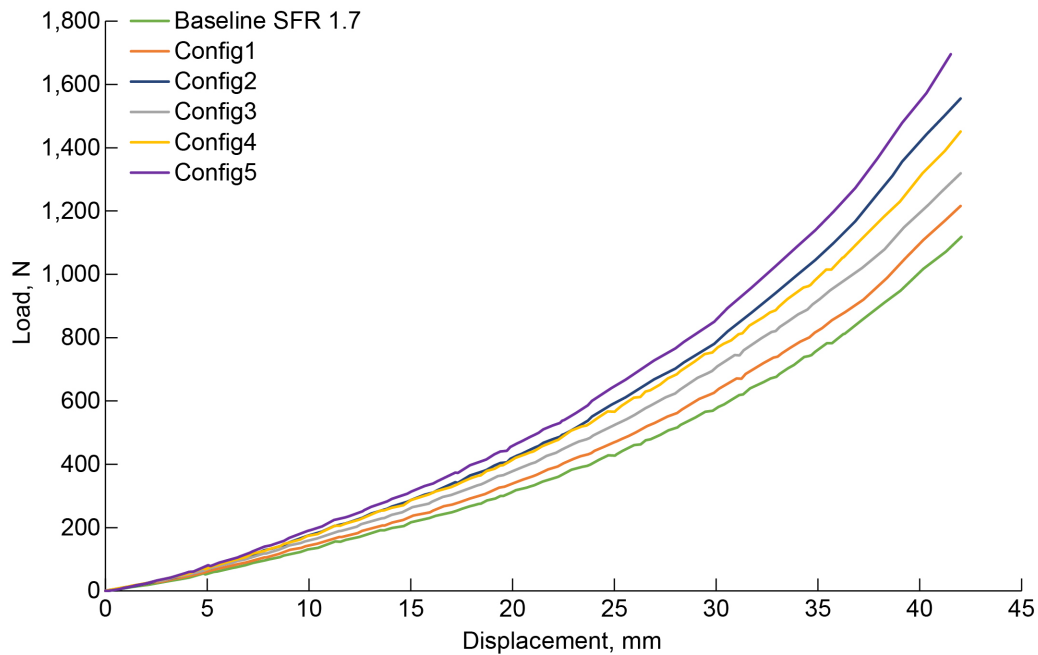


Figure 9.—Load-displacement curves for SMA Spring Tire construct with variations in spring pitch; tire loaded radially with a plate.

## 5.2 Bead Angle Effect

A lower bead angle (Figure 10, Config6, bead angle of  $70^\circ$ ) results in load-displacement behavior that is more compliant and has a more “flat-like” ascent compared to a design with higher bead angle (Figure 10, Baseline SFR 1.7, bead angle of  $85^\circ$ ). One of the major theoretical benefits of a lower bead angle is a wider footprint, extending the tires outside the bounds of the rim, which not only protects the rim from rock impacts and abrasion but is ideal (and essential) for better tractive performance in soft soil. However, if the bead angle is too low, it could risk making the tire overly soft and reduce the overall strength and durability of the tire. Given the high sensitivity of tire stiffness to bead angle, it was decided to only consider two bead angle cases for this study. A major change in bead angle would have required significant changes to many other design parameters, which would have made the sensitivity study unmanageable within the schedule constraints. Although Config6 demonstrates a more compliant load-displacement response when compared to Baseline SFR 1.7, with some other geometrical modifications (e.g., changing wire diam. and coil diam.), a desired stiffness can be reached while maintaining the optimal footprint.

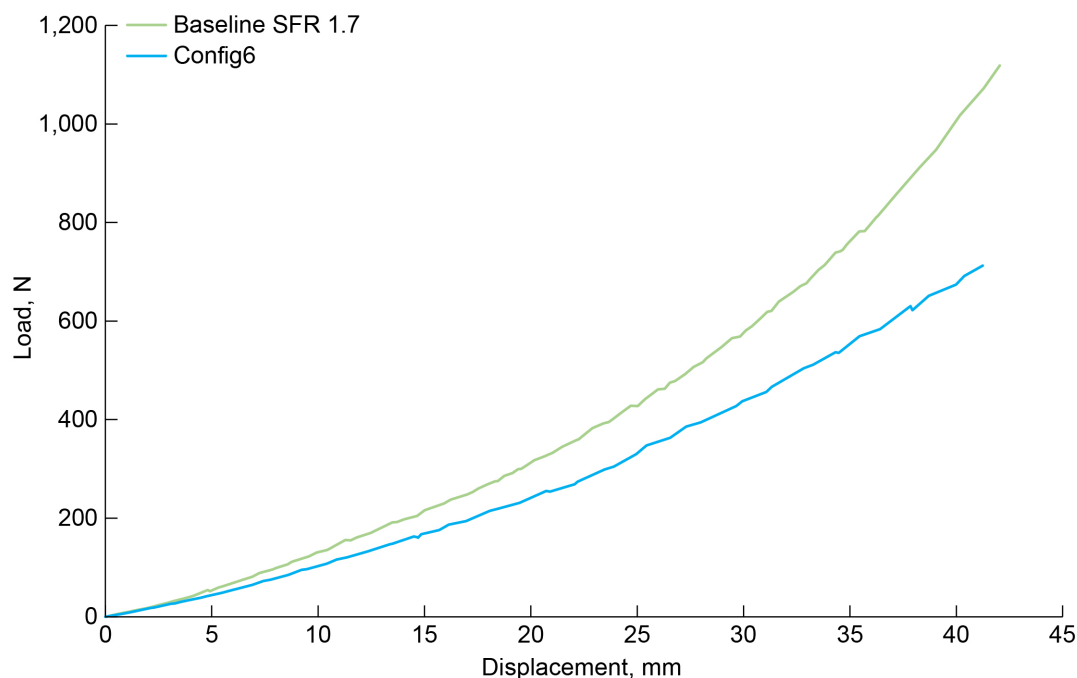


Figure 10.—Load-displacement curves for SMA Spring Tire construct with variations in bead angle; tire loaded radially with a plate.

### 5.3 Coil OD and Wire Diameter Effects

Coil outer diameter (OD) and wire diameter are highly coupled with other design parameters and produce the most manufacturing challenges when new sizes are needed. For example, a change in wire diameter could require new processing steps to ensure the material properties remain the same. Also, extensive data already existed on wire at the size used in the baseline design. Changes in coil diameters requires a new setup, which can take much time to fine tune. Since the genesis of the first SMA Spring Tire, a fairly wide range of coil ODs and wire diameters have been explored. For a variety of reasons, including tire requirements and manufacturability, a baseline design was converged upon with a specific set of spring geometries (referred to as “Baseline SFR 1.7”). Meeting the mission requirements required changes to some of these parameters; however, the range of potential changes was limited to reduce risk and added schedule. Decreases in coil diameter were considered to increase stiffness and traction (by reducing the void sizes in the mesh). These changes were limited by what was manufacturable for a given wire size and what could be woven together (if the springs were too small, they would not be able to weave together or seat nicely at the rim). Because a change in wire diameter produced the greatest manufacturing challenges, only a small change was considered. The approach was to only reduce the wire diameter if the desired coil diameter could not be achieved with the baseline wire diameter. For future applications, a wider range of wire diameters and coil diameters should be considered. The variations in coil diameter (OD) are reflected in the load-displacement curves shown in Figure 11. By systemically lowering coil diameter, even though in small intervals, one can achieve a higher structural stiffness while maintaining an acceptable tire footprint and overall performance. Figure 12 depicts load-displacement response of the SMA tire with a lower wire diameter as the coil diameter is being decreased.

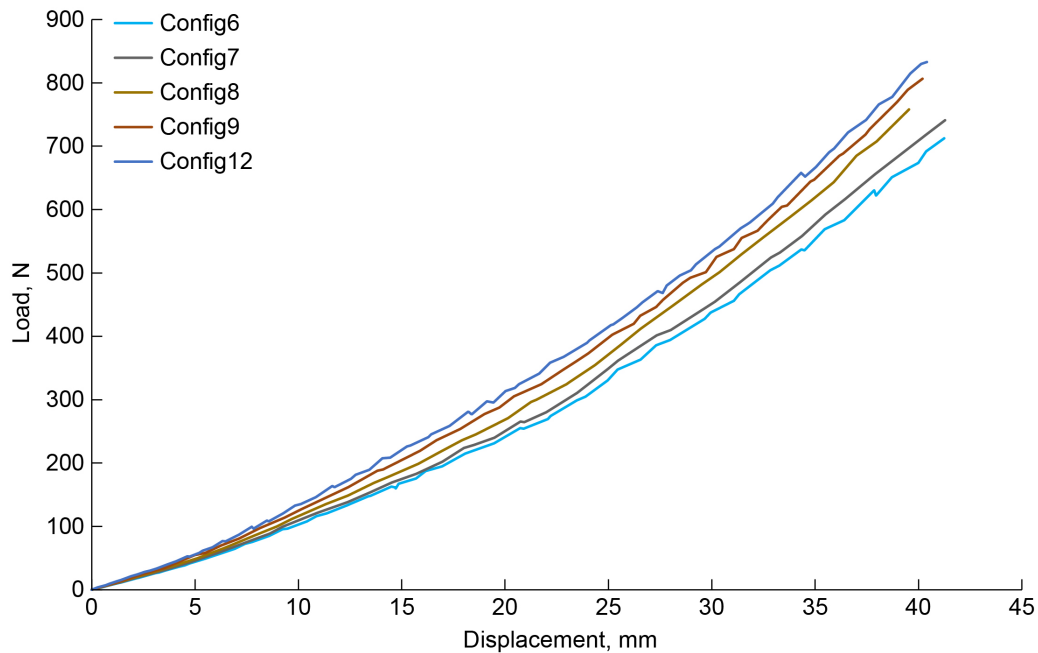


Figure 11.—Load-displacement curves for SMA Spring Tire construct with variations in coil OD with baseline wire diameter; tire is loaded radially with plate.

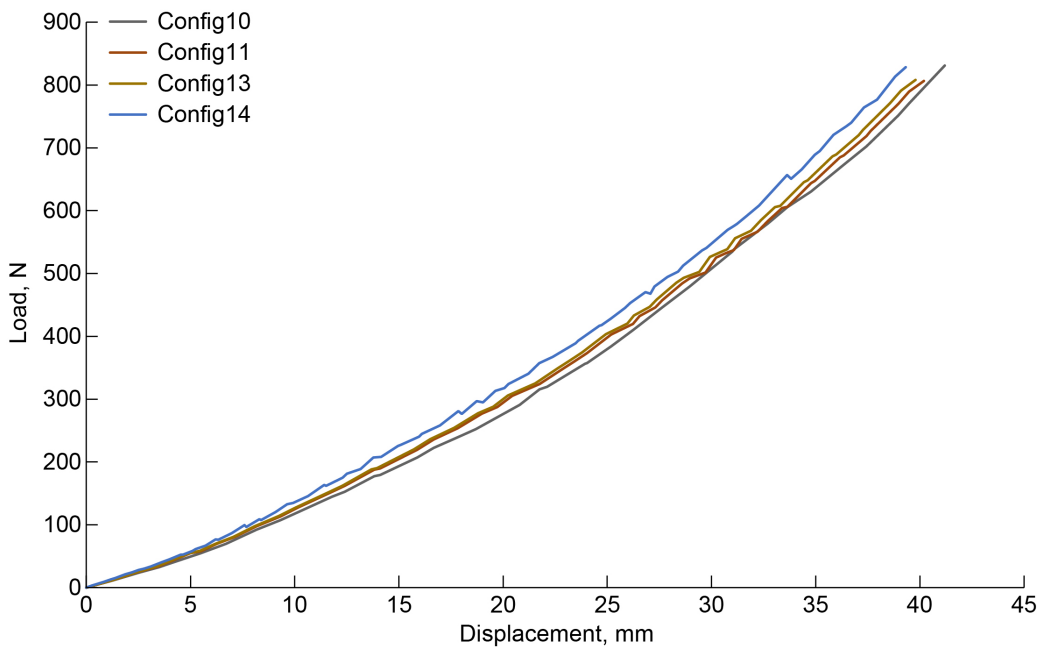


Figure 12.—Load-displacement curves for SMA Spring Tire construct with variations in coil OD with wire diameter reduced by 10 percent from baseline; tire is loaded radially with plate.

As mentioned in the previous paragraphs, performing the numerical sensitivity study aided in quickly determining the geometric modifications that needed to be made at the subcomponent level (i.e., spring) to improve the structural performance of the tire without the need of building and testing each configuration.

## 6.0 SMA Tire Stress-Strain Analysis

When it comes to an extremely heterogeneous structure, (e.g., a nonpneumatic compliant Spring Tire), one of the major design considerations is the durability. Regardless of the material chosen, the durability is directly related to the maximum stresses and strains that arise during operation. The magnitudes of these stresses and strains in relation to known limits for any desired material, used to fabricate the component, will inevitably dictate life. With regard to complex structures such as the Spring Tire, direct measurements of the stresses and strains cannot be achieved. In some cases, full-field photogrammetry or digital image correlation (DIC) can be used to determine a portion of the stresses/strains, but these techniques only produce surface measurements and would be extremely time consuming for a structure like a Spring Tire. Additionally, the cost associated with producing each of the tire designs to make the measurements would be prohibitive. Conversely, a properly formulated material model embedded in an accurate FE model can be applied to any geometric configuration to elucidate the entirety of the internal stresses and strains within the structure in an ultraefficient and cost-effective manner.

Figure 13 shows snapshots of maximum principal stress and strain contours at half side-wall height displacement at room temperature for three example tire configurations: TO#11-Spring C (the stiffest TO#11 design, Table I), TO#11-Spring F (the most compliant TO#11 design, Table I), and Baseline SFR 1.7 design. The maximum principal stress (Figure 13(a)) does not surpass 750 MPa in any of the three designs, ensuring all material points within individual SMA springs stay within a reasonable stress threshold for the material as the whole tire structure is being deformed. The circled elements in Figure 13(b) are an approximate measure of the elements undergoing 1.5 percent maximum principal strain. (In order to minimize damage over the lifetime of the structure, the conservative 1.5 percent margin was chosen based on previous works of the authors). The majority of these elements are located around the rim where the restrictive boundary constraint is the highest, whereas most of the other elements within the tire experience strains that are significantly lower than the “allowable” design margins.

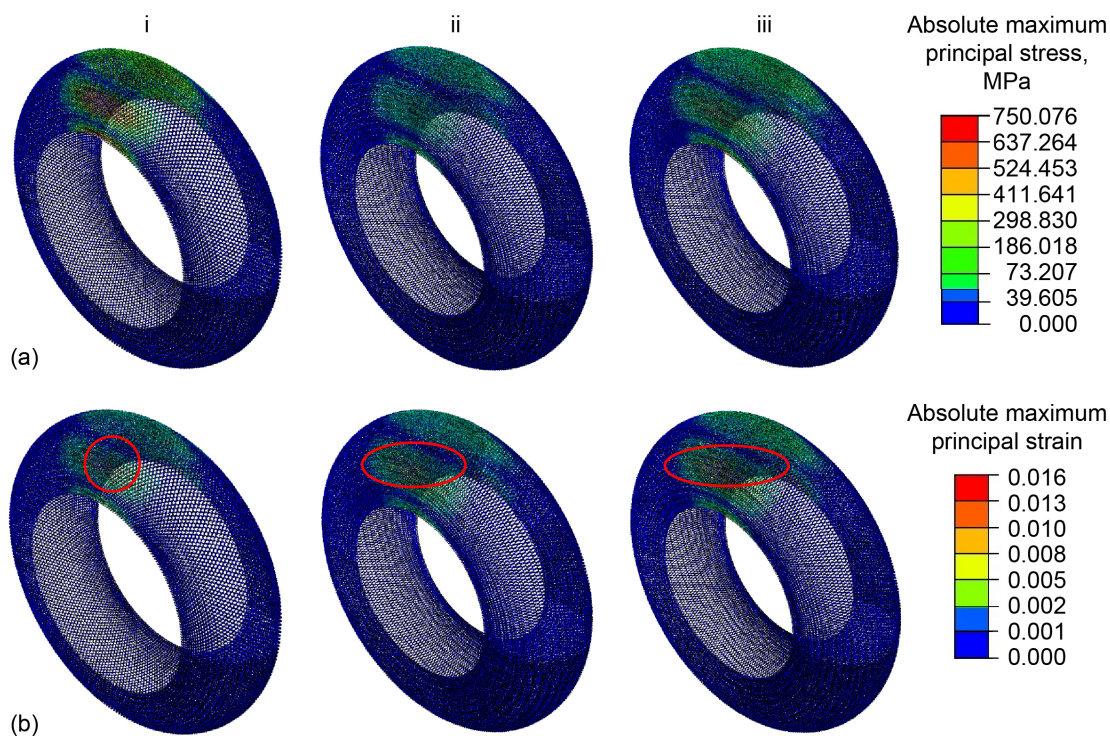


Figure 13.—Contours at half side-wall height displacement for three tire configurations at 25 °C (i: Baseline SFR 1.7, ii: TO#11-Spring C, and iii: TO#11-Spring F). (a) Stress. (b) Strain.

Leveraging this framework, it is also possible to investigate the maximum principal stress and strain for all three tire configurations under extreme temperature conditions (noting that this is a fully numerical investigation, as there were no experiments conducted on the tire construct at extreme temperatures). Figure 14 shows snapshots of maximum principal stress and strain contours at half side-wall height displacement for the same three configurations, but at a temperature of  $-65^{\circ}\text{C}$ . Comparison of the results in Figure 14 and those in Figure 13 shows that the model can accurately illustrate the slight change in tire compliance that results from the change in material properties as the tire is cooled from room temperature to  $-65^{\circ}\text{C}$ . The tire is expected to have a more compliant behavior at  $-65^{\circ}\text{C}$ , which is captured successfully by the model within both stress and strain profiles. In accordance with a more compliant SMA Spring Tire behavior at a cooler temperature, the circled zone in Figure 14(b) (approximate measure of the elements undergoing 1.5 percent maximum principal strain), encompasses a slightly larger area compared with Figure 13(b). However, most of these elements are still concentrated around the rim, with the majority of the tire experiencing much lower strain levels. Of course, this result is a complex material-structural coupling interaction given that the Spring Tire is an extremely heterogeneous structure. Nevertheless, the true power of the framework is exhibited in its ability to determine how the internal stresses and strains evolve or change as the temperature of the component is altered. This in turn allows the structure to be assessed across the entire range of temperatures important to the mission to ensure that the tire's design configuration will not exceed any of the allowable design criteria during the course of operation. Not only does this make it faster and easier to design a tire to meet multiple design objectives, but it also decreases the amount of costly and time-intensive testing.

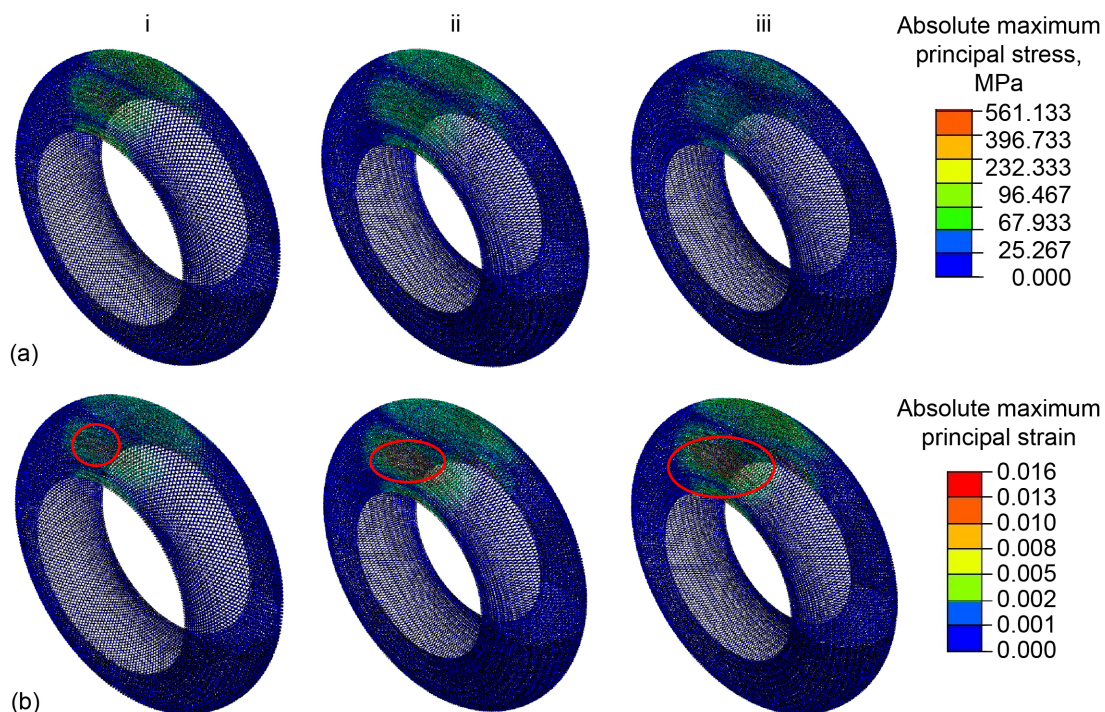


Figure 14.—Contours at half side-wall height displacement for three tire configurations at  $-65^{\circ}\text{C}$  (i: Baseline SFR 1.7, ii: TO#11-Spring C, and iii: TO#11-Spring F). (a) Stress. (b) Strain.

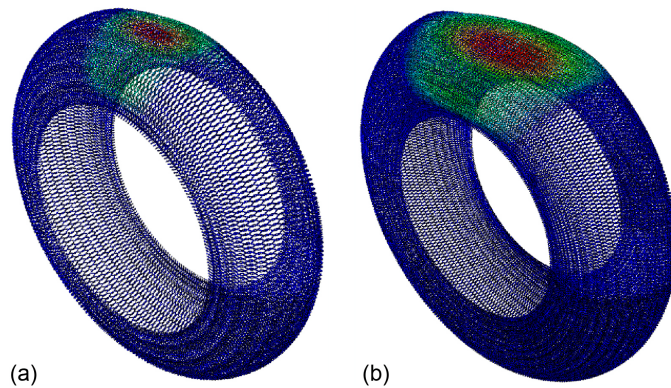


Figure 15.—Footprint profile examples achieved through design variations in Table II. (a) Config5. (b) Config11.

Other information that can be elucidated from the analyses include parameters like footprint area and footprint shape. Figure 15 illustrates differences in the footprint area with changes in the tire architecture; for example, the tire in Figure 15(a) is designed with a higher pitch, which can lead to a poorer footprint. Since the footprint area has been shown to be related to traction potential (with a higher weighting being given to footprint areas having longer footprint length), this parameter can be used to help rank tire architectures with respect to higher performance. Additionally, some geometries can show signs of local buckling within the footprint area, a condition known as oil canning, and this can lead to more heterogeneity in the contact pressure. In cases where oil canning is observed in practice, it often leads to low traction and therefore is undesirable. Hence, the model can be used to interrogate design configurations that exhibit this phenomenon so that they can be avoided and eliminated.

## 7.0 Concluding Remarks

In summary, the constitutive shape memory alloy (SMA) model implemented in the finite element analysis (FEA) program ABAQUS as a user-defined material model has been successfully utilized for large-scale simulations of the SMA Spring Tire developed at the NASA Glenn Research Center. The Spring Tire is a complex heterogeneous structure, which is expensive and time consuming to build and test. Though effective for determining tractive performance, testing alone is not able to provide the internal stresses and strains necessary for determining the durability and limitations of the tire. For these reasons, an analytical means of evaluating the tire construct and varying spring parameters is critical. The FE model consists of a full Spring Tire constructed through an automated Python scripting algorithm in the FE software ABAQUS. After assigning proper element types, material properties, and boundary conditions, a thorough mesh convergence study was conducted. A tire model with a fully elastic material was run to completion, and once the functionality and accuracy of the elastic model was fully established, the nonlinear user-defined material routine for the SMA was implemented to perform tire analyses that were validated against compressive plate-loading tests performed at room temperature.

This unique modeling capability provides critical benefits to the development and design of SMA Spring Tires. Because of the complex nature of the Spring Tire, this modeling capability allows for design choices to be made with fewer iterations of design and fewer full-scale tire builds and tests, which ultimately leads to reduced cost and schedule. The modeling approach described herein can be used to assess the effects of specific parameters (spring pitch, spring diam., wire diam., bead angle, etc.) on the overall tire performance, allowing designers to better refine the tire for a given application. Through these sensitivity studies, it was shown that spring pitch and bead angle play an important role in the compliance

of the tire. Coil outer diameter and wire diameter also have an effect on the tire compliance and can be coupled with the spring pitch and bead angle to obtain the desired tire footprint and stiffness to meet mission requirements. In addition, the model can be used to predict the performance of the tire at extreme temperature conditions—something that is not easily tested nor cost effective to determine through empirical means alone. Finally, the model can be used to assess the internal stress-strain state of the springs under various loading conditions, which is critical to understand the limitations of the tire.

Although the model is currently being used for very specific point designs, the framework could be adapted for a variety of SMA structural applications. Other future work includes validating the model at temperature, predicting prestress in the springs created during tire assembly, and modeling the interaction between the tire and a variety of terrain obstacles like rocks and granular soil.

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