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Performance Comparison of Solid Tires and Non-Pneumatic Tires Using Finite Element Method: Application to Military Vehicles

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Abstract: Tire technologies are growing rapidly due to the high demand for applications in harsh environmental conditions. Solid and non-pneumatic (NP) tires are utilized in such conditions as transporting excessive loads, operating on rough surfaces, agriculture, construction industries and for military applications. These tires experience high stresses and excessive deformations due to sudden impacts and heavy loads. These factors are not easy to analyse experimentally due to complex experimental setups and high cost. Hence, the following study is focused on the characteristic comparisons of solid and NP tires by developing three dimensional (3D) Finite Element (FE) models under static and dynamic conditions. Initially, two FE tire models are developed for equal size of solid and NP tires. To obtain material behaviour of the tires, the suitable hyper-elastic material models are required and those are selected using a curve fitting approach. Experimental data are compared with numerical results to validate the developed models. The validated models show good agreement with experimental models. The static numerical results of the validated model show that high stresses are located in the base section of the solid tire. For NP tires, spokes and shear layer bear the stresses more than the other rubber sections. Moreover, curb impact is conducted for both tires by changing tire impact velocity. Results show that, the NP tire experiences higher impact stresses than the solid tire.

Keywords: Curb Impact Simulation, Hyper-Elastic Materials, Nonlinear Numerical Modelling, Non-Pneumatic Tire, Solid Tire

Introduction

There are three basic types of tires which are mainly used in the tire industry. These are pneumatic tires, solid tires and non-pneumatic tires. The pneumatic tires are the more popular tire type in the world. These tires are utilized in a wide variety of applications and mostly used in passenger vehicles. Solid tires are the more popular tire type in the construction fields, transportation sectors as well as nowadays, in military applications. These tires are flat free tires which have zero downtime and less maintenance requirements when compared to the pneumatic tires. In contrast, solid resilient tires are more popular in heavy duty vehicles due to its ability to operate in harsh environments while bearing excessive loads (Suripa, 2008; Phromjan, 2018). The non-pneumatic tires (NPT) and solid resilient tires (SRT) are the main airless tire types. Non-pneumatic tires have higher flexibility regardless of the running surface conditions, higher driver comfort level, do not burst and gives good stability to the vehicle (Baranowski 2015; Yazid 2015). Further, NP tires are utilized in military vehicles due to its ability to sustain and even operate under bullet hits and blasting conditions.

In the literature, limited studies have been conducted on solid tires. Suripa (2008), developed a simplified solid resilient tire FE model to investigate the distribution of tire strain energy density and deformation under different loads and different arrangements of the rubber layers on static conditions. Dechwayukul et al. (2010), proposed an experimental method to evaluate tire service life, life time of the tire at different loading conditions and speeds of selected industrial solid tires. Rukkur et al. (2013), conducted a laboratory experimental study to improve and reduce heat build-up at the tread layer of a solid industrial tire. Phromjan (2018), developed 3D FE tire model to analyse the tire behaviour on static conditions. Tire stress distributions and deformations were analysed using a detailed tire FE model. In addition, by conducting compression tests and curve fitting approach, the Ogden material model was selected as the best fitted constitutive model.

For non-pneumatic tires, an experimental and numerical investigation was conducted to reduce rolling resistance and energy dissipation of the NP tire by introducing porous composite shear band (Veeramurthy et al., 2013). In Baranowski (2015), a light military armoured vehicle blast loading was simulated for NP tires. To improve vehicle tire strength and resistance against the blast, the honeycomb type NP tires were introduced in their model. Yazid (2015), analysed the effect of NPT spokes arrangement on its performance. In 2017, Karthick et al., developed three different designs of NPT FE models by changing their thickness and shear modulus of the spokes and shear bands to analyse those modification's effects on the vertical stiffness, contact pressure and rolling resistance. Further in 2019, Zmuda et al., developed a validated numerical model of NP tires to observe the spokes and shear beam deformations under different loading conditions. In addition, the tire contact pressure was also investigated.

Only a static analysis was performed in the above articles. Further, according to the above studies it is highlighted that lack of dynamic analyses and characteristic comparisons of tires are investigated on both SR and NP tires. Hence, this study is conducted to compare the performance of SR and NP tires under static and dynamic conditions and evaluate their usability in military applications.

Methodology

This study is focused on the development of static and dynamic simulation models of tires with mathematical representations of SR and NP tires in three dimension (3D) to compare the performance of SR and NP tires. Figure 1 shows the methodology of the study. In the SR tire, base, cushion and tread are the main three rubber layers. Moreover, few bead bundles (reinforcements) are embedded into the base layer as the structural reinforcements. These three rubber layers are made by using three different rubber compounds and their properties are different to each other. The cross-section view of an SR tire is presented on Figure 2. In contrast, the NP tire has shear layer and flexible spokes which are made usually from polyurethane. In addition, it consists of a tread layer (Rubber), two reinforcement rings and steel rings. Figure 3 shows the corresponding view of a Tweel type NP tire.

The 3D hybrid hexahedron elements are used to model all the sections in SR and NP tires except two reinforcement rings in the NP tire. These reinforcements in NP tire are modelled using membrane elements. Further, suitable hyper-elastic material models are obtained by using relevant tensile data and curve fitting approach. The static FE models of tires are simulated by using Abaqus/Std 6.14.

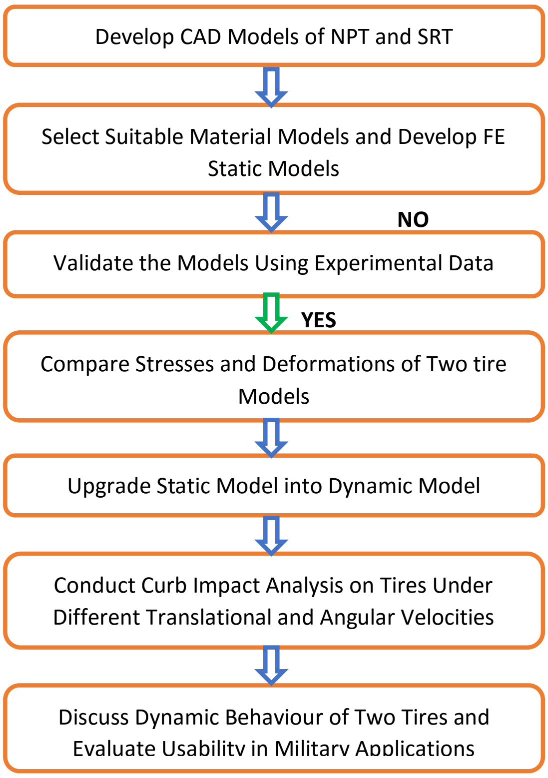


Figure 1. The flow diagram of the methodology

The properly validated detailed tire FE models are then used to compare stress and deformation behaviours of an actual SR and NP tires under different load conditions. Further, the developed static models are upgraded into dynamic models by introducing time dependent material properties, relevant boundary conditions and simplified tire models. The Abaqus/Explicit solver is utilized to conduct curb impact analysis on tires.

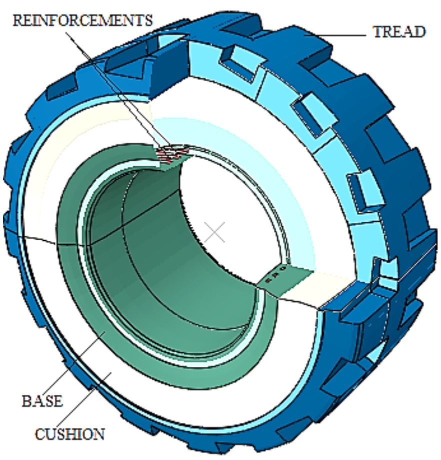


Figure 2. Cross section of a SR tire

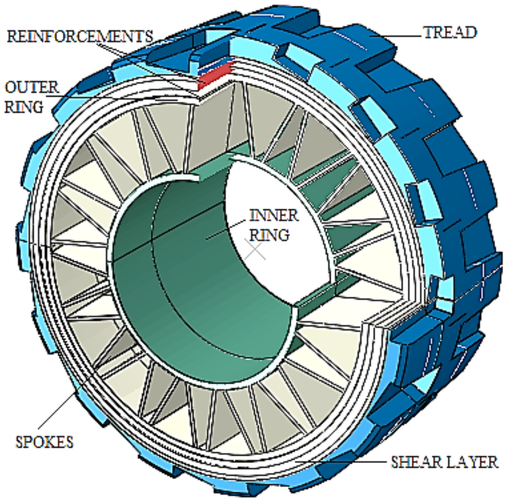


Figure 3. Cross section of a NP tire

Numerical Simulation of Tires

This section describes the development of static numerical models of SR and NP tires and their validations. In addition, the evolution of the curb impact dynamic models of the two tire types are presented.

A. Development of Static Numerical Models

In the static analysis, the detailed tire models are considered and tire deformations are gathered under different loading conditions to compare both SR and NP tire characteristics. In this study, a Tweel type NP tire and forklift SR tire of the same size are used for the analysis. The interactions and boundary conditions are applied on both tire models. Road is designed as rigid body and surface to surface interactions are applied both tire tread surfaces and road. A Control point is assigned on the centre of the tire rim which uses to apply loads. Furthermore, hexahedral elements are used to generate the FE mesh of both tires. The SR tire consists total elements 32204 and NP tire consists total elements 33132.

1) Best Fitted Hyper-Elastic Material Models and Static FE Models: To develop the FE models, the required best fitted constitutive models and material properties of the filled rubber, polyurethane (PU) and other reinforcements of the tires are gathered through conducting relevant laboratory experiments. Here, the Yeoh hyper-elastic material model is selected using curve fitting approach to describe the mechanical behaviour of the filled rubber sections of both tires. Moreover, Mooney Rivlin material model is used to describe the behaviour of tire polyurethane sections. The corresponding constitutive models of Yeoh and Mooney Rivlin are presented in Eq. (1) and Eq. (2) respectively. Table 1 shows the coefficients of each material model.

$$W = \sum_{i=0}^{3} C_{10}(\bar{I}_1 - 3)^i \qquad (1)$$

$$W = C_{10}(\bar{I}_1 - 3) + C_{01}(\bar{I}_2 - 3) \qquad (2)$$

Where;

$\bar{I}_1, \bar{I}_2$ - The principal invariants

C_{ij} - Material constants

Table 1. Coefficients of material models

Rubber/PU Section	**Coefficients (MPa)**		
Base	C10	C20	C30
	4.993	-8.846	0.212
Cushion	C10	C20	C30
	0.671	-0.003	0.007
Tread	C10	C20	C30
	0.689	-0.021	0.008
Shear Layer and Spokes	C10	C01	
	-6.7	15.1	

C. Validation of Numerical Models

Figure 4 and Figure 5 show the comparisons of numerical and experimental data of tire vertical deformations under different load conditions. The deformation values of both numerical tire models show a good agreement with their physical experimental data.

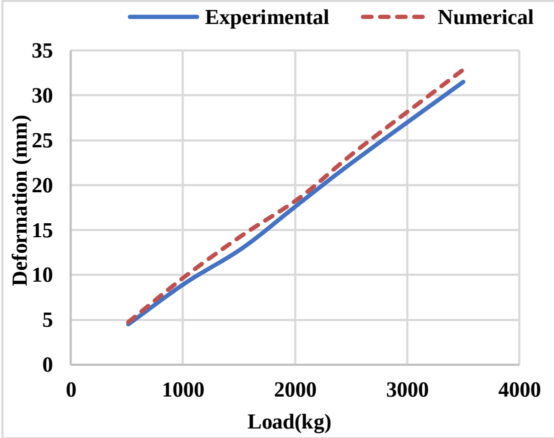


Figure 4. NP Tire vertical deformation: Experimental vs Numerical

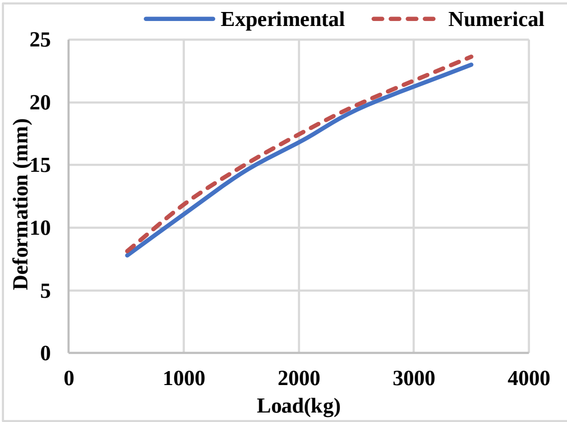


Figure 5. SR Tire vertical deformation: Experimental vs Numerical

C. Modelling and Analysis of Dynamic Numerical Models – Curb Impact

The dynamic models of the tires are created by introducing time dependent material properties of the rubber sections and polyurethane sections. Each material viscoelastic properties are defined using material relaxation data.

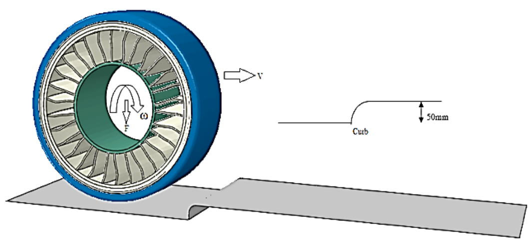


Figure 6. Visualization of tire rolling over curb

The tire tread patterns are ignored due to their insignificant effect on final results of tire curb impact. Hence, simplified tire models are considered for developing dynamic models in order to reduce unnecessary simulation effort and time. To analyse curb impact, the road and curb are modelled as discrete rigid bodies shown in Figure 6. Further, three different translational velocities of $25 kmh^{-1}$, $15 kmh^{-1}$ and $5 kmh^{-1}$ are applied on the centre of the tire rim while keeping applied axial load constant (1530 kg) for three stages. The axial load is applied smoothly on the rim before starting translational and rotational motions of the tire. After that, the translational velocities and angular velocities ($21.14 rads^{-1}$, $12.68 rads^{-1}$ and $4.23 rads^{-1}$) are applied on the tire. The angular velocities are applied on the clockwise direction as shown in Figure 6.

Results and Discussion

A. *Stress Comparison of SRT and NPT Under Static Conditions*

The loads are applied on the tire models as 510kg, 1020kg, 1530kg, 2040kg, 2550kg, 3500kg respectively. The corresponding stress distributions of SR tire and NP tire are shown in Figure 7 and Figure 8 for rubber and polyurethane sections. Maximum von mises stress is observed on the base section of the SR tire. Moreover, for NP tire, the spokes and shear band are controlled the maximum stress.

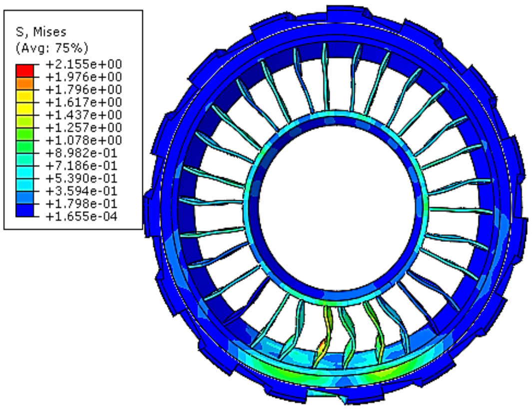


Figure 7. Max. von mises stress distribution of NPT rubber and PU components: Load-1530 kg

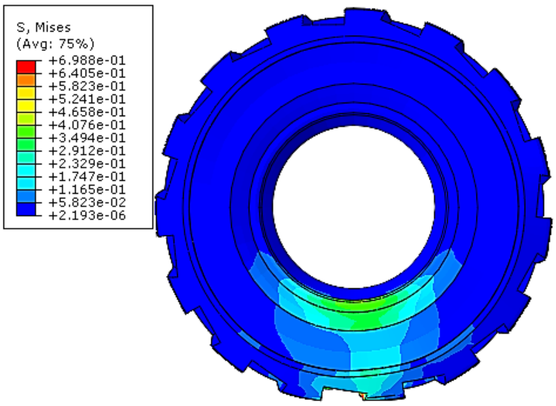


Figure 8. Max. von mises stress distribution of SRT rubber components: Load - 1530 kg

The stress variation and deformation comparisons of two tire models are presented in Figure 9 and Figure 10. For higher loads the stress of the NP tire is more dominant than the SR tire.

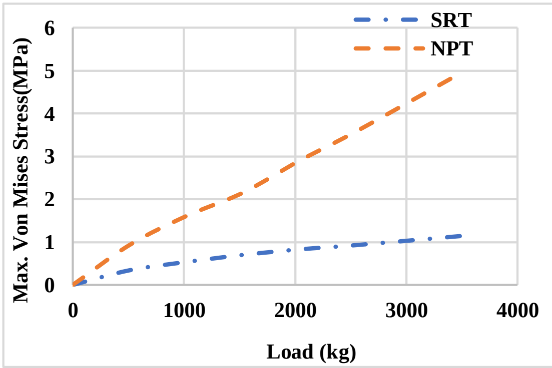


Figure 9. Max. von mises stress distribution comparison of SRT and NPT under different loads

Further, deformation (16.38mm) of NP tire (Figure 10: Point A) and the deformation of SR tire is the same at load 1750kg. Beyond load level 1750kg the deformation of NP tire higher than the deformation of SR tire. When load level is increased, the NP tire deformation level is increasing. That increases tire contact area and leads to higher wearing rate than the SR tire at the same load condition. Moreover, according to the industrial standards the maximum recommended load for NP tire varies between 1500kg to 2000kg such that, beyond these maximum limits NP tires perform poorly. Cron (2010) observed the intersection of two deformation curves at a specific load level on non-pneumatic tires and pneumatic tires under static conditions. A similar intersection behaviour is observed for NP and SR tires in Figure 10. Furthermore, at point A, the secant stiffness value is the same for both the tires.

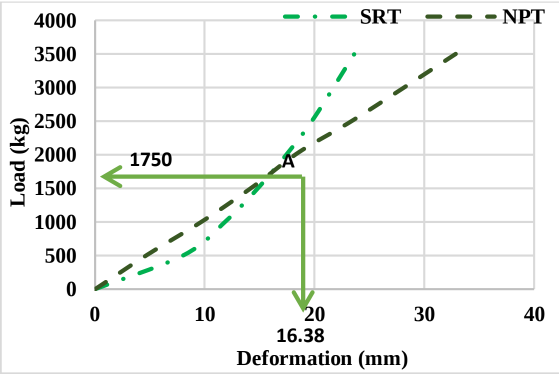
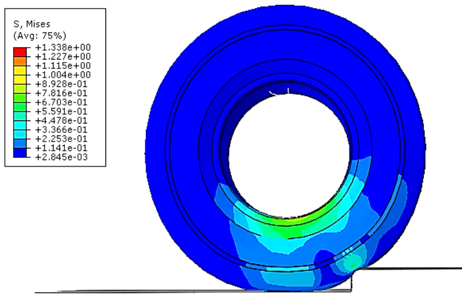


Figure 10. Deformation comparison of SRT and NPT under different loads

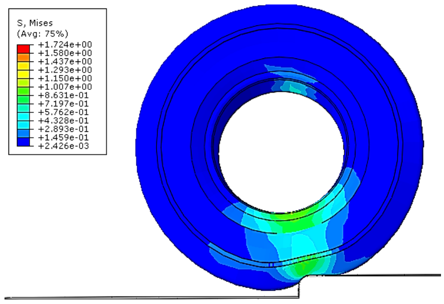
B. *Stress Comparison of SRT and NPT Under Curb Impact*

Figure 11 and Figure 12 present the tire positions and max. von mises stress distributions at different time stages of the two tire models. It clearly shows that the stresses in both of the tires vary with respect to time and speed. Further, at a speed of 5kmh^{-1}, the front side of the tires hit the curb at time 0.11 sec and maximum stress is obtained at time 0.15 sec. Further, the tires leave the curb at time 0.2 sec. These time frames are decreasing when the applied speeds are increased.

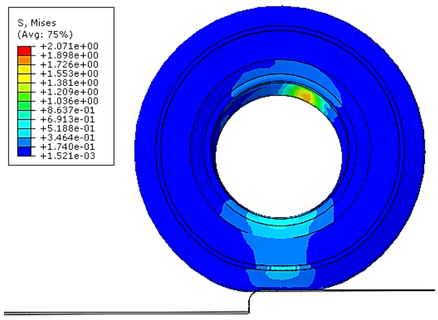
Moreover, when the SR tire is crossing the curb, the maximum stresses occurred at the base and tread layers of the tire rubber sections. Here, the cushion layer acts as a stress transferring medium in between the base and tread. In the NP tire, the maximum stresses are governed by shear layer and spokes.



(a). 0.11 sec



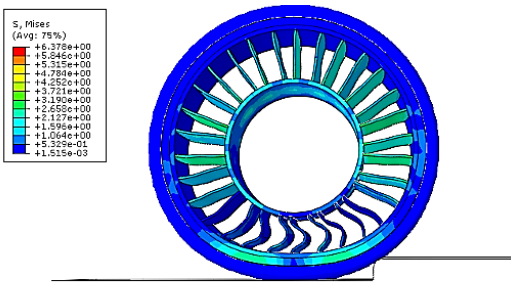
(b). 0.15 sec



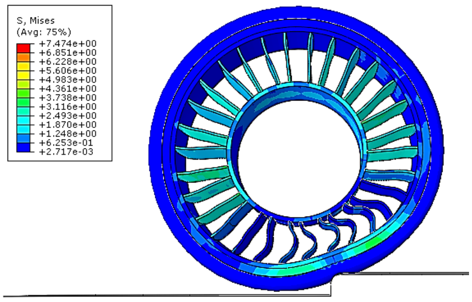
(c). 0.2 sec

Figure 11. Max. von mises stress distribution at different time frames of rubber sections in SRT: (a) 0.11 sec; (b) 0.15 sec; and (c) 0.2 sec

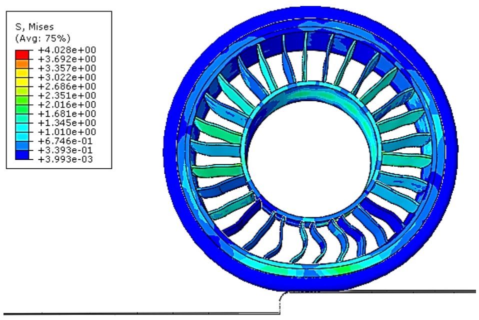
Further, Figure 13 shows the comparison of stresses on both tires at different velocities. Here, the stress on NP tire is dominant than the stress on SR tire. This means that, at low load levels, the high stresses are efficiently captured and absorbed by rubber and polyurethane sections in NP tires than SR tires without transferring them to the vehicle body. The elastic and viscous parts in rubber and polyurethane sections, stores as well as returns the energy and absorbs energy respectively. Hence, NP tires produces a more comfortable ride, good stability and better mobility than SR tires.



0.11 sec



0.15 sec



0.2 sec

Figure 12. Max. von mises stress distribution at different time frames of rubber and polyurethane sections in NPT: (a) 0.11 sec; (b) 0.15 sec; and (c) 0.2 sec

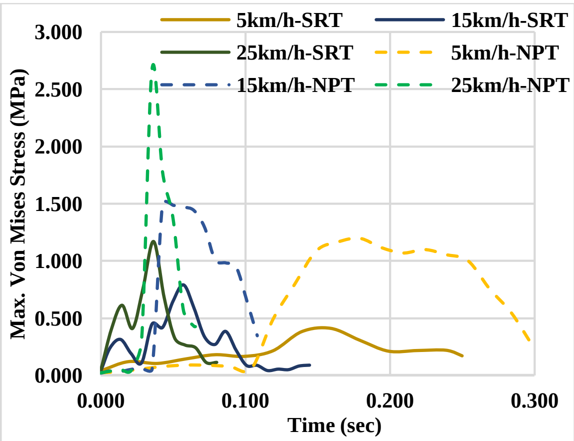


Figure 13. Max. von mises stress variation comparison of NPT and SRT under different velocities

Further, Figure 13 shows that the higher the velocity, lesser the impact time and higher the stresses generated on the tires.

Conclusion

Solid resilient tires (SRT) and non-pneumatic tires (NPT) are numerically modelled to analyse the comparisons of their characteristics under static and dynamic conditions. The FE models were developed to analyse and compare both SR and NP tires and their usability in military applications. The best fitted hyper-elastic material models were selected by curve fitting on test data. Yeoh and Mooney Rivlin hyper-elastic material models showed a good agreement with experimental stress-strain curves of rubber and PU sections respectively, and these material models were used to develop the numerical models. The numerical results were compared with experimental data to validate the models. The numerical results showed good accuracy in comparison with the experimental results.

Further, the validated numerical models were used to compare stresses and deformations of both SR tire and NP tire under different load levels in the static condition. The results emphasized that localized high stresses were mainly distributed in the base section than the other rubber sections of the SR tire. For the NP tire, high stresses were obtained on spokes and the shear layer than the rubber section. Moreover, NP tire model showed higher stress and deformation readings than SR tire under higher load levels. It was observed that, beyond certain loading limits the NP tire shows poor performances than the SR tire.

Additionally, an analysis of the tire impact on the curb was performed. To develop dynamic models the material time dependent data and relevant boundary conditions were introduced into the models. Here, stress variations of two tire models are investigated and compared under different impact velocities for a constant load level. NP tire presented higher stress levels than the SR tire when the tires rolled at the same speed. This showed that the NP tires were more suitable for light military vehicles (military UTV and military ATV) because it has the ability to move at considerably high speeds on harsh surface conditions with more stability and mobility on the vehicle. In addition, the SR tires were more suitable for heavy military equipment and transporting goods.

The above analysis can be effectively performed using FE simulation methods and it can be used to investigate the capabilities of the different tire types and their characteristics. Moreover, this study can be further extended to improve tire performances on dynamic behaviour by changing tire design.

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