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Non-Pneumatic Tire Design and Modeling: An Overview of Research

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Abstract

The research provides valuable insights into the intricate world of Non-Pneumatic (NP) tire technology, covering various facets from modeling and validation to material properties, design optimization, and tire-soil interactions. It begins with an exploration of existing NP tire modeling techniques, emphasizing the importance of accurate and reliable models for NP tires, including static and dynamic validation methods, and demonstrating the influence of structural features and material properties on tire performance. The review emphasizes the challenges and prospects of NP tires and aims to support the development of innovative airless tire solutions. The reviewed papers collectively contribute to a deeper understanding of NP tires, their applications, and potential enhancements in performance and efficiency across various industries.

Keywords

Non-Pneumatic Tires, Finite Element Analysis, Tire Mechanics, Vehicle Dynamics

1. Introduction

Tire engineering stands at the intersection of innovation, performance, and sustainability, playing a pivotal role in diverse sectors, including transportation, agriculture, construction, and even space exploration. The development and validation of NP tire technology has become a central theme in the automotive and engineering fields, driven by the increasing demand for innovative and sustainable tire solutions. NP tires, also known as airless tires, have gained attention due to their potential advantages over traditional pneumatic tires, including reduced rolling resistance and improved recyclability.

This paper embarks on a comprehensive exploration of the modeling and validation of NP tires. In recent years, several research endeavors have addressed various aspects of NP tire technology, shedding light on its mechanical design, material properties, and performance characteristics.

This research encompasses a wide spectrum, from investigating the influence of spoke shapes on vertical stiffness to the utilization of gradient anti-tetrachiral structures to enhance load capacity. Sardinha *et al.* [1] conducted a comprehensive analysis of the mechanical design and development of NP tires, addressing the contemporary challenges and potential prospects in NP tire technology, serving as a valuable resource for the advancement of innovative and efficient airless tire solutions. Additionally, this explores the complexities of NP tire behavior, scrutinizing dynamic and quasi-static characteristics, deformation patterns. It provides a comprehensive overview of NP tire mechanics and capabilities, achieved through the analysis of finite element simulations, experimental tests, and theoretical models. Tire performance parameters explore the fundamental parameters that govern tire performance, including grip, rolling resistance, and wear. Liu *et al.* [2] conducted a study with a primary focus on evaluating the static stiffness properties of a newly designed high-load capacity NP tire with various tread structures. Zheng *et al.* [3] explored into the multi-axis stiffness and road contact characteristics of NP tires featuring varying honeycomb cell angles. Rugsaj *et al.* [4] investigated the geometric effects on NP tires by formulating a finite element model that integrated different spoke shapes. Understanding and optimizing these parameters are essential for the advancement of NP tire technology. Exploring NP tire technology, examines NP tire models using numerical techniques like finite element analysis discusses their validation against real-world testing data and the potential benefits they offer, such as reduced puncture risk. Chakrit *et al.* [5] developed a Finite Element Model of the NP tire, employing 3D hexagonal and 2D quadrilateral elements to represent the Tread band and Spokes, respectively. Aldeen *et al.* [6] explored the distinctive mechanical properties of hyperelastic materials and underscored the significance of precise modeling for comprehending their behavior in various engineering applications. Baran *et al.* [7] enhanced the in-plane rigidity of classical re-entrant honeycomb cells by introducing inclined walls to the structure, thus improving core cell stiffness. Tire-Soil Interaction investigates the interaction between tires and soil. This section studies soil compaction, sinkage, and traction using experimental methods like indoor soil bins and field tests. El-Sayegh *et al.* [8] [9] presented a study on the calibration of three soil types using the Smoothed Particle Hydrodynamics technique to precisely create and verify Smoothed Particle Hydrodynamics-based representations of terrain materials for the purpose tire-terrain interactions. It highlights the need for accurate tire-soil interaction models to enhance tire performance in various environments. Focusing on NP tire spoke structures, this part explores spoke geometries, materials, and manufacturing techniques. Montgomery-Liljeroth *et al.* [10] explored the mechanical properties associated with two-dimensional auxetic honeycomb structures. It identifies gaps in our understanding of vibration, thermal-mechanical coupling, and other characteristics of NP tires with flexible spoke structures.

The ultimate goal is to address the need for more environmentally friendly and high-performance tire solutions in the context of sustainable transportation and energy efficiency. The studies highlighted in this paper contribute significantly to the evolving body of knowledge in this field, offering valuable insights poised to revolutionize the automotive industry. By building upon the foundations laid by these researchers, we envision a future where NP tires play a pivotal role in shaping the mobility landscape.

2. Tire Performance Parameters

Tires serve a triple role: supporting the vehicle's weight, resisting external disturbances, and facilitating braking and acceleration forces on the road [11]. Consequently, throughout the vehicle's operation, forces and moments act continuously along all three axes **Figure 1**. These functions are sustained by three main forces: Longitudinal Force (F_x) [12], affecting acceleration and deceleration; Lateral Force (F_y) [12], crucial for cornering and maneuvering; and Vertical Force (F_z) [12], sustaining the vehicle's weight and ensuring traction.

Additionally, tires experience three key moments: Overturning Moment (M_x) [12], influencing stability during cornering; Rolling Resistance Moment (M_y) [12], impacting energy consumption; and Self-aligning Moment (M_z) [12], ensuring stable handling. The interaction of these forces and moments with the road depends on the slip angle (α) and Camber angle (γ). The slip angle influences the tire's alignment with its intended path, while the camber angle affects its contact patch orientation. It is important to note that these interactions are

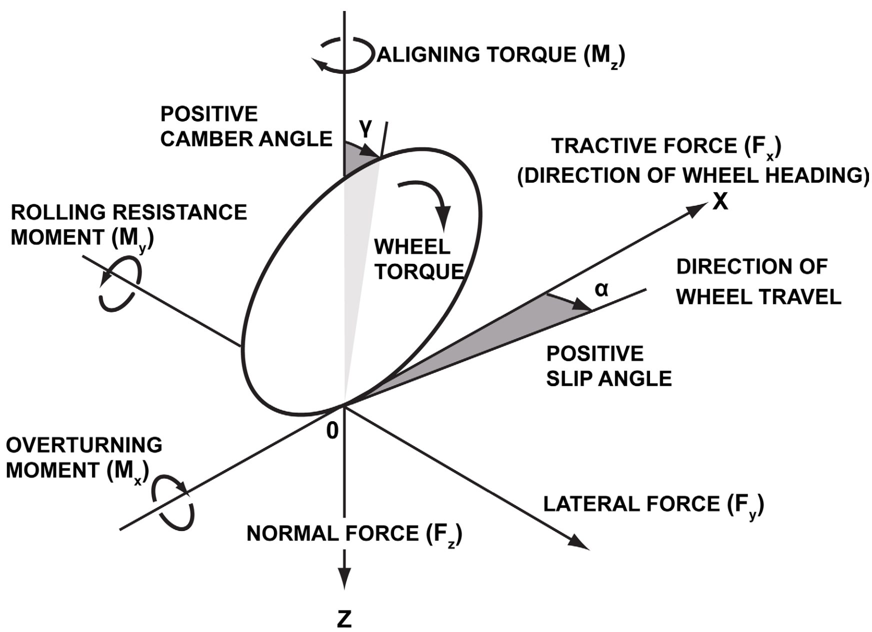

Figure 1. Tire Axis system (Source: Wong [12]).

absent when the tire loses contact with the road, but they are critical for normal tire performance and vehicle dynamics.

3. Non-Pneumatic Tire Modeling and Validation

The literature review chapter begins with an exploration of existing NP (Non-pneumatic) tire modeling techniques. It discusses various approaches and methodologies used to develop accurate and reliable NP tire models. The review also encompasses the validation of NP tire models, including static and dynamic validation methods used in previous research.

In 2023, Sardinha *et al.* [1] conducted a comprehensive review of NP tire technology. They examined the mechanical design, development, and characteristics of NP tires, including structural features, mechanical behavior analysis, standards, analysis methods, materials, production techniques, and end-of-life considerations (see **Figure 2**). The review also addressed the challenges and prospects of NP tires and aimed to support the development of innovative and efficient airless tire solutions. NP tires have garnered attention due to their potential advantages over traditional rubber-based pneumatic tires, such as reduced rolling resistance and improved recyclability. While NP tires were already used in specific applications like forklifts, electric scooters, and wheelchairs, large-scale production for most uses remained limited. The review provides an in-depth overview of NP tire research, highlighting key research areas and the potential to revolutionize the automotive industry. Researchers have focused on intricate NP tire designs with complex cellular structures and spoke arrangements, demanding advanced manufacturing processes and material selection. Future research should prioritize simpler and more scalable NP tire designs, addressing stiffness concerns for improved performance. Various materials and Advanced Manufacturing (AM) technologies have been explored for NP tire fabrication, but their scalability for mass production remains uncertain, especially in the automotive sector.

In 2023, Zhu *et al.* [13] presented an experimental and numerical investigation of the static load and pure longitudinal slip characteristics of an NP tire.

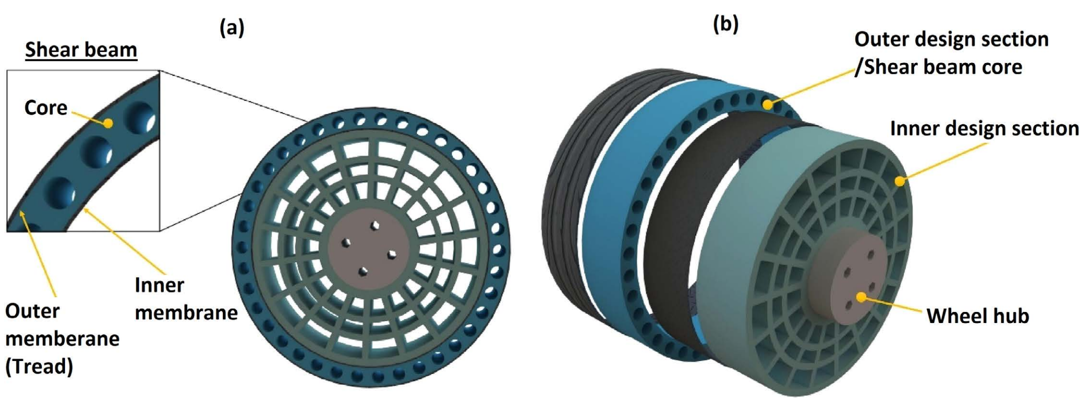

Figure 2. General composition of a non-pneumatic tire. (a) Front view of components and shear beam detail view. (b) Exploded view (Source: Sardinha *et al.* [1]).

The authors described the experimental setup and procedure used to test the NP tire. The tests were carried out on a specially designed test rig, which was used to apply static loads and pure longitudinal slips to the tire. The data obtained from the tests were used to determine the vertical stiffness, longitudinal stiffness, and longitudinal slip stiffness of the NP tire. The authors observed good agreement between the experimental and simulation results, indicating the accuracy of the FEM model. The authors note that the static load and pure longitudinal slip characteristics of NP tires were influenced by various factors such as the tire structure, material properties, and load conditions.

In the same year, Montgomery-Liljeroth *et al.* [10] provided a comprehensive review of the mechanical properties of 2D auxetic honeycomb structures **Figure 3**. The authors first introduced the concept of auxetic materials, which exhibit a negative Poisson's ratio, meaning that they expand in transverse directions when stretched longitudinally. Auxetic honeycomb structures have been proposed as a potential candidate for various applications, such as in protective gear and energy absorption. The study then presents various approaches to modeling the elastic properties of auxetic honeycomb structures, including analytical, numerical, and experimental methods. They discuss the effects of various fabrication parameters, such as cell size and shape, on the mechanical properties of the resulting structures.

In 2023, Liu *et al.* [2] conducted a study to analyze the static stiffness properties of a newly designed high-load capacity NP tire with different tread structures. They considered two tread designs, one with a built-in spiral steel ring and one without. The tire was primarily composed of polyurethane and silicon manganese steel, featuring a "π"-shaped support substructure (see **Figure 4**). The experiments assessed the static vertical, longitudinal, lateral, and torsional stiffness of the NP tire at 0 and 5-degree test points.

The NP tire had a bottom bearing mechanism, and its unit load capacity was 2.972 times that of solid tires and 1.615 times that of pneumatic tires. The study revealed that the spiral steel ring in the tread reduced vertical stiffness fluctuations and increased overall vertical stiffness. In terms of longitudinal stiffness, the reinforced NP tire initially decreased, then increased with vertical load until

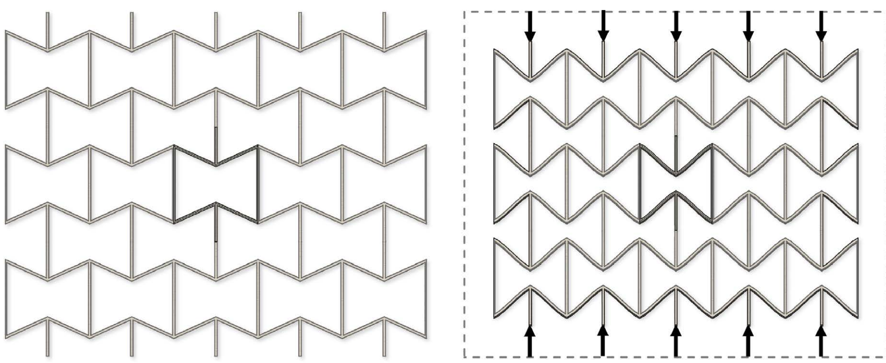

Figure 3. Effect of uniaxial compressive deformation on re-entrant hexagonal honeycomb. (Source: Montgomery-Liljeroth *et al.* [10]).

Figure 4. Polyurethane and silicon manganese steel, and a "π"-shaped support substructure NP tire (Source: Liu *et al.* [2]).

reaching a minimum of 51.45 kN. Conversely, the unreinforced NP tire's longitudinal stiffness decreased and stabilized at vertical loads exceeding 51.45 kN. The spiral steel ring increased longitudinal stiffness but did not reduce fluctuations. Additionally, the lateral stiffness of the NP tire exhibited a complex pattern, initially increasing, then decreasing, and finally increasing again with increasing vertical load. The spiral steel ring altered the lateral stiffness trend but did not reduce fluctuations. These findings have practical implications for designing more efficient NP tires, particularly in the automotive and construction industries.

In 2023, Hong *et al.* [14] discussed the development of NP tires, emphasizing their benefits like puncture resistance and energy efficiency. Their study primarily focused on refining the injection molding process for NP tires, with special attention to the role of the cooling system in the mold. The authors introduced a novel concept of a conformal cooling layout for the molds and created a 3D model to enhance the cooling system's efficiency. By employing process simulations and the Taguchi method [14], in their experimental design, the authors examined how the cooling system influenced the molding process and quality. They compared three different cooling system designs and assessed parameters such as cooling loop pressure loss, molding cycle time, and product quality. The results showed that the semi-annular conformal cooling channel layout outperformed traditional direct cooling systems, reducing pressure loss by 77% and decreasing molding cycle and cooling times by 9.6%. It also lowered tire volume shrinkage by 0.012% and improved temperature uniformity, reducing defects like depressions and shrinkage marks in NP tires. The authors recommended specific design parameters for the semi-annular conformal cooling system. They concluded that this innovative cooling system had significant potential for enhancing the production of high-quality NP tires, offering better efficiency and assembly accuracy. Additionally, they suggested the need for future research on cost-effective fabrication methods to facilitate broader adoption. Overall, this study provides valuable insights into optimizing mold cooling systems for NP tire manufacturing.

In 2022, Xu *et al.* [15] focused on developing NP tires, emphasizing the significance of radial stiffness and weight in assessing their performance. They proposed optimizing spoke thickness distribution to reduce weight while maintaining radial stiffness (see **Figure 5**). To achieve this, they introduced a topology optimization algorithm, utilizing MATLAB and ABAQUS software. Their research followed these steps: first, they determined the material properties through testing.

Then, they created and validated a Finite Element model of the NP tire with a Fibonacci spoke structure [15], verifying its reliability through radial-stiffness testing.

Subsequently, they applied the topology optimization algorithm to find the best spoke thickness distribution, minimizing mass while meeting radial stiffness requirements. The optimized tire was manufactured, and stiffness testing confirmed a 9% spoke mass reduction while satisfying requirements. Variable thicknesses in both radial and tire-width directions contributed to this reduction.

However, there were some remaining thickness discontinuities, which they planned to address in future work by establishing a node-based relationship to eliminate such discontinuities. In summary, their study presented an innovative optimization algorithm for lightweight NP tires, achieving a 9% mass reduction without compromising performance.

In 2022, Zheng *et al.* [16] discussed the development and performance analysis of NP tires with honeycomb spokes **Figure 6**. The main objective of the

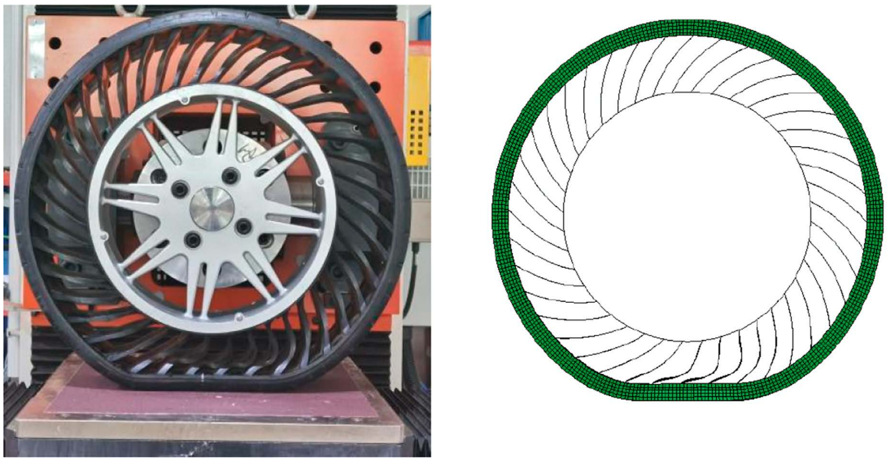

Figure 5. Spoke with variable thickness of NP tire shows consistent deformation in both the test and Simulation (Source: Xu *et al.* [15]).

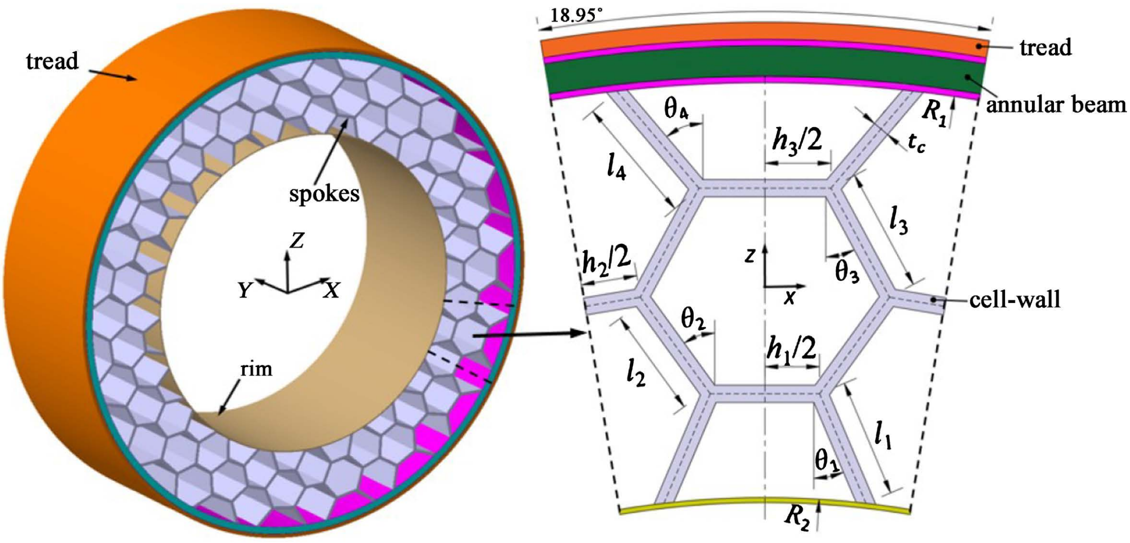

Figure 6. Components of the honeycomb NP tire with 31.5˚ cell angle (Source: Zheng *et al.* [16]).

research was to design NP tires that have comparable in-plane and out-of-plane force-deflection and force-slip characteristics to pneumatic tires. The study reviewed that prior studies on NP tires with honeycomb spokes have mainly focused on their static and dynamic responses to normal wheel loads, with minimal attention given to out-of-plane responses crucial for handling and directional control. To address this research gap, the author developed three-dimensional FE models of honeycomb NP tires with different spokes configurations using ABAQUS software.

The mechanical characteristics of honeycomb structures were notably impacted by the geometry of the spokes and the properties of the material composing the cell walls. The effective elastic moduli and shear modulus of a two-dimensional honeycomb spoke in the linear deformation range can be estimated using the following equations [10] [16]:

$$E_Z = E\left(\frac{t_c}{l}\right)^3 \frac{\cos\theta}{\left(\frac{h}{l}+\sin\theta\right)\sin^2\theta} \tag{1}$$

$$E_X = E\left(\frac{t_c}{l}\right)^3 \frac{\left(\frac{h}{l}+\sin\theta\right)}{\cos^3\theta} \tag{2}$$

$$G_{ZX} = E\left(\frac{t_c}{l}\right)^3 \frac{\left(\frac{h}{l}+\sin\theta\right)}{\left(\frac{h}{l}\right)^2 (1+2h/l)cos\theta} \tag{3}$$

Here, in these equations symbols E_Z (1) and E_x (2) represent the effective elastic moduli in the Z and X directions respectively (as depicted in **Figure 6**), while G_{ZX} equation (3) corresponds to the effective shear modulus [10] [16]. In these Equations (1)-(3), E stands for the elastic modulus of the material forming the cell walls, t_c represents the thickness of the cell walls, and the parameters l, h, and θ were connected to the average lengths (I_i, i = 1,..., 4), heights (I_j, j = 1,..., 3), and angles (θ_k, k = 1,..., 4) of the cell walls respectively, as illustrated in **Figure 6** [10] [16]. Mesh convergence studies were conducted to determine optimal element sizes, and the validity of the models was verified by comparing the predicted responses with available results. The models were then used to evaluate the feasibility and merits of the NP tires by comparing their properties with a reference pneumatic tire. The results showed that the honeycomb NP tire designs can achieve comparable vertical and longitudinal stiffness to pneumatic tires while having significantly higher lateral and cornering stiffness.

In 2022, Zang *et al.* [17] investigated the mechanical characteristics of NP tires with a rhombic porous structure **Figure 7** under complex pavement conditions. Study presented a mechanical model of the rhombic structure based on the hexagonal honeycomb theory and examined the differences in mechanical characteristics between the rhombic NP tire tread and a pneumatic tire on horizontal and complex pavements. The results of the study showed that the average contact pressure of the NP tire with a rhombic structure on a horizontal road was much lower than that of a pneumatic tire. The study also revealed that the vertical displacement and contact pressure of the NP tires were decoupled on the complex pavement.

In the same year, Fu *et al.* [18] summarized the study on the key mechanical properties of FS-NP tire (Flexible spoke non-pneumatic tire) under thermo-mechanical coupling conditions. They used numerical analysis and prototype testing to investigate these properties, including vertical displacement, grounding area, and axial displacement during tire rolling. The results indicated that under thermal and mechanical coupling, these properties increased compared to non-coupled conditions. They predicted a fatigue failure mileage of (2.67×10^4 km) for FS-NP tires using the J-integral method [18], which aligned with indoor drum test results (2.44×10^4 km). The study revealed that load had a more significant impact on tire temperature than driving speed, and reducing load or increasing speed could reduce high-temperature failure risks during high-speed operation. The authors stressed the theoretical and practical importance of this research for tire safety technology, emphasizing the benefits of

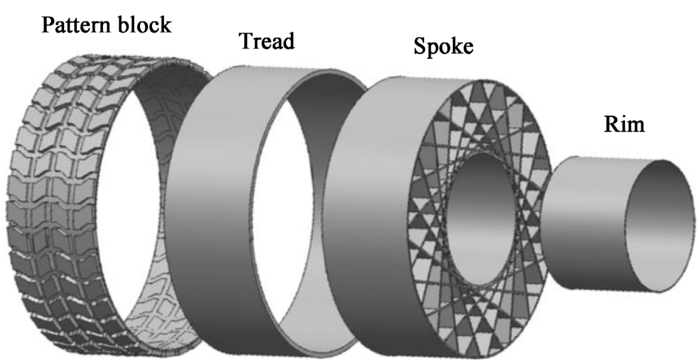

Figure 7. Structure of the NP tire with rhombic spokes (Source: Zang *et al.* [17]).

increasing speed and optimizing structural parameters to enhance FS-NP tire service life.

In 2022 Alobaid *et al*. [19] presented a modal analysis of a discrete tire model using the finite difference method. The study aimed to investigate the dynamic behavior of the tire model under different rolling conditions, with a focus on the effect of the contact patch on the natural frequencies and mode shapes of the tire. In other words, the study of the modal analysis of the tire model, considering the rolling conditions and contact patch. The authors started by describing the mathematical model used for the tire, which was based on a finite difference approach. The tire was discretized into a series of finite difference elements, and the dynamic equations of motion were derived. The authors then perform a modal analysis of the tire model, computing the natural frequencies and mode shapes of the tire under different rolling conditions. The results show that the contact patch has a significant effect on the natural frequencies and mode shapes of the tire, particularly in the low-frequency range.

In 2022, Sardinha *et al*. [20] discussed the mechanical design of NP tires and their suitability for additive manufacturing, specifically Fused Filament Fabrication (FFF). The authors focused on the geometric design of NP tires and how it affects their damping and stiffness behaviour. The research acknowledged that tireless wheel concepts already exist in commercial solutions, but there were still unresolved issues, such as dealing with trapped debris within the spokes, distributing weight evenly, and predicting the collapse of NP tires. Additive manufacturing technologies, particularly FFF, were seen as suitable for producing the complex geometries required for NP tires. The research included a compilation of research designs proposed for NP tires and evaluated their suitability for FFF manufacturing. The designs were categorized based on whether they specifically addressed the annular conception of NP tires or focus on individual components such as shear rings or spokes. The review emphasized the need for methodologies that consider functionality and context to improve product efficiency and guide innovative creations. It suggested that NP tires produced using FFF could be a potential solution for customizable and environmentally friendly tire manufacturing in the future.

In 2022, Andriya *et al*. [21] discussed the use of a customized 3D printer to create cost-effective and usable rapid prototypes of TPU (Thermoplastic Polyurethane)-based NP tires using FDM (Fused Deposition Modeling) 3D printing technique. The objective of the research was to investigate the feasibility of using TPU-based auxetic structures in NP tires to provide a cushioning effect and a relaxing journey for passengers. The study conducted a comparative analysis of three different cell geometries to develop simple NP tire models. These models were subjected to static loading conditions of a standard passenger vehicle using FEA software. CAD models were generated, and a static analysis was performed using ANSYS software. Based on the FEA simulations, the researchers found that the re-entrant hexagonal-type auxetic structure was the most suitable for a city utilitarian vehicle in terms of its performance under static loading conditions.

In 2021, Zheng *et al.* [22] conducted a comparative study of the static and dynamic properties of honeycomb NP tires and a pneumatic wheel. The authors aimed to explore the performance of honeycomb NP tires under different loading and operating conditions and compare their performance with a traditional pneumatic wheel. The study focused on the static and dynamic stiffness, damping, and natural frequency of the wheels. The authors used FEA and experimental tests to compare the mechanical properties of the three types (three different spokes configurations by varying the cell angle) of wheels. The honeycomb NP tire consisted of a deformable honeycomb core and an outer rubber layer, while the pneumatic wheel had a traditional inner tube and outer rubber layer. The FEA simulations showed that the honeycomb NP tire had a lower vertical stiffness and higher lateral stiffness compared to the pneumatic wheel. Additionally, the honeycomb NP tire had a lower natural frequency and higher damping ratio, which was attributed to the deformable honeycomb core. The experimental tests validated the FEA results, demonstrating that the honeycomb NP tires had a lower vertical stiffness and higher lateral stiffness compared to the pneumatic wheel.

In the same year, Sim *et al.* [23] aimed to investigate the influence of the spoke shape on the vertical stiffness of NP tires. They discussed the advantages of NP tires over traditional pneumatic ones and concentrated on assessing vertical stiffness by altering spoke shapes. The authors outlined the calculation method for vertical stiffness and examined the impact of different spoke shapes on it. They performed finite element method simulations on NP tires with four distinct spoke shapes: Fillet-applied, Asymmetric-spoke division, and Symmetric-spoke division models. Results showed that the Filter-applied model exhibited 1.56% less deformation compared to the reference model, indicating greater rigidity. Conversely, the Asymmetric-spoke division and Symmetric-spoke division models experienced 4.09% and 6.43% more deformation, respectively, indicating reduced stiffness. Additionally, stress levels were higher in the Fillet-applied (11.13%), Asymmetric-spoke division (5.34%), and Symmetric-spoke division (9.81%) models compared to the reference model. This study provides insights into how design changes, like fillet application and spoke division, affect stress, deformation, and vertical stiffness in NP tires.

Also in 2021, Liang *et al.* [24] proposed to build an analysis model of NP tire static grounding, which considers the non-linearity of spoke stiffness. The proposed analysis model first simplified the shear band, rigid rim, and spoke structure of the NP tire and extracted the main structural parameters and mechanical parameters to establish an analysis model. Then, the stiffness of the spokes during tension and compression was considered, and an iterative method was used to compensate for the difference in deformation caused by the difference in radial stiffness of the spokes. The contact between the tire and the road surface was introduced to iteratively compensate for the reaction force of the road surface. The analysis model of the NP tire proposed in this study sets up a non-linear radial stiffness of the spoke that can more accurately describe the structural performance of the NP tire.

Another research in 2021 conducted by Li *et al.* [25] involved three main phases: simulation, modeling, and wind tunnel testing. Results showed that reducing the tire width and spoke length and increasing spoke thickness can effectively decrease the aerodynamic coefficient. However, spoke curvature and spoke offset did not have a significant influence on the aerodynamic coefficient. Compared to solid tires, NP tires increased the drag coefficient of the whole vehicle by 8.20%, with NP tire drag accounting for 21.21% of the whole vehicle. The drag from the NP tire was primarily provided by the front wheel, which accounted for 65.79% of the tire drag. Consequently, the authors emphasized the need for further design improvements in NP tires to reduce resistance. The study proved the importance of optimizing NP tire design to enhance vehicle performance and reduce drag.

In 2021, Jafferson *et al.* [26] presented a novel approach to designing airless tires using 3D printing technology and a software tool called NTopology. The research focused on designing energy-absorbing core structures for airless tires using NTopology software. Twelve different volume lattice structures, sixteen Triple Poly Minimal Surface (TPMS) lattices, and hybrid TPMS designs were created and compared. The study evaluated the weight, material cost, and ease of design using TPU material by BigRep [26]. The goal was to identify optimal lattice and surface patterns that offer efficient energy absorption within airless tire cores. The authors described the design process, material selection, and manufacturing methods used to produce a functional prototype of an airless tire. The design parameters for the tire included the tread pattern, sidewall shape, and internal structure. The authors explained how they used NTopology to optimize the internal structure of the tire for maximum strength and durability. The authors chose a polyurethane-based material for the tire due to its superior mechanical properties. The authors also concluded that their approach to designing and manufacturing airless tires using 3D printing technology and NTopology is a promising direction for future research in this area.

In 2021, Jackowski *et al.* [27] investigated the impact of NP tire geometry on quasi-static characteristics for All-Terrain Vehicles (ATVs) and Utility Task Vehicles (UTVs). They conducted experiments to determine radial stiffness on flat and obstacle surfaces and assessed deformation in the elastic structure and belt. Results emphasized the significant influence of elastic structure shape and elastomer on radial stiffness. The study examined NP tires' quasi-static behavior, including load-bearing structure, and elastic and belt deformation, revealing differences from pneumatic tires due to unique material properties. It underscores the complexity of NP tires, suggesting further research avenues such as temperature effects and energy consumption.

In 2021, Genovese *et al.* [28] used a Michelin X-Tweel UTV as a reference tire and performed an experimental study using a 3D scanner (FARO CAM2 Edge

ScanArm HD) to acquire the shape of the NP tire. A footprint analysis was also performed to calculate the radial stiffness and contact patch pressure distribution. Additionally, the Digital Image Correlation (DIC) technique was used to study the spoke's deformation. From the acquired 3D model, the authors built a finite element model and performed a steady-state analysis to simulate the rolling of the tire at a velocity of 10 km/h. The simulation allowed the authors to obtain the effective rolling radius, longitudinal force vs. slip ratio graph, and vertical reaction vs. slip graph. The results from the numerical simulations were in good agreement with the experimental data, validating the methodology. The authors were outlining three key directions for future research related to the NP tire: exploring the impact of different camber values on longitudinal behavior, applying the research methodology to the study of lateral dynamics, and validating the obtained results through outdoor testing.

In 2021, Wu *et al.* [29] introduced a novel concept for an NP tire, replacing traditional pneumatic elements with a gradient anti-tetrachiral structure. Their study involved examining this structure's mechanical properties and elastic limit load through experimental, finite element, and theoretical analysis. They then applied this structure to design the NP tire, evaluating its mechanical characteristics under compression loads using finite element analysis. The research aimed to establish the practical significance of the gradient anti-tetrachiral structure in NP tire design and its potential engineering applications. Initial investigations focused on the in-plane mechanical properties and elastic limit load of gradient anti-tetrachiral structures, with varying gradient factors. Results showed that increasing the gradient factor reduced the elastic limit load. Experimental values consistently yielded lower elastic limit loads compared to theoretical values due to ligament dislocation, with a reasonable error margin of 13%. Based on these findings, the authors proposed an innovative NP tire design using the gradient anti-tetrachiral structure, which significantly enhanced load capacity compared to the structure alone, achieving a tenfold increase.

In 2020, Chakrit *et al.* [5] developed a FEM of the NP tire, which consisted of the Tread band and Spokes. The 3D hexagonal and 2D Quadrilateral elements were employed to model these components, respectively. The steel belt layers of the NP tire were modeled using rebar elements and tying equations. The mechanical behavior of the NP tire components, which was time-dependent, was modeled using a visco-hyperelastic constitutive model (Ogden). The validated Ogden hyperelastic material model and generalized Maxwell viscoelastic material model were used to model nonlinear elastic and inelastic behaviors of NP tire components. The developed FEM of the NP tire was then subjected to traverse different cleat heights to investigate the effect of obstacles on tire-road interaction and the dynamic response of the NP tire. The impact force history and deformation behavior of the NP tire at various time points were analyzed. The results were compared to assess the validity of the model in capturing important dynamic characteristics. The study found that the FEM of the NP tire with the highest cleat height (30 mm) exhibited the greatest average vertical displacement of the tire center and average impact force, measuring 5.617848 mm and 30.87236N, respectively. The analysis revealed underdamped oscillatory behavior in both the vertical displacement and impact force, indicating that NP tires have the potential to be optimized for ride comfort properties.

In 2020, Phromjan *et al.* [30] focused on a research study that attempts to simplify the modeling and analysis of airless tires by modifying the steel belt layers. The material properties of the tread and spokes were described using the Mooney-Rivlin hyperelastic model, and the constitutive model constants were determined through tensile and compressive tests following ASTM D412 and D575 standards, respectively. The modified steel belt, developed through a homogenization approach, was integrated into the shear band component. The resulting airless tire model with modified steel belt layers aimed to reduce complexity and analysis time while maintaining accurate results. The modification of the steel belt layer in the shear band of the airless tire model using the homogenization approach with isotropic material led to more accurate results compared to the model employing the rebar element approach when compared to experimental data. Additionally, the analysis time was not significantly increased and could be neglected. The airless tire model with modified steel belt layers, incorporating the use of hyperelastic material properties for the rubber part, proved effective in reducing model complexity and analysis time while still providing accurate results.

Another study in the same year by Wang *et al.* [31] conducted a study on 3D printing technology for NP tires, focusing on thermoplastic polyurethane (TPU) and fused deposition modeling (FDM). They explored 3D printing's potential advantages like customization and cost-effectiveness but noted its limited use in NP tires. They tested TPU material for 3D printing, determining the optimal temperature as 210˚C. FDM was used to successfully produce NP tires, with their stiffness at 50% of simulated values. To ensure accurate predictions, they recommended adjusting material properties during structural design. Rheological tests showed TPU's viscosity decreased with increasing shear rate, requiring a minimum of 195˚C for stable 3D printing. TPU exhibited superior wear resistance compared to natural rubber, butadiene rubber, and styrene butadiene rubber. Adjusting 3D printing parameters, such as filling percentage, improved sample performance, with the best results at 210˚C and 100% filling.

In 2019, Marcin *et al.* [32] presented a study on NP tires, The authors developed a numerical model of an NP Tire and validated it with experimental results to determine its quasi-static and dynamic characteristics. They validated their model by comparing the results of simulations with experimental research on the behavior of the wheel under different normal loads. The static radial characteristic, distribution of contact pressure, and deflection of individual NP tire spokes were determined. The authors note that their numerical results have a high convergence with experimental research, with differences within the area of standard deviation.

In the same year 2019, Du *et al.* [33] focused on the grounding characteristics of an NP tire mechanical elastic tire (ME wheel) in a rolling state with a camber angle. They conducted stiffness tests to validate the ME wheel's simulation model. A comparison was made between the ME wheel and an inflatable tire in terms of their grounding characteristics under different camber angles in free rolling, braking, and driving conditions. They also examined the impact of slip ratio on grounding characteristics during driving. The results revealed that in free-rolling conditions, the ME wheel exhibited symmetrical ground pressure along the width direction of the grounding mark. However, with increasing camber angle, both the ME wheel and inflatable tire showed pressure concentration on the roll side, leading to uneven pressure distribution and partial tread wear. Under braking conditions, the camber angle's effect on the ME wheel's pressure distribution was similar to free rolling, but it was no longer symmetrical. In driving conditions, the high-pressure zone of the ME wheel moved opposite to that in braking, offsetting the rear end of the contact patch. Additionally, the maximum pressure of the contact patch increased with higher slip ratios while keeping the camber angle constant.

In 2018, Zhao *et al.* [34] study aimed to investigate the influence of high thermal conditions on the structural dynamic response of Mechanical elastic wheels (ME-Wheel) using a combination of FEM and Experiment Modal Analysis (EMA). The results showed that the EMA results agreed with those obtained using the FE model, indicating the high reliability of the proposed analysis method. The temperature had a significant effect on the modal characteristics of the ME-Wheel. The frequency modal of the ME-Wheel grew linearly with the increase of the model order under the operating thermal environment, and the deformation degree of the elastic wheel modal shape under thermic conditions was larger than the cold-modal shape in the same order.

In the same year 2018, Jin *et al.* [35] examined the static and dynamic behaviors of NP tires with different honeycomb spokes. The authors used numerical simulations to investigate the stress distribution and rolling resistance of three types of NP tires with different geometric parameters but the same cell wall thickness or load-carrying capacity. Based on the results, the authors found that the load-carrying capacity of NP tires with honeycomb spokes was higher than traditional pneumatic tires. The maximum stresses in the spokes and tread of NP tires were much lower than that of traditional pneumatic tires. The authors also observed that the maximum stresses in spokes and tread under dynamic loading were higher than those under static loading.

In 2017, Mohan *et al.* [36] proposed a new design of an NP tire that can withstand the challenging terrain vehicles. The authors described their proposed design, which consists of a combination of a flexible central hub and outer spokes made of a rigid material. The hub was designed to absorb the impact of bumps and obstacles, while the spokes distribute the load evenly across the tire.

In the same year 2017, Fu *et al.* [37] presented a new design of a honeycomb structure that combines the re-entrant hexagonal configuration with the rhombic configuration **Figure 8**. The objective of this research was to enhance the in-plane mechanical properties of the honeycomb, particularly it's Young's modulus, Poisson's ratio, and critical buckling strength while maintaining its auxetic behavior. The authors employed both theoretical analysis and numerical simulations to investigate the mechanical properties of the new honeycomb.

4. Tire-Soil Interaction

The literature review then delves into the tire-soil interaction research. Tire-soil interaction was a critical factor in vehicle dynamics, affecting vehicle performance, safety, and mobility. It explores previous studies on the interaction between NP tires and different types of soil, including soil compaction, sinkage, and deformations. The review also highlights the factors that influence tire performance in soil, such as tire pressure, tread design, and wheel load.

In 2023, Deng *et al.* [38] provided a detailed review of the state-of-the-art research on NP tires. The authors discussed a comprehensive overview of the different types of NP tires, including those based on cellular solids, shear band materials, and shape memory alloys, among others. The study also discussed the challenges associated with the design and analysis of NP tires, including the need for accurate models of tire-soil interaction, and the need to optimize the tire structure to achieve the desired performance characteristics. The study also reviewed recent advances in NP tire design, including the use of new materials such as graphene, carbon nanotubes, and shape memory alloys, and the use of advanced manufacturing techniques such as 3D printing.

In 2019, Sandu *et al.* [39] summarized the first paper in a series of three, focusing on the development of a lumped-mass discretized tire model using

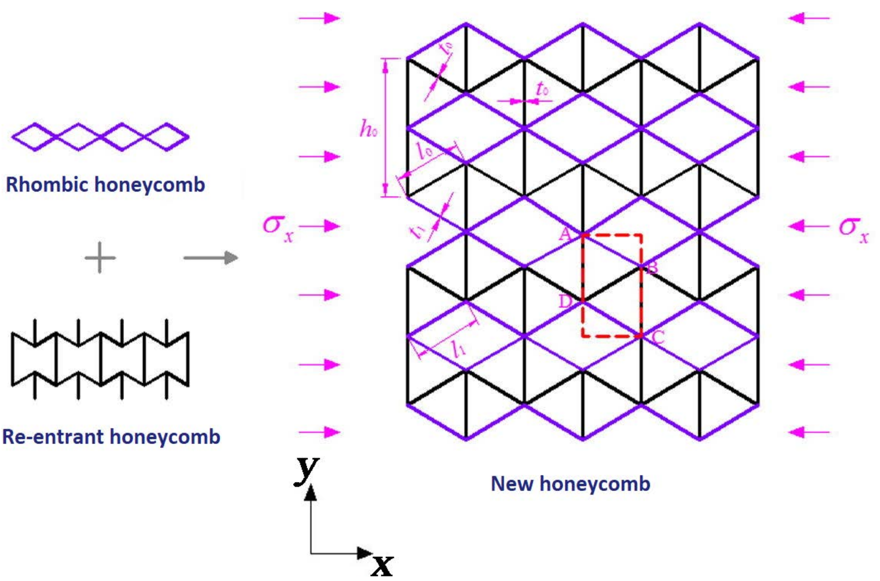

Figure 8. New design of a honeycomb structure that combines the re-entrant hexagonal with the rhombic configuration (Source: Fu *et al.* [37]).

Kelvin-Voigt material elements. This tire model Figure 9 aimed to accurately simulate tire behavior during interactions with both soft soil and rigid surfaces. The research overviewed their modeling approach, which employed three-dimensional discretization to describe the tire's structure using Kelvin-Voigt elements. The tire's belt was divided into segments connected to the rim through springs and dampers, with further subdivision into belt elements to account for lateral road inputs. The level of discretization was determined based on road wavelength and computational load.

This approach led to the development of the Hybrid Soft Soil Tire Model (HSSTM), designed to accurately represent off-road perturbations and soft-soil capabilities efficiently. Integration with the CarSim vehicle model enabled simulations on deformable terrains, utilizing empirical equations for terrain behavior. Computational optimizations, such as stiffness matrix partitioning and multi-processing, improved efficiency, making it compatible with commercial vehicle simulation packages. This work provided mathematical formulations for tire material properties, tire structure kinetics and kinematics, while Kelvin-Voigt elements ensured accurate visco-elastic representation without sacrificing computational efficiency. Ultimately, this research advanced off-road tire modeling, offering valuable insights into tire-soft soil interactions and their

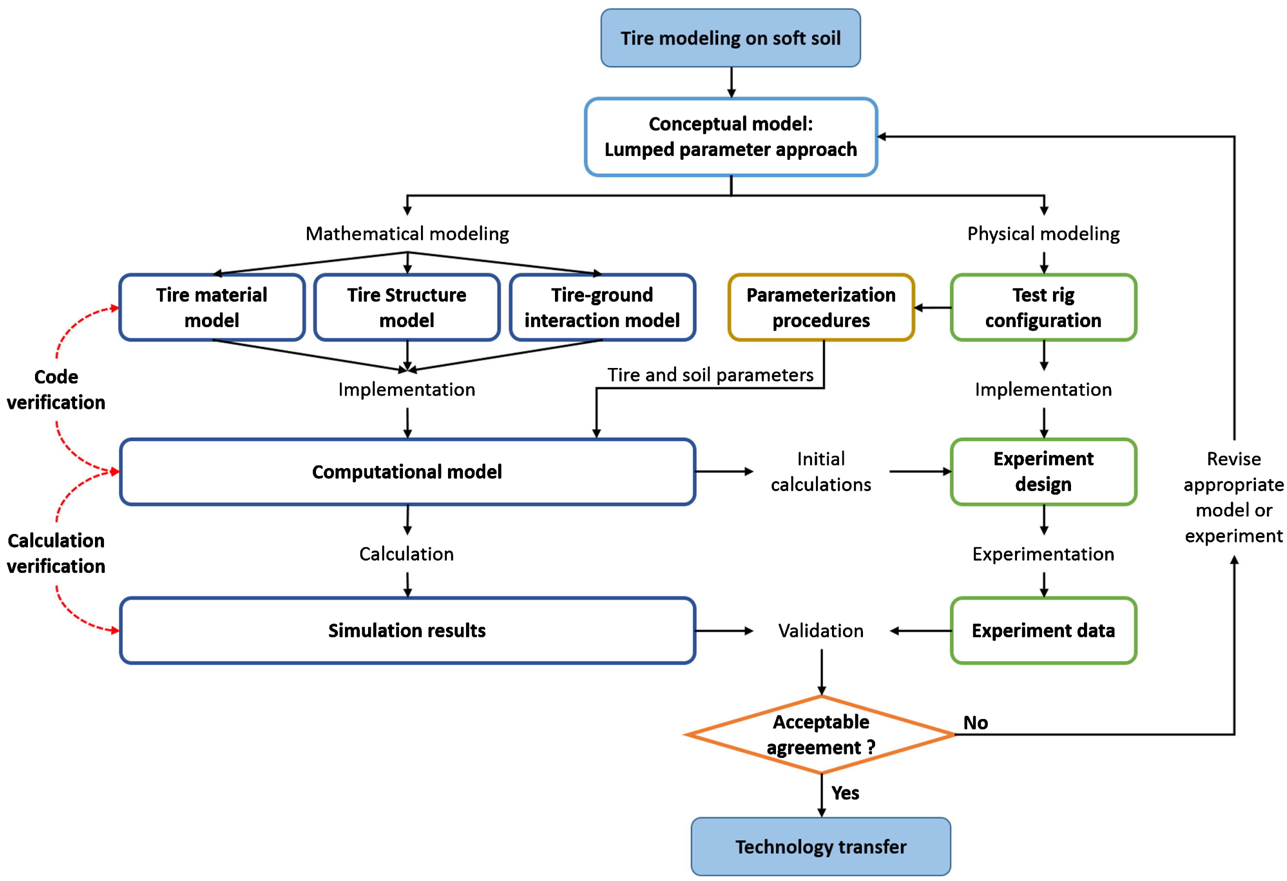

Figure 9. Semi-empirical mathematical tire modeling on soft soil: Modeling, simulation, and experimental procedures workflow. (Source: Sandu *et al.* [39]).

integration into vehicle dynamics simulations, promising increased accuracy and efficiency in off-road vehicle simulations.

In 2019, Sandu *et al.* [40] reviewed and discussed the second paper in a series of three, focusing on the HSSTM and its tire-terrain interaction capabilities. Part I of the series introduced the tire structure model, while Part III presented the tire model parameterization and validation. Part II, the subject of this review, explored the computational contact models used to analyze tire interactions with various terrains, including both rigid and deformable surfaces. The main objective was to characterize terrain behavior during these interactions, as illustrated in **Figure 10**. The authors introduced two crucial modules for terrain interaction within the High-Fidelity Soil-Tire Interaction Simulation (HSSTM): the contact search and contact interface units. These modules allowed the tire model to interact with different terrains effectively. For deformable terrains, the contact search algorithm identified tire nodal points near the ground and managed surface penetration, while the subsequent contact interface algorithm applied constraints to minimize or eliminate penetration. The deformable terrain model relied on semi-empirical formulations, combining empirical data with analytical approaches to achieve accuracy while maintaining computational efficiency. It is important to note that these semi-empirical formulations were limited in their applicability to conditions resembling the available test data. Simulations were conducted to validate the deformable terrain model by analyzing stress distribution during rigid wheel-soil contact, and comparing results with experimental data.

The model successfully described pressure-sinkage and terrain behavior across various types. In the case of rigid terrains, the contact interface model used a 3D distributed brush model with LuGre friction for dynamic maneuvers. Model parameters were determined through a nonlinear least-square method, minimizing discrepancies between model predictions and experimental data derived from

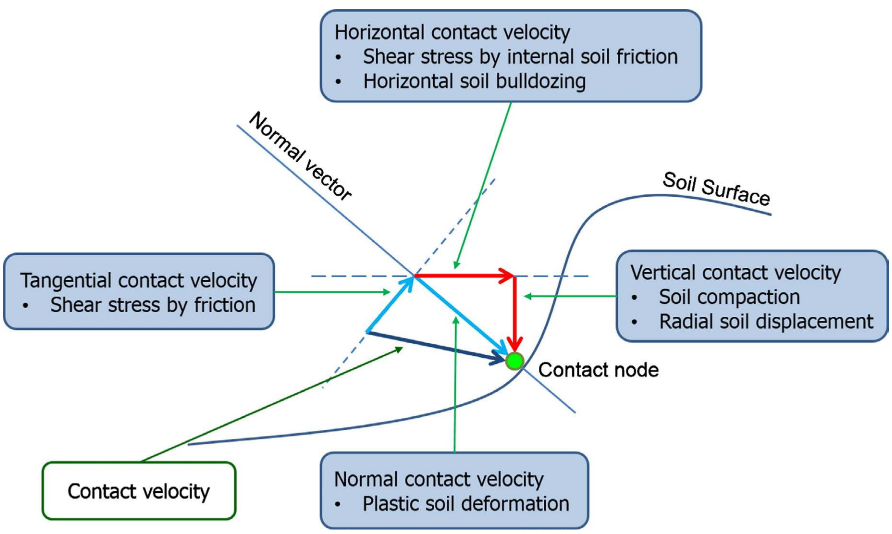

Figure 10. Terrain responses to tire loading depend on contact node velocity, angle of attack, and relative penetration into the ground surface. (Source: Sandu *et al.* [40]).

the Magic Formula [41]. This model was integrated into the HSSTM by connecting deformable bristles to tire belt elements, eliminating the need for predefined normal pressure assumptions. In conclusion, this Part II paper effectively elucidated the computational contact models used in conjunction with the HSSTM, enhancing our understanding of tire-terrain interactions and contributing to more accurate vehicle dynamics simulations across diverse terrains.

In 2019, Sandu *et al.* [42] covered the third paper in a series of three, focusing on the parameterization and validation of the HSSTM. The preceding papers, Part I and Part II, respectively, described the tire structure model and the contact detection and contact interface models for both rigid and deformable terrains. This study estimated the model parameters for the HSSTM using non-linear least-square optimization and validated the model against experimental data. Experimental tests were performed on the Terramechanics test rig at Virginia Tech **Figure 11**, using the Michelin LTX 235/85R16 tire on sandy loam. The parameterization process involved estimating the model parameters that minimize the error between the HSSTM simulation results and experimental data.

To initialize the parameterization routines, modal analysis in radial and circumferential directions was used. Frequency response functions (FRFs) were constructed based on input and output acceleration signals obtained from modal analysis. The tire mode shapes, natural frequencies, and damping values were

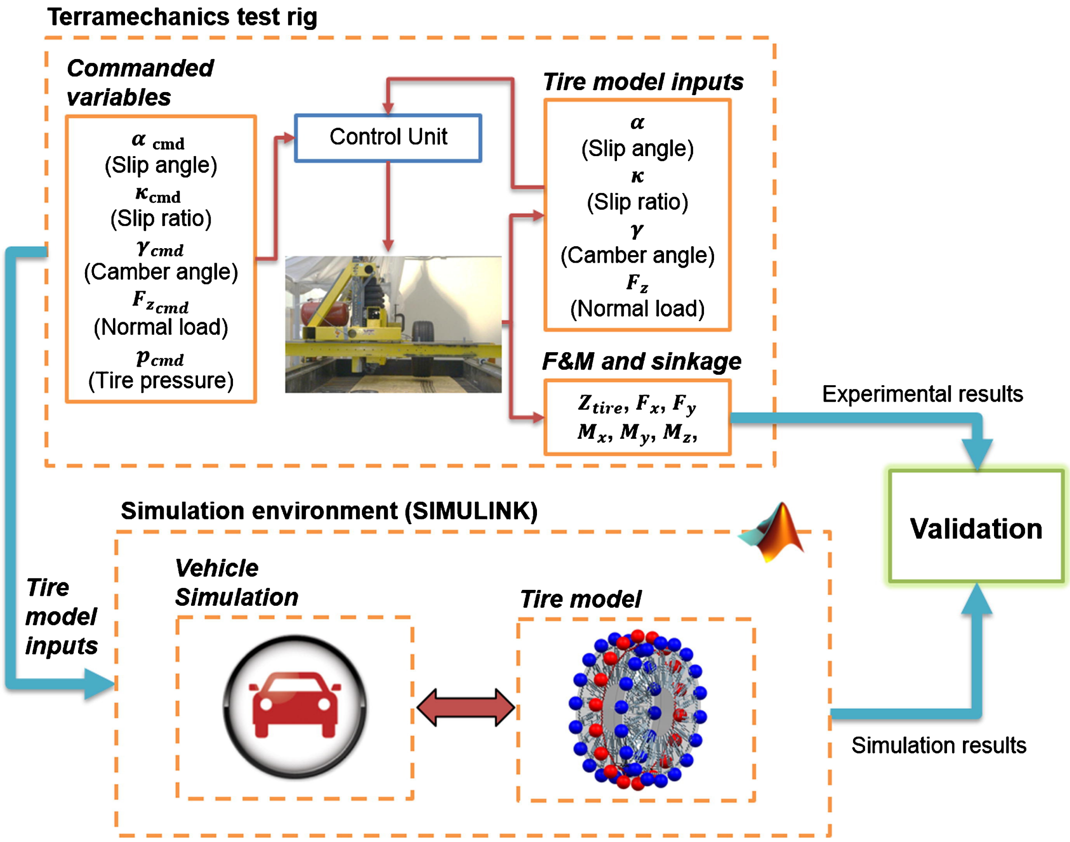

Figure 11. Validating the tire model results using experimental data from Terramechanics test rig. (Source: Sandu *et al.* [42]).

extracted from these FRFs. The initial stiffness and damping values for the in-plane force elements used in the HSSTM were identified based on this information. A least-square curve-fitting algorithm was then employed to find the model parameters in the radial, longitudinal, and lateral directions. Quasi-static cleat loading tests were utilized to determine the tire model sidewall and belt radial parameters. The accuracy of the tire structure model in estimating tire radial behavior was assessed by comparing the vertical force at the spindle and tire contact patch area from the model with experimental results. Cleat test simulations were conducted to evaluate the dynamic behavior of the tire structure model, and the results were then compared with those of three commercially available tire models. The HSSTM showed good performance in negotiating short-wavelength road perturbations. For the validation on deformable surfaces, driving and cornering maneuvers were conducted at constant normal load and varying slip values. The HSSTM's estimations of longitudinal force, lateral force, and sinkage were compared with experimental data, and the model was shown to provide reasonably accurate results. The deformable tire structure model of the HSSTM offers more accurate contact patch pressure distributions and, consequently, more precise sinkage and force estimations compared to the rigid wheel model when simulated with NWVPM (Nepean Wheeled Vehicle Performance Model) [12].

In 2018, El-Sayegh *et al.* [43] presented an improved tire-soil interaction model using a combination of FEA and SPH simulations. The authors highlighted the importance of accurately modeling the interaction between tires and soil to understand vehicle performance and predict tire wear and soil compaction.

In the same year, El-Sayegh *et al.* [8] presented a study on the calibration of three soil types using the Smoothed Particle Hydrodynamics (SPH) technique **Figure 12**. The study aimed to accurately model and validate SPH terrain materials for tire-terrain interaction research. The paper highlights the importance of soil calibration for the accurate prediction of tire-soil interaction and presents

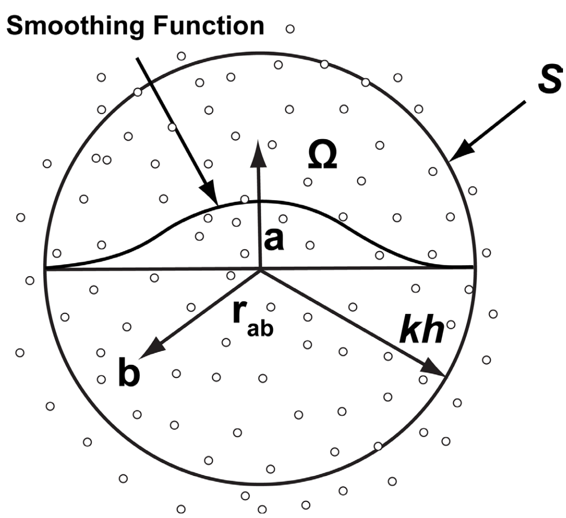

Figure 12. SPH particle with ratio 1.5. (Source: El-Sayegh *et al.* [8]).

two soil validation tests, the pressure-sinkage test and the direct shear-strength test, which were used to predict soil characteristics.

The three soil types calibrated in the study were dry sand, dense sand, and clayey soil, which were significant for off-road vehicles operating in different environments. The cohesion and internal friction angle were calculated and validated against physical terramechanics published parameters.

In 2017, El-Sayegh *et al.* [9] provided a literature survey on the modeling and testing of truck tire-terrain interaction. The authors presented an overview of the various modeling and testing techniques used to study the interaction between truck tires and different types of terrain. The study aimed to provide insight into the behavior of truck tires in various off-road conditions, which was crucial for the development of more efficient and durable tire technology. They discussed the advantages and limitations of various modeling approaches, including analytical, empirical, and numerical methods.

In 2017, Recuero *et al.* [44] conducted a comprehensive study focusing on the assessment of off-road vehicle mobility using physics-based methodologies. Their research emphasized the critical interaction between vehicles, deformable tires, and granular terrains and proposed the adoption of high-fidelity representations and computational tools for predicting dynamic vehicle behavior in diverse scenarios. Unlike traditional semi-empirical approaches, their approach employed physics-based methodologies within a three-dimensional multibody system framework, accounting for tire flexibility and terrain deformation. The study utilized advanced techniques like the absolute nodal coordinate formulation (ANCF) for tire representation and discrete element modeling for soil behavior. To manage the computational complexity, they employed a co-simulation framework based on the open-source multi-physics package Chrono, utilizing MPI and shared-memory techniques for parallelization. Numerical sensitivity studies demonstrated the impact of various parameters on mobility measures, offering a valuable alternative to empirical methods. The authors suggested future research directions, including model validation, improved numerical formulations, and the utilization of parallel computing to enhance efficiency in predicting dynamic vehicle behavior and mobility measures.

5. Non-Pneumatic Spoke Design and Material Analysis

This section discusses the design and analysis of NP tire spokes including focuses on tread materials and design. It reviews the various spoke configurations used in NP tire designs and their impact on tire performance. The review includes studies on spoke stiffness, durability, and weight optimization. It also examines the different materials used in NP tire treads, such as rubber compounds and composites, and discusses their mechanical properties and suitability for different terrains. The review also explores the optimization of tread patterns to enhance traction and grip.

In 2023, Bari *et al.* [45] conducted a study focused on analyzing tire vibrations and their impact on vehicle ride characteristics. The goal was to gain a deeper understanding of how the properties and operation of a tire affect its vibration patterns. They introduced a novel approach representing the tire as an inflated orthotropic toroidal shell with an elliptical cross-section, utilizing Sanders' shell theory to formulate equations. These equations were solved as an eigenvalue problem using Galerkin projection. This analytical model allowed efficient parametric studies, unlike time-consuming finite element (FE) models. To validate their approach, they created a detailed FE model in ABAQUS and conducted experimental modal analysis, confirming alignment with both FE simulations and real-world data. This analytical model provided an accurate approximation of tire behavior, considering its unique shape and material properties. It demonstrated good agreement with FE simulations and experiments, proving its accuracy and usefulness for vehicle ride simulations. The study proposed further research directions, including accounting for tire cross-section variations due to factors like inflation pressure, exploring wave finite element (WFE) approaches, incorporating tire damping properties, studying the effects of static and dynamic loads on tire vibrations, investigating tire rotation's influence on modal characteristics, and exploring the coupling between structural modes and tire cavity resonance (TCR) noise.

In 2022, Fu *et al.* [46] presented a study on a novel NP tire **Figure 13** featuring a flexible spoke structure, aimed at improving upon traditional pneumatic tires. Their research examined into understanding how this innovative tire's temperature behaved under different conditions. They created a 3D model of the tire and used a thermal-mechanical analysis to study deformation, energy loss, and heat distribution. The study aimed to uncover insights into the tire's temperature patterns and potential failure mechanisms due to thermal-mechanical effects. The findings showed that the highest tire temperatures occurred in the middle

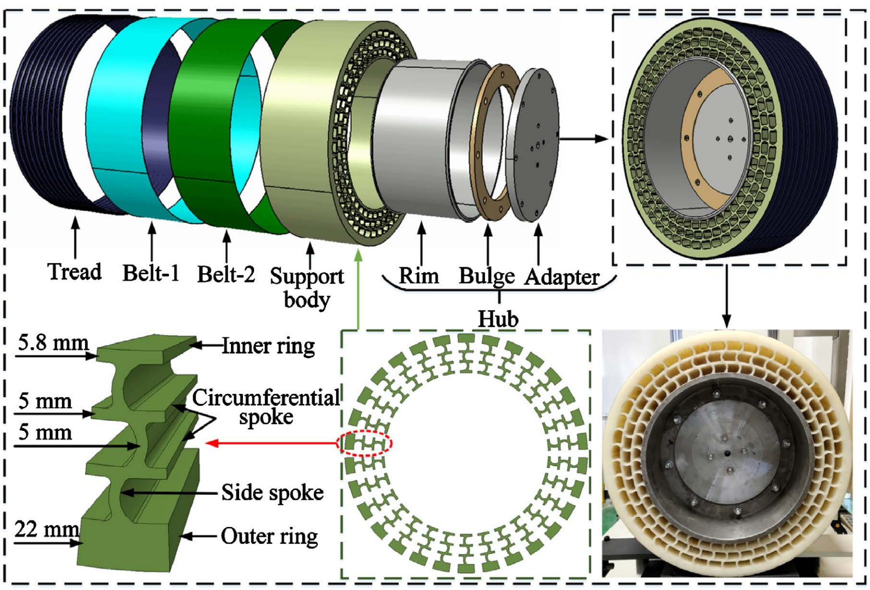

Figure 13. 3D model of the flexible spoke non-pneumatic tire. (Source: Fu *et al.* [46]).

bending part of the flexible spoke, aligning with the primary stress area. The temperature gradually decreased from the center of the spoke towards the tire's edges. They also found that increasing driving speed and vertical load both raised the overall tire temperature, with vertical load having a more significant impact. This implies that reducing the load while increasing speed could mitigate high-temperature failures in NP tires caused by high-speed operation. The research not only provided valuable insights for addressing temperature-related issues in NP tires but also introduced a useful modeling technique for further tire design improvements. It also suggested strategies for optimizing NP tire performance by adjusting driving speed and vertical load. Overall, this study laid the groundwork for enhancing the reliability and efficiency of NP tires.

In 2022, Zheng *et al.* [3] investigated the stiffness and road contact properties of NP tires with varying honeycomb cell angles **Figure 14**, using finite element models and orthogonal array experiments. They found that higher cell angles (e.g., 47.1˚) caused excessive spoke deformations near the contact area due to reduced radial elastic modulus. NP tires had lower longitudinal stiffness and higher lateral stiffness compared to pneumatic tires, and increasing the cell angle decreased lateral stiffness but increased longitudinal stiffness. Design parameters, particularly spokes and tread design, significantly influenced vertical and

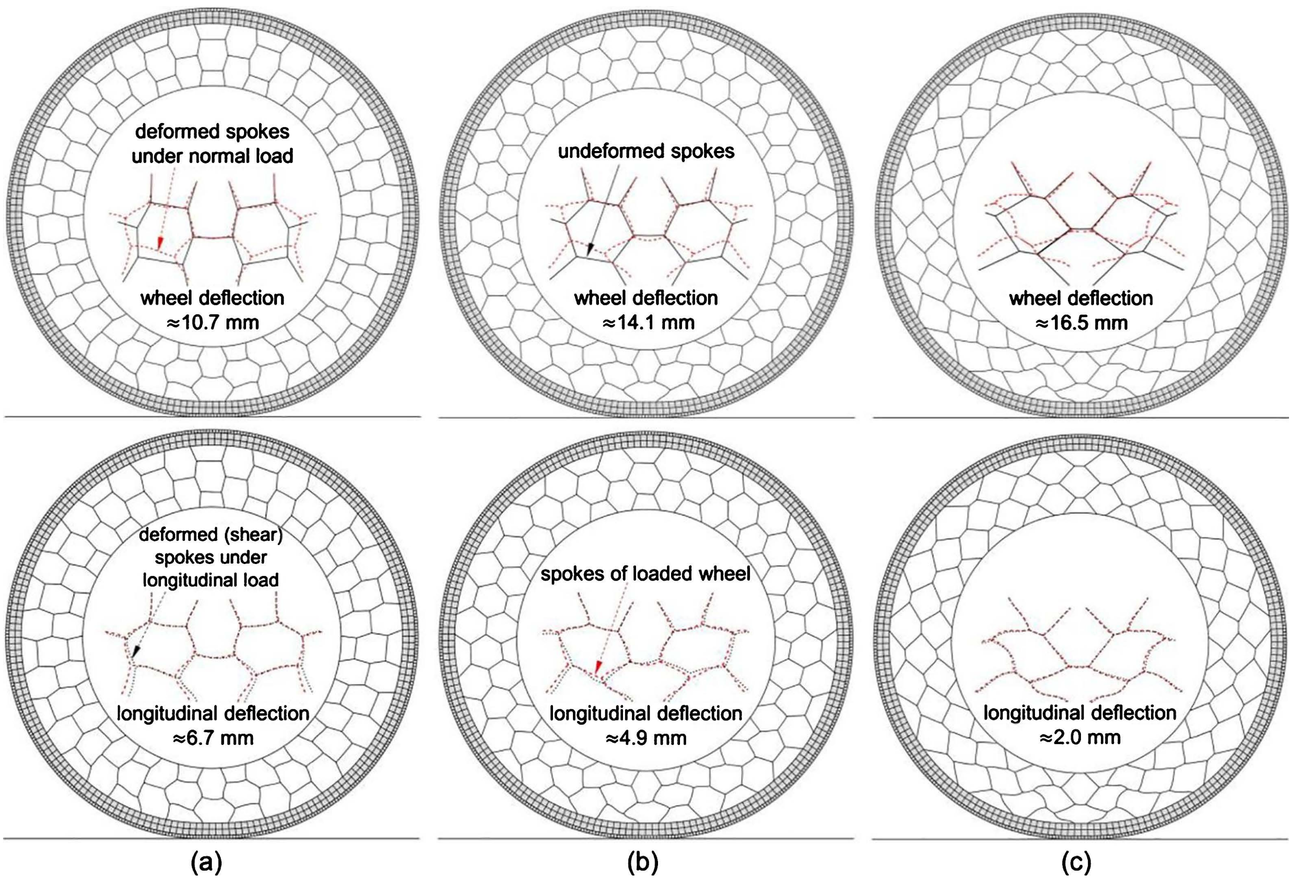

Figure 14. Elastic buckling and shear deformations of spokes of the wheel models with different cell angles: (a) 15.8 deg, (b) 31.5 deg and (c) 47.1 deg (normal load = 3 kN, longitudinal load = 350 N). (Source: Zheng *et al.* [3]).

longitudinal stiffness, while spokes had minimal effects on peak contact pressure. Optimizing NP tire designs could enhance contact area and reduce peak contact pressure. The study also identified nonlinear effects of spoke and tread properties on contact area, peak contact pressure, and lateral stiffness, crucial for NP tire design. In summary, the research underscored the importance of design parameters like spokes and annular beam properties in shaping tire stiffness and road contact behavior, offering insights for NP tire optimization to match pneumatic tire performance while preserving durability and puncture resistance advantages.

In 2022, Rugsaj *et al.* [4] investigated the impact of geometric factors on NP tires. They developed a finite element model featuring various spoke shapes (as shown in **Figure 15**) to optimize stiffness and minimize local stress. Four spoke structure types were chosen based on ease of manufacturing and simplicity. These models were compared to identify the most suitable geometry for construction purposes. The study emphasized that NP tire performance is greatly influenced by their geometric design, specifically the spoke structure. Finite element analysis was employed to create NP tire models with different spoke shapes, while keeping other tire dimensions consistent. The study utilized hyperelastic constitutive equations to model the tire's behavior. Vertical stiffness testing was conducted using skid-steer loaders. Among the four-spoke structures tested (curved single spokes, hexagonal honeycomb spokes, auxetic honeycomb spokes, and polygonal cellular spokes), the study found that the polygonal cellular spoke structure (NP tire type D) with 24 spokes, each 5.4 mm thick, demonstrated the best balance of vertical stiffness and local stress for construction applications. This research laid the foundation for designing more efficient NP tires by exploring various spoke structures, curvature, angles, and thickness distributions to meet specific application requirements.

In 2021, Fu *et al.* [47] conducted a study on mesh flexible spoke NP tires, focusing on the impact of various structural factors on tire fatigue life. They introduced a theoretical approach using the J-integral and the Thomas crack model to predict fatigue life. By analyzing these factors, including side spoke curvature, unit angle, and thickness of side spoke and tread, they found that optimizing

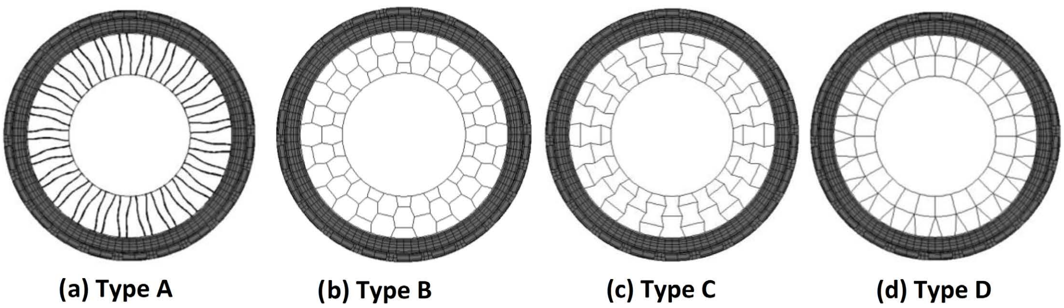

Figure 15. NP tire spoke structures (a) Type A: Curved isolated spokes, (b) Type B: Hexagonal honeycomb spokes, (c) Type C: Auxetic honeycomb spokes, and (d) Type D: Polygonal cellular spoke structure (Interconnected mesh spokes). (Source: Rugsaj *et al.* [4]).

these parameters can enhance tire fatigue performance.

In 2021, Abd-elhafiz *et al.* [48] conducted a study using finite element analysis with ABAQUS software to assess the performance of NP tires on unpaved soil. They examined three-spoke geometries: honeycomb, hexagonal re-entrant (lattice), and spoke pairs **Figure 16**. The study analyzed contact pressure, contact shear stress, vertical stiffness, von Mises stress, and rolling resistance for each geometry. The results showed that spoke geometry significantly affected tire performance. Honeycomb spokes demonstrated the best performance with low von Mises stress and rolling resistance.

Spoke-pair models were better for soft soils, while honeycomb and lattice spoke models suited medium and hard soils. This research provides valuable insights for optimizing NP tire design for off-road applications, suggesting that different terrains may require tailored spoke geometries. Further research should validate these findings and enhance practical NP tire applicability in real-world scenarios.

In 2021, Rugsaj *et al.* [49] conducted a study using both waterjet cutting and 3D printing techniques to create specimens from actual NP tire spokes **Figure 17**. These specimens underwent tensile testing following ASTM D412 and D638 standards. They varied printing conditions, such as printing speed, to assess the impact of strain rate on the mechanical properties of 3D printed spokes. The study compared the mechanical properties of actual NP tire spokes with 100% infill 3D printed specimens. Results indicated that the real tire spokes had higher ultimate stress and breaking strain in the radial direction compared to 3D printed

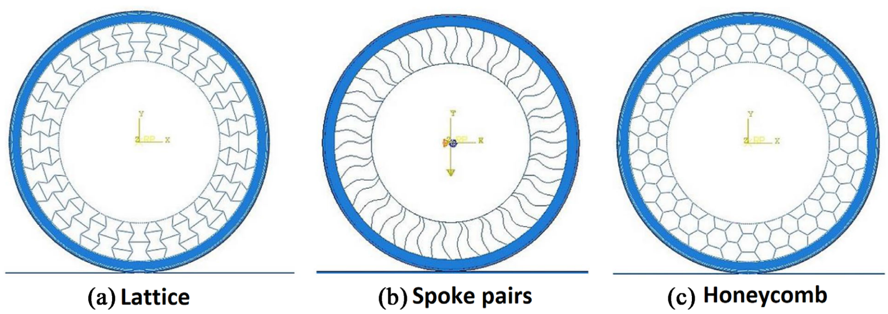

Figure 16. Three NP tire Models. (Source: Abd-elhafiz *et al.* [48]).

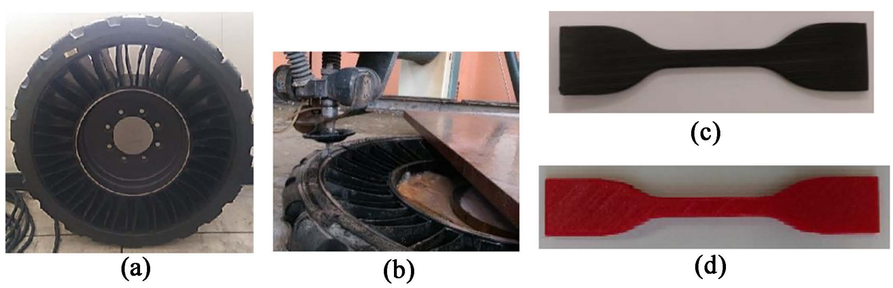

Figure 17. (a) The NP Tire, Tweel 12N16.5 All Terrain, (b) the extraction of spokes using waterjet cutting technique, and (c) a waterjet cut specimen (d) 3D printed specimen. (Source: Rugsaj *et al.* [49]).

ones, suggesting a need for further optimization. However, more research is required to investigate the mechanical properties of 3D printed spokes, particularly under varying printing conditions, to ensure their suitability for NP tires. This study offers valuable insights into the behavior of 3D printed TPU spokes, serving as a foundation for future research to enhance NP tire design using 3D printing.

In 2020, Lu *et al.* [50] studied the auxetic properties of tetrachiral honeycombs, which are materials that expand sideways when stretched lengthwise (opposite to most materials). They focused on the specific tetrachiral chiral honeycombs **Figure 18**, known for their auxetic behavior. The study examined the relationship between geometric dimensions and auxeticity in monoclinic tetrarchical honeycombs, confirming their auxetic behavior. However, they discovered a coupling effect between shearing and stretching that made traditional Poisson's ratio calculations ambiguous. To address this, they introduced the "effective Poisson's ratio", derived from the stiffness matrix, which accurately described auxetic behavior. They also presented an analytical expression for this ratio, establishing a quantitative link between geometry and auxetic properties. This research enhanced our understanding of chiral honeycombs, emphasizing the importance of considering shearing-stretching coupling. The effective Poisson's ratio, validated against simulations, offers practical insights for designing materials with auxetic properties.

In 2020, Suraj *et al.* [51] investigated the inflation of a circular membrane using the Mooney-Rivlin hyper-elastic material model. Circular membrane inflation is a significant problem in mechanics, dependent on material properties and boundary conditions. The authors reduced this problem to three first-order (Ordinary Differential Equations) ODEs and used the Mooney-Rivlin model, suitable for studying rubber-like materials with nonlinear elastic behavior. They explored how changing the material model parameter, influenced pressure and principal stresses concerning the radial coordinate. The findings revealed that higher material model parameter values lead to stiffer membranes during inflation, emphasizing the importance of material model selection and boundary conditions. This research is valuable for engineers working with hyper-elastic materials, providing insights into mechanical behavior and aiding innovative design. It contributes to mechanics and materials science, serving as a foundation

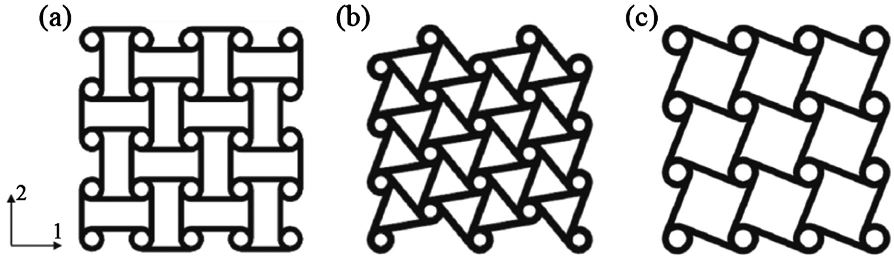

Figure 18. Chiral and antichiral honeycombs: (a) anti-tetrachiral; (b) hexachiral; (c) tetrachiral. (Source: Lu *et al.* [50]).

for further research and practical applications in hyper-elastic material inflation.

In 2020, Aldeen *et al.* [6] focused on exploring the unique mechanical properties of hyperelastic materials and accurately modeling them for engineering applications. They emphasized the necessity of establishing a mathematical model, particularly the two-parameter Mooney-Rivlin model, to describe the mechanical behavior of hyperelastic materials. The study outlined the process of determining material constants by fitting experimental data or conducting specialized tests. The Mooney-Rivlin model, known for its simplicity and accuracy in describing incompressible hyperelastic materials, was employed. The authors used Matlab to simulate various tension tests and compared the results to Abaqus experimental data. The Matlab simulations demonstrated a close agreement with the experimental data, with lower absolute errors, highlighting the importance of accurate mathematical models for reliable finite element simulations. The study's approach can be extended to other polynomial constitutive models, ultimately enhancing our understanding of hyperelastic materials and improving the accuracy of engineering simulations.

In 2020, Zhang *et al.* [52] conducted an extensive study on the dynamic tensile behavior of auxetic structures, particularly re-entrant honeycombs **Figure 19**. Their research encompassed both quasi-static and dynamic tensile tests on these honeycombs, which were 3D-printed $AlSi_{12}$ powder through selective laser melting (SLM).

The primary objective of the study was to comprehensively understand how auxetic materials deform and their corresponding force-displacement curves under dynamic loading conditions. The authors reported a strong agreement between numerical simulations and experimental results, achieved through finite element simulations. They identified three deformation modes, with a special focus on the Localized deformation mode, characterized by a tensile shock wave. An analytical equation for dynamic force was derived and aligned well with the

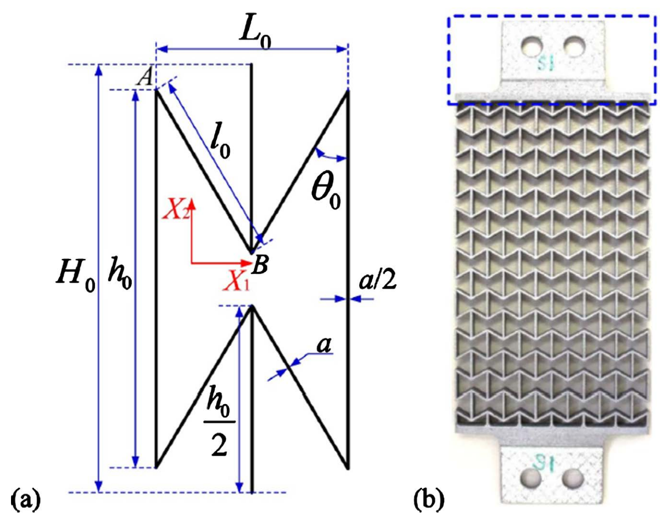

Figure 19. (a) Sketch of a repeatable re-entrant unit cell. (b) A sample. (Source: Zhang *et al.* [52]).

finite element simulation results. The study also investigated the impact of loading velocity and cell geometries on the material's behavior. Ultimately, the research shed light on the mechanical properties of auxetic materials under varying loading conditions, providing valuable insights for potential engineering applications.

In 2020, Baran *et al.* [7] introduced a novel method to enhance the in-plane rigidity of the traditional re-entrant honeycomb cell by incorporating inclined walls. The primary objective was to increase the cell's stiffness without significantly altering its auxetic properties, especially negative Poisson's ratios along the main axes. The study also explored the in-plane elastic characteristics of the modified cell by adjusting the geometric, sectional, and material parameters of the new walls. The researchers developed analytical expressions to determine the mechanical properties of the enhanced cell, validating them through finite element modeling and experiments from existing literature. Both analytical and modeling results demonstrated a notable improvement in the rigidity of the proposed cell. This research established a benchmark for comparing the new cell with the traditional version, allowing for tailored adjustments of in-plane elasticity and negative Poisson's ratios to suit various applications. In summary, this study effectively increased the stiffness of the classical re-entrant core cell by introducing inclined walls, providing analytical tools for predicting the mechanical properties of both the modified and traditional cells. It emphasized the potential for lightweight yet rigid structures with minor structural adjustments, offering versatility in tailoring mechanical properties. This work significantly advanced the design and application of honeycomb cells in industries requiring lightweight and rigid structures.

In 2019, Szurgott *et al.* [53] examined hyper-elastic materials, commonly used in engineering for their ability to withstand significant deformations and return to their original shape when external forces are removed. Accurate modeling of such materials is vital for successful engineering designs. The study aimed to select an appropriate material model for a specific hyper-elastic material, polyurethane rail pad, and considered Mooney-Rivlin models in MSC.Marc/Mentat. Selection criteria included accuracy, complexity, verification in different states, and computational efficiency. Primary selection factors were accuracy in approximating uniaxial tension/compression behavior and model simplicity. Verification in diverse states and finite element analysis convergence was also important. The study concluded that Mooney's model with two constants, C_{10} and C_{01}, was best for the polyurethane rail pad due to accurate approximation, simplicity, and computational stability. These findings apply specifically to this material and should not be generalized. However, they offer insights for similar materials, emphasizing the importance of considering multiple criteria for informed model selection. Using the absolute error criterion for determining C_{ij} constants is a reasonable approach. Further research is encouraged to explore material models for different hyper-elastic materials and verify their applicability under various deformation modes to enhance engineering analysis and design processes.

In 2019, He *et al.* [54] conducted a study on hierarchical honeycombs, exploring their self-similar properties and their impact on mechanical behavior. They introduced a hierarchical structure to conventional honeycombs, modifying vertex shapes. The study identified three deformation modes during impact: quasi-static, transition, and dynamic, each associated with distinct deformation patterns such as "X"-shaped, double "V"-shaped, and "I"-shaped bands. Impact velocity and structural parameters significantly influenced energy absorption. The authors established a critical velocity classification map, analyzed plateau stress, and found that hierarchical honeycombs with specific structural parameters performed best. Densification strain depended on both structural parameters and impact velocity. Empirical equations for dynamic densification strain were derived. In summary, the study emphasized the importance of hierarchical properties for improving energy absorption in honeycombs under dynamic loading, offering insights for engineering applications.

In 2018, Pewekar *et al.* [55] conducted a comprehensive study on NP tires featuring a hexagonal lattice structure. Utilizing Finite Element Analysis with the ANSYS Mechanical APDL solver, they investigated the tire's response to various loading conditions, including compression, lateral shear, lateral torsion, and circumferential torsion. This research was crucial for ensuring the tire's strength and suitability for automotive applications. The study revealed that the hexagonal lattice structure, combined with hyperelastic materials, showed promise in withstanding diverse road stresses. It also indicated the tire's resilience within its elastic limit, essential for long-term performance. While the tire exhibited high torsional stiffness, it demonstrated lower lateral stiffness, prompting further research for improvement.

In 2018, Wang *et al.* [56] conducted a study focusing on optimizing natural frequency and reducing weight in cellular structures through 3D printing. Their approach employed homogenization-based topology optimization, involving three key steps: homogenization, optimization, and construction. Homogenization entailed using Finite Element Analysis to derive scaling laws for elastic properties in relation to relative density. Optimization utilized these scaling laws to maximize fundamental frequency while constraining total volume. In the construction phase, continuous parameters were converted into explicit cellular structures. Validation was done on a cantilevered plate with a honeycomb structure, supported by detailed finite element analysis and experimental testing. This study showcased the potential of topology optimization for Additive Manufacturing parts with variable-density cellular structures, resulting in improved natural frequency and weight reduction, ultimately enhancing mechanical properties in lightweight components.

In 2017, Abdelsalam *et al.* [57] investigated elastomers, a unique class of polymers widely used in structural and engineering applications due to their elasticity and flexibility. They focused on hyperelasticity, a non-linear stress-strain behavior common in elastomers, and aimed to find the best model to predict the behavior of elastomer nanocomposites, specifically styrene-butadiene rubber (SBR) with varying graphene platelet (GnP) content. Using numerical analysis, they compared different material models to experimental SBR/GnP data. The third order deformation model showed the most accurate fit, with a maximum relative error of 2.7%. While promising, further research is needed, particularly using biaxial testing for improved predictions, especially for GnP volume fractions over 10.5%. This study underscores the importance of precise material modeling in understanding elastomer nanocomposite behavior and highlights the effectiveness of the third order deformation model in predicting hyperelastic responses in SBR/GnP samples, benefiting elastomer-based materials in diverse applications.

In 2017, Huang *et al.* [58] introduced a unique honeycomb design with a negative Poisson's ratio, which means it expands sideways when stretched. This honeycomb structure (see **Figure 20**) consisted of two distinct components: re-entrant hexagonal segments and thin plate sections, each contributing differently to mechanical properties. The re-entrant hexagons provided in-plane negative Poisson's ratio, in-plane compliance, and out-of-plane compressive strength, while the thin plate part enhanced out-of-plane flexibility.

The study primarily focused on analyzing the in-plane mechanical properties, developing theoretical models and conducting numerical simulations for uniaxial tensile modulus, shear modulus, and Poisson's ratios. They also explored the impact of geometric parameters on in-plane behavior through parametric analysis. The research revealed that this honeycomb design had exceptional mechanical properties for large out-of-plane deformations and morphing structures, allowing separate design considerations for in-plane and out-of-plane performance.

Theoretical and numerical models matched well, indicating potential applications in morphing structures. Varying unit cell parameters significantly influenced in-plane mechanics. In conclusion, this innovative auxetic honeycomb structure, comprising re-entrant hexagons and thin plate parts, holds promise for morphing structures due to its unique mechanical properties, offering insights for engineering applications requiring unconventional mechanical behavior.

6. Summary

Summary of the literature review, emphasizing the gaps and limitations in the existing research and offers a comprehensive summary of a literature review on

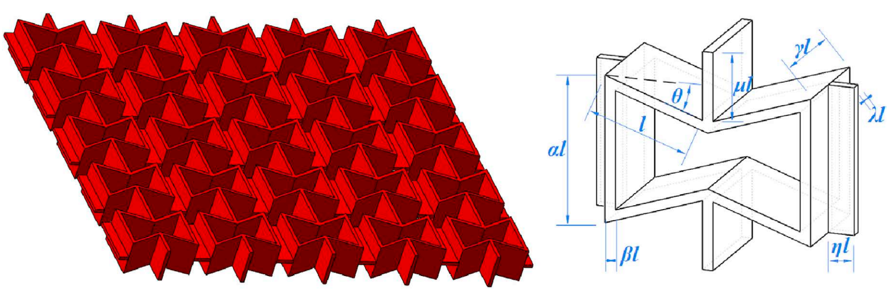

Figure 20. Geometry of the novel auxetic honeycomb structures. (Source: Huang *et al.* [58]).

various aspects of tire performance, modeling, and analysis. Underscoring the need for further investigation and optimization of NP tire models. First, the intention in the literature was identifying gaps and limitations in existing research. These gaps are essential touchpoints for future investigations that can further advance NP tire technology. Findings emphasize the need for in-depth inquiry and optimization of NP tire models to address these gaps and create more robust solutions.

Within the scope of study, NP tire technology discretized into distinct components, each contributing to a holistic understanding of tire performance: Tire Performance Parameters: This section emphasizes the fundamental parameters governing tire performance, including grip, rolling resistance, and wear. Understanding and optimizing these parameters are essential for the advancement of NP tire technology.

NP Tire Modeling and Validation: Exploring NP tires technology, this part examines NP tire models using numerical techniques like finite element analysis and computational fluid dynamics. It discusses their validation against real-world testing data and potential benefits such as reduced puncture risk.

Tire-Soil Interaction: Investigating the interaction between tires and soil, this section studies soil compaction, sinkage, and traction using experimental methods like indoor soil bins and field tests. It identifies the need for accurate tire-soil interaction models.

NP Spoke Design and Material Analysis: Focusing on NP tire spoke structures, this part explored the spokes geometries, materials, and manufacturing techniques. It points out gaps in understanding vibration, thermal-mechanical coupling, and other characteristics of NP tires with flexible spoke structures.

As this research unfolds, its impact extends far beyond academic confines. Transportation, agriculture, construction, and space exploration—each of these sectors stands to benefit from NP tire technology that is meticulously refined through research. The work conducted could lead to tires that exhibit superior performance, durability, and environmental sustainability. It could redefine how tire engineering is perceived, marking a shift towards innovation-driven solutions that conquer longstanding challenges.

Further research can serve as a springboard for transformative advancements in tire engineering. Deeper into the territories identified in this literature review, moving towards the opportunity to unlock valuable insights involves the analysis of spokes sensitivity and tread wear analysis can contribute to the evolution of improved NP tire technology. In future studies, analyzing the sensitivity of spokes within NP tires could shed light on a critical aspect that influences overall tire performance. Furthermore, focusing on tread materials and wear analysis, Smart Tire Technologies-Investigate how sensors can monitor tire performance in real-time, including factors like tire pressure, temperature, and wear, Conduct a comprehensive life cycle assessment of NP tires to understand their environmental impact, Develop standardized testing procedures and safety guidelines for NP tires, Research the impact of NP tires on the overall energy efficiency of vehicles and their contribution to sustainable mobility, Develop advanced optimization algorithms for designing NP tire structures, Investigate sustainable approaches for managing waste NP tires, Investigate methods for reducing noise and vibrations produced by NP tires, Exploring adaptive NP tires that can adjust their characteristics (e.g., stiffness, tread pattern) in response to changing road or environmental conditions, Investigate how NP tires can be optimized for autonomous vehicles, Study the long-term durability and aging characteristics of NP tires, offers a pathway to address a fundamental challenge in tire engineering.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Abbreviations and Acronyms

FE—Finite Element, NP—Non-Pneumatic, Advanced Manufacturing (AM), FEM—Finite Element Method, FS-NP tire (Flexible spoke non-pneumatic tire), Fused Filament Fabrication (FFF).