Sigma J Eng Nat Sci, Vol. 44, No. 2, pp. 843–855, April, 2026

Sigma Journal of Engineering and Natural Sciences
Web page info: https://sigma.yildiz.edu.tr
DOI: 10.14744/sigma.2026.2015

Research Article

Finite element modeling and nonlinear analysis of tire deformation using hyperelastic material models

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ARTICLE INFO

Article history
Received: 08 December 2024
Revised: 15 January 2025
Accepted: 03 March

Keywords:
Abaqus; Finite Element Modelling; Hyper Elastic Material; Mooney-Rivlin Model; Tire Deformation Simulation

ABSTRACT

Tires are critical components for automobile and aircraft applications from vehicle dynamics, safety and overall performance perspective. The work in this paper discusses finite lement analysis of tire deformation subjected to 3.5 bar pressure using ABAQUS tool. The hyperelastic material models viz Neo-Hookean and Mooney-Rivlin are used to capture the nonlinear behavior of tire. The simulation focuses on investigation of key tire parameters like tread width, tread pattern, and sidewall thickness in order to assess their impact on stress distribution and deformation. Stress concentrations (320 MPa) were observed in high-stress regions, such as the bead wire, belt edges, and sidewalls, which are imporatnt for maintaining structural integrity. Belt reinforcement were modelled using rebar layer function. This enhanced tread stability by distributing stress and reducing deformation in high stress zones. The results obtained from finite element simulation showed that the Mooney-Rivlin model gives more accuracy in predicting stress-strain behavior as compared to the Neo-Hookean model. Further contact pressure was observed varying across the tread region providing insights into tire-road interactions. The precise material modeling and reinforcement strategies found to be imporatnt for improving tire durability, safety, and performance.

Cite this article as: Mache A, Kothekar S, Salve A, Kulkarni N. Finite element modeling and nonlinear analysis of tire deformation using hyperelastic material models. Sigma J Eng Nat Sci 2026;44(2):843–855.

INTRODUCTION

Tires play a very important role in the automotive field as tires are the only components of a vehicle that are in direct contact with the road surface. Due to this, tires affects the vehicle dynamics, overall safety, and even fuel efficiency. The tire construction and their material properties decides their perfomance as these influnces important characteristics such as braking performance, traction, and also the vehicle handling. In recent developments, sustainability has become an important consideration in the design of tires. Researchers are focusing on developing effective and durable tire materials with reduced environmental impact caused by its production and disposal. Earlier, tyre design iterations and further

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This paper was recommended for publication in revised form by Editor-in Chief Ahmet Selim Dalkilic

Published by Yıldız Technical University Press, İstanbul, Turkey

improvements were validated mostly by doing prototype testing. However, physical testing for every alternative design is not only expensive but also time consuming. This does not fully align with the sustainability objective. As a result, numerical simulations based on the finite element method (FEM), have become practical approach for analyzing the tire behavior before carrying out any experimental testing. This approach is an efficient way to simulate and analyze complex mechanical behaviors under various loading conditions. This saves time and cost for prototype development and experimental testing.

Finite element modelling of the tire is carried out in different stages. Initially, in preprocessing stage, the tire geometry is discretised into finite elements called as meshing. Then material properties are assigned which are obtained from experimental testing, laboratory test result data or standard industry catalogues. Proper contact algorithm definitions are provided to represent the interaction between the tire and the road surface. Finite element model is then solved in FEA solver here ABAQUS. Once the analysis is completed, the results are interpreted during the post-processing stage. There parameters such as stresses, strains, deformations, and suitable failure criteria are studied to understand tire performance under different loading and operating conditions. One of the major difficulties in tire analysis is precisely modelling the tyre and road surface interaction. This interaction is basically three-dimensional in nature and involves force distributions at the contact area which is complex in nature. In real conditions, these forces continuously vary with load, road profile and also with inflation pressure. This makes the simulation more challenging. Further complexity arises due to the construction of the tire which has cross-section composite in nature. This is because tire consists of multiple components such as tread, sidewalls, bead cores, belts, and plies. Further they are made of different materials and serving specific structural functions. The overall mechanical behaviour of the tire depends on how these layers interact with each other, and therefore their coupling effects must be modelled and captured in the FE model. In addition to structural complexity, tires are subjected to various loading conditions which includes internal inflation pressure, vertical load due to vehicle weight, impact loads from curbs or potholes, and thermal effects generated by friction during rolling. All these factors together makes tyre modelling a highly detailed and computationally intensive task.

In commercial and non-commercial vehicle, tire mechanics is a very critical area to understand and requires special material models to simulate the deformation which occur in rubber components present in tire. To study this, hyperelastic material models have gaining the importance in simulation work. These material models allow researchers to report the nonlinear stress-strain behaviour of such materials. The previous two decades, the finite element method has become a popular tool for evaluating the performance of tire under different operating conditions. Korunovic et al. [1] conducted simulation work and reported various challenges under static loads on pneumatic tires and further presents a well-structured approach for modelling of tire using composite materials. Furthermore, study also examined how pressure and applied load affect the performance of tires and identified the critical stresses in bead as well as sidewall areas and validate with experimental observations. Top of the this Helnwein et al. [2], developed 3D model for tires with cord reinforcement. In their study, rebar elements were effectively utilized to represent the layers of cords in the structure. A significant advancement for later tyre models, their work used the Mooney material law to obtain accuracy while lowering computing costs.

In addition, Anoop et al. [3] has refined these techniques and compared the various tire balancing conditions by employing finite element analysis to study the effect on tire performance giving more importance on material nonlinearity in tread and sidewall areas. In another study, Nazari et al. [4] reported the direct relation between tread geometry, skid resistance with rubber properties. Similarly, Zhang et al. [5] carried out a study on heavy duty tire application and developed a Rivlin model for radial truck tire under heavy loading condition and accurately predicted deformation patterns along with stress distributions. Dring simulation work, selection of correct hyperelastic model is crucial. Models like Mooney-Rivlin, Neo-Hookean and Ogden are commonly utilized, and their effectiveness varies with end application. Kim et al. [6] confirmed that Mooney-Rivlin and Ogden models gives better results against large deformations while Neo-Hookean model may work for small-strain analyses. A similar kind of trend also reported by Jebur et al. [7] also reported a similar kind of trend in their research work carried out on tires made locally. Apart from rubber matrix, reinforcement layers in modelling are also important. In another study, using multiscale modelling of cord-rubber composites in intelligent tires, Behroozinia et al. [8] in their study demonstrated that reinforcing the layers reduces deformation and maximum stress. Behroozi et al. [9], carried out advanced finite element simulations to study failure of aeroplane tyre when it is inflated. Author demostrated the importance of accurate modelling of tyres to capture realistic behaviour in flated condition. Hernandez et al. [10] studied the effect of pavement stiffness on vertical stress patterns and rolling resistance. The results indicated that fuel efficiency is improved by optimizing tire–pavement interactions. Nowadays, researchers have explored non-pneumatic tires (NPTs), the reason behind this is to offer better safety and lower maintenance costs. Rugsaj and Suvanjumrat [11,12] studied and optimize the spoke design for NPT which reduces the stress concentrations and enhances the load carrying capacity. Similarly, in another study carried out by Kiran et al. [13] optimized tread patterns in non-pneumatic tires, which minimize energy losses. Further research was also carried out on recycled tire materials, such as tire-derived materials.

Montella et al. [14] tested tire-derived materials under compressive and shear loads. Author found that these materials can be useful for reducing vibrations. Hence waste rubber can be reused in construction. Kabe et al. [15] explored the tire corner area and suggested implicit methods for efficient steady-state simulation with detailed transient modelling. Reida et al. [16] prepared and studied a detailed LS-DYNA model for addressing complex impacts such as curb strikes and rock traversal. Sheshenin [17] studied behavior of pneumatic tires during rolling. He suggested using both shell theory and 3D elasticity models together to get more accurate results. The work focuses on complex properties of rubber, like anisotropy and viscoelastic behavior making tire analysis more realistic. Korunovic et al. [18] suggested Marlow model for defining the non-linear behaviour of cord reinforced composites. Additional research work has focused on the dynamic behaviour of the hybrid composite in terms of minimisation of vibration and analysing thermal effects in materials; all these contribute to improving the accuracy of tyre models [19-23] .

Overall, use of finite element modelling improves the tire behaviour prediction under various conditions. Studies underline the tire durability and hyperelastic tread performance and further validation with experimental results [24,25] Furthermore, both experimental and numerical methods improve the material modeling accuracy, making FEA-based tire models more reliable in terms of structural integrity and performance evaluation [26,27].

From above reviewed literature it is evident that, study of advanced simulation techniques like finite element analysis are important to accurately predict the tire performance in actual service condition. However, challenges remain in integrating dynamic loading conditions, thermal effects, and road-tire interactions into these models, suggesting areas for future research. The outcome of this research paper will help new researchers in this field, automotive tyre manufacturing companies and also belt manufacturing companies for virtual testing purposes since experimental testing is challenging and requires special equipment and instrumentation.

MATERIAL AND METHODS

Tire Nomenclature and Structural Components

Tire geometry and structural elements are imporatnt for developing accurate finite element model and carrying out nonlinear analysis using hyper-elastic materials. This section describes imporatnt aspects of tire design, tire construction and operating conditions. Tire size is generally printed on tire sidewalls as shown in Figure 1 [3].

The tire construction code gives information about the internal structure of the tyre. For example, letter “R” is for radial construction and “B” for bias-ply construction, which appear after the aspect ratio in the tyre specification. These letters indicate how the reinforcement cords are arranged inside the tire. In radial ply tires, the cords are placed radially from the centre to the outer edge, running perpendicular to the direction of travel, as shown in Figure 2. This type of construction is commonly preferred in passenger vehicles since it gives better traction during braking and acceleration. This in turn reduces rolling resistance resulting improved fuel efficiency, and ride comfort. Because of these advantages, radial ply tyres are widely preferred in modern automotive applications [28].

Figure 1. Standardized annotation of tire size.

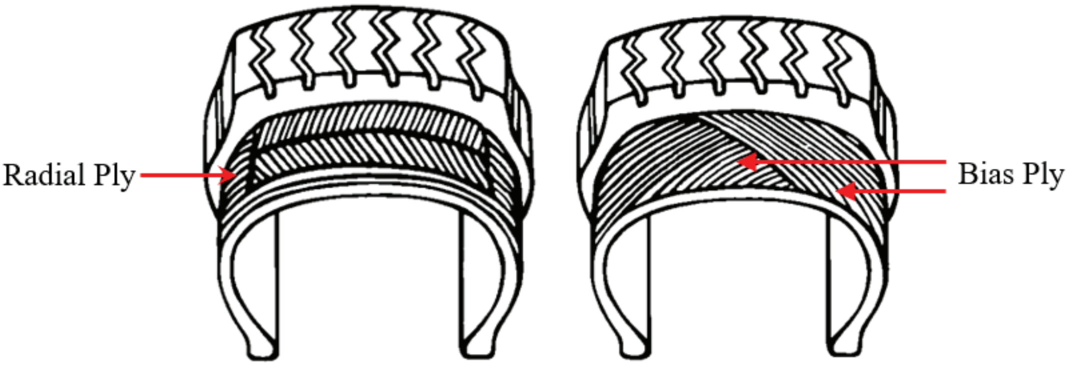


Figure 2. Radial tire configuration with core structural components.

In contrast, in bias-ply tires, cords are arranged diagonally in a crisscross pattern. This makes an angle between successive layers. This construction provides them distinct characteristics. Due to their higher rigidity and strength, bias-ply tires are well suited for heavy-duty and off-road applications. However, their comparatively stiff structure results in a harsher ride, and the crisscross cord arrangement may generate more heat, especially during prolonged high-speed or high-load operation.

Tire size information, typically marked on the sidewall, follows a standardized annotation format. The tire type prefix is an optional letter, such as “P” for passenger cars or “LT” for light trucks. Following this, the tire width in millimeters represents the width from sidewall to sidewall when mounted. The next figure, the aspect ratio, indicates the sidewall height as a percentage of the tire width. The wheel diameter, expressed in inches, specifies the intended wheel size, while an optional speed rating denotes the tire’s maximum safe speed. Another Here it is considered a radial tire constituent with three sections.

- **Carcass:** The carcass represents the internal structure of tire. The carcass gives strength and flexibility to tire.
- **Belt:** Belt layer reinforces the the thread of tire. Belt is for improving stability and durability.
- **Bead wire:** Bead wire holds the tire firmly onto the wheel rim and ensure a secure fit. Figure 3 shows radial tire model and its major components.

Tire Materials

Tire materials are made from different components. ASTM D3492 sets standards for the rubber compounds used in tire manufacturing to ensure consistent quality. SAE J2047 provides guidelines for tire performance and durability. Table 1 shows the constituents of tires with percentage and examples.

Tire Manufacturing Process

Tire manufacturing is a multi-stage process that demands precision and expertise. It consist of follwing stages [30].

- Tire components are first assembled on a drum to form a green tire.
- The green tire is then placed inside a mould.
- A bladder inside the mould is inflated to give the tire its final shape.

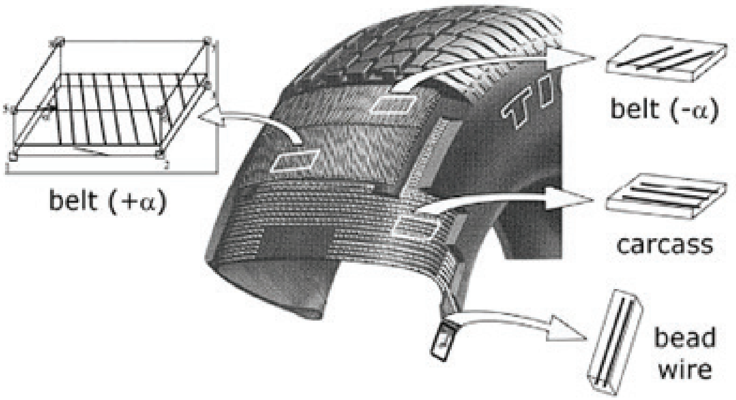


Figure 3. Radial tire and its major components [From Korunović et al. [1], with permission from Serbian Society for Computational Mechanics].

Table 1. Major constituents, ingredients, functions, and environmental aspects of rubber in vehicle tires [From Peterson [29] , with permission from ASME]

Constituent	Composition	Ingredients
Rubber polymer	40–60%	Natural rubber Isoprene rubber Styrene–butadiene rubber, Butadiene rubber, Chlornobyl rubber
Reinforcement aids	25–35%	Mainly carbon black
Softeners	15– 20%	Usually, HA oil but can be replaced with other oils
Activators	2–5%	Mainly Sulphur
Antidegradants	1–2%	Chemical compounds, e.g.: MBT, CBS, TBBS, MBS, HMT, MBTS, DCBS and TMTDb
Vulcanizers	1–2%	Zinc oxide+ fatty acid, or alternatively zinc stearate
Accelerators	0.5–2%	Antioxidants and antiozonants, e.g., TMQ, IPPD, 6PPD and 77PDc

- Heat is applied during curing to make the tire strong and durable.
- Finally, the mould is removed, and the finished tire is ready for use.

Tire Modelling

Rubber material reinforced in construction of tires is characterised by the phenomenon that it deforms under load application and regain its original shape and size when load is removed. This typical elastic behaviour of rubber makes it suitable choice for tire.

This typically follows Hooks law where force and deformation are proportional. In tire modelling, beyond elastic limits, model is not suitable to predict the rubber behaviour.

Elastic modulus is the measure of stiffness. Sidewalls use softer compounds to flex and absorb road bumps. Tread uses stiffer compounds to hold shape under cornering and braking forces. In tire models, this stiffness value directly controls contact patch size, load spread, and grip output.

Elastic limit

Elastic materials in tires flex within the elastic region only up to a defined elastic limit. Beyond elastic region, releasing the load does not restore the material to its original geometry, as the compound has entered the plastic region and the deformation becomes irreversible. The behavior of elastic materials such as mild steel and aluminum is shown below in Figure 4.

Elastic energy storage

When elastic material is subjected to deformation, it stores the energy. This energy is released when material returns to original shape. This is typical application used in springs and rubber band. Unlike this rubber is a hyper elastic material which certainly does not follow Hooke's law. Rubber is often described as a hyper elastic material due to its pronounced nonlinearity in response to deformation [31]. Behaviour of stress-strain graph for hyperelastic materials like rubber is as shown in the below Figure 5.

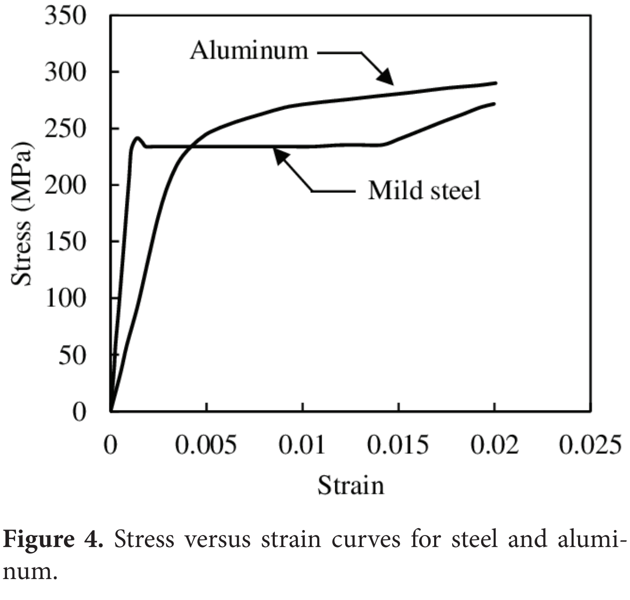


Figure 4. Stress versus strain curves for steel and aluminum.

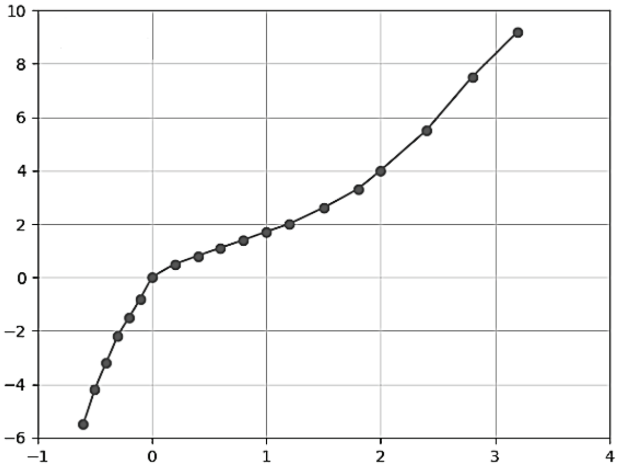


Figure 5. The stress-strain curve of the rubber material.

This behavior can certainly be seen in dynamic rolling of tires. While vehicle is stationary on ground, the tire contact patch is at centerline assuming side point of view. However, the front portion of the tire contacts the ground when the car drives, but the rear tire does not leave the ground as quickly as the front portion of tire encounters ground. This shifts the dynamic contact rearwards. Further this phenomenon causes pneumatic trail, and it has a major role in dynamic handling of vehicles.

1. Strain-Energy Function: Hyper elasticity in rubber is characterized by a strain-energy function, which quantifies the energy stored in the material as it deforms. The neo-Hookean model, for example, expresses the strain-energy function as a function of the deformation gradient.
2. Large Deformations: Rubber exhibits substantial deformations while remaining highly elastic. It can stretch many times its original length, and this behaviour is not described by linear elasticity theory.
3. Nonlinear Stress-Strain Behaviour: In rubber, the stress-strain relationship is nonlinear.
4. Incompressibility: Rubber materials are typically nearly incompressible. Rubber material has Poissons ratio near to 0.5 and they resist changes in volume during deformation.

Material Models for Tire Analysis

Hyperelastic material models viz. Neo-Hookean and Mooney-Rivlin models have been discussed in this section. These are widely used in tire modeling becasuse of their ability to represent the stress-strain behavior like of that rubber materials.

Neo-Hookean model

The A Neo-Hookean model is a hyperelastic material model that can be used for predicting the stress-strain behavior of materials, and the model is like Hooke's law but for hyper elastic materials. A Neo Hookean model is one of the simple models and the strain energy density function for an incompressible Neo-Hookean material is shown as follows [6]:

$$W = C_1(\overline{I_1} - 3) \tag{1}$$

Where, C_1 is a material constant, and $\overline{I_1}$ is the first invariant of the left Cauchy-Green deformation tensor C. It is a tensor that describes how material elements within a deformable body change their relative distances and angles due to deformation.

The left Cauchy-Green deformation tensor C is defined as

$$C = F^T.F \tag{2}$$

Where F is the deformation gradient tensor, and F^T is its transpose. The deformation gradient tensor captures the local deformation of material points within the body, and $F^T.F$ describe strain energy without considering particle displacements directly. This approach is based on the thermodynamic behavior of cross-linked polymers. Neo-Hookean model effectively predicts behavior at low-strain. At high strains, it fails to provide accurate predictions because there is a rapid increase in the elastic modulus as covalent bonds approach their extension limits. This limitation makes it less accurate for high-stress applications in tires.

Mooney-Rivlin model

It is a progressed version of neo Hookean model, where strain energy is function of two invariants of left Cauchy-Green deformation tensor. The strain energy density function W for the Mooney-Rivlin model is expressed as [6]:

$$W = C_1(\bar{I}_1 - 3) + C_2(\bar{I}_2 - 3) \tag{3}$$

Where C_1 and C_1 are material constants determined empirically, and $\bar{I}_1$ and $\bar{I}_2$ represent the first and second invariants of the deviatoric component of C respectively. The inclusion of a second invariant $\bar{I}_2$ allows the model to better capture the material's response to multi-axial loading and large deformations, which are critical in tire performance under various operational stresses.

$$G = 2(C_1 + C_2) \tag{4}$$

This relationship explores need of quasi-static temperature dependency adjustments in the Mooney-Rivlin model to account for shear modulus variations as a function of temperature. The Mooney-Rivlin model is widely preferred in simulations of rubber-like materials because precise stress predictions across a range of strain levels and temperatures are crucial in the simulations of applications like tires.

These models provide the mathematical basis for precisely modeling tire materials in finite element analysis, enabling the accurate prediction of tire behavior under real-world conditions. These models possess this capability as they incorporate deformation invariants and strain energy density functions.

In ABAQUS, the parameters "C10," "C01," and "D1" are coefficients used for defining hyperelastic materials. Their roles are varying depending on the selection of specific model. Each parameter contributes in characterizing the material responses towards shear, volumetric, and compressibility effects. This is essential for accurate modeling of rubber-like materials. The breakdown of each term is given here.

- C10: C10 is a coefficient of material used in hyperelastic material models. The response of the material to shear deformation is represented by C10 in hyperelastic modeling. This coefficient meaning varies as per the hyperelastic model selected in ABAQUS.
- C01: C01 is also material coefficient used in some hyperelastic models. It is related to volumetric or dilatational deformation behavior of the material. Similar to C10, the use and exact meaning depend on the selection of specific hyperelastic model.
- D1: D1 is a parameter available under different hyperelastic material models in ABAQUS. It is associated with different material behavior parameters, such as the starting modulus or a scaling factor. Although the precise interpretation of D1 may differ based on the particular material model selected.

Values of the material coefficients required for tire modelling are given in Table 2.

Geometry Modeling and Simulation Setup

Tires are made by stacking different layers in a circular pattern Therefore, the finite element (FE) model of a tire can be developed using a 2D sectional model, which is then axially swept with the required modifications to represent the full geometry. This approach reduces computational time significantly without requiring a full 3D model. Figure 6 illustrates the axisymmetric model developed in the simulation software.

Table 2. Material property used for modelling materials [From Nazari et al. [4], with permission from ASME]

Element	C10 (MPa)	D1 (MPa)
Carcass	0.446	0.045
Sidewall	0.318	0.063
Rim strip	0.930	0.021
Belt	1.022	0.019
Tread	0.685	0.029
Apex	3.512	0.006

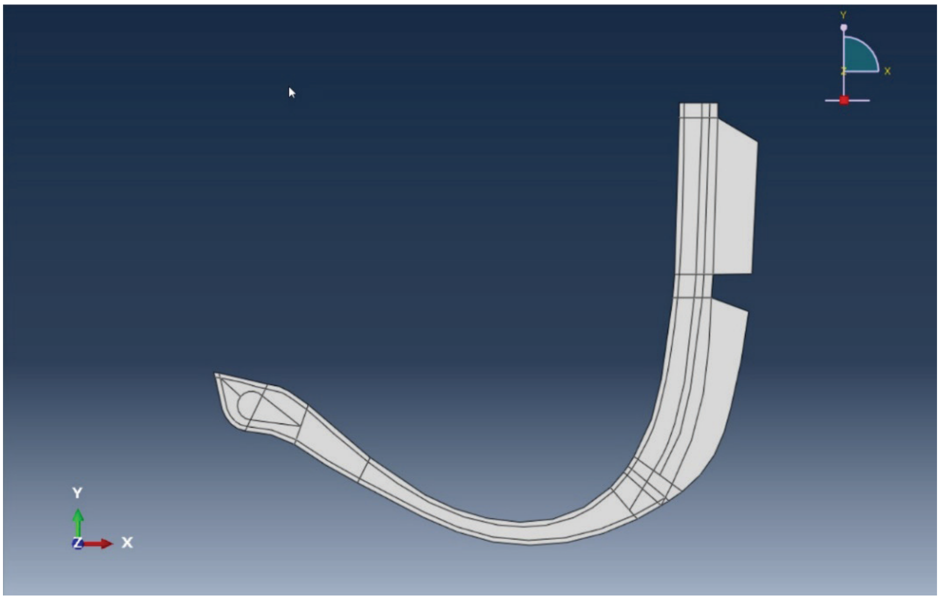


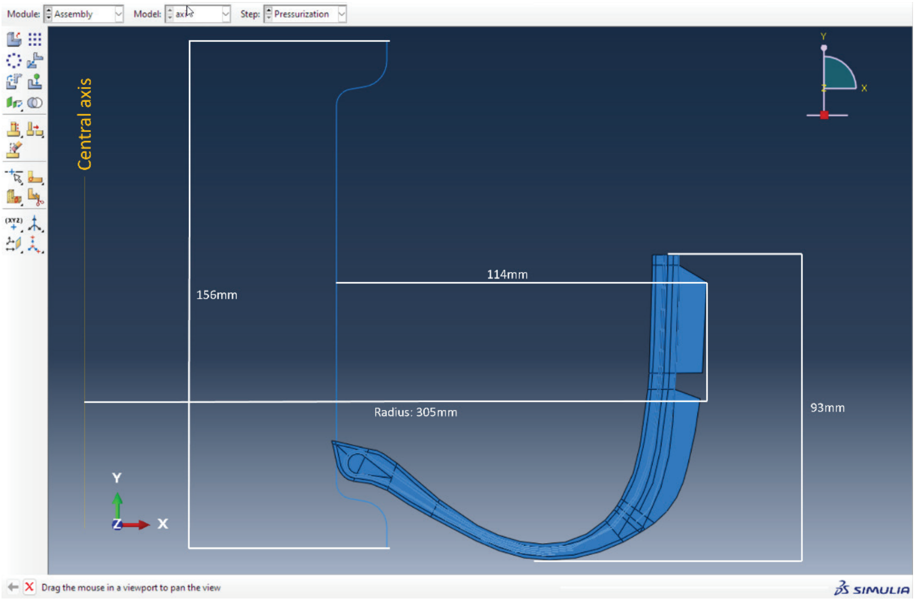
Figure 6. Axisymmetric model built in simulation software.

Figure 7 shows the assembly model of rim and tire components with assumed dimensions for creating the geometry.

After importing the 2D geometry, section creation and material assignment for each section are completed. The Rebar layer function is used to model rubber-reinforced belts [8]. Figure 8 shows this representing parameter definition like area per rebar and orientation angle.

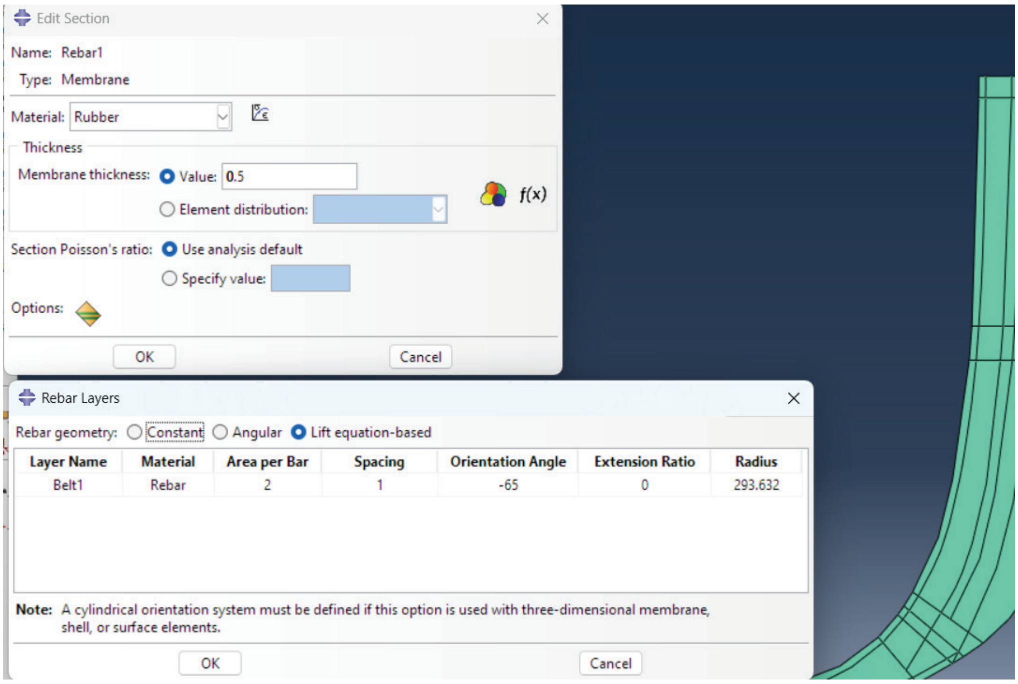
The plies are embedded within the rubber and nylon material is assigned. The rim is modeled as a rigid body. In the post processing step, for rebar, output cards are defined to capture essential simulation results, including stress, rebar orientation angle changes, and reaction forces in the rebar. The contact defination of interference fit is applied for the rim-tire connection and surface smoothness parameter set to 0.2 with finite sliding. This ensures a realistic and secure connection. Four node quad elements are used for meshing.

The carcass, sidewall, and apex are meshed separately. The plies are modeled as wires with 1D element. The


Module: Assembly
Model: ax
Step: Pressurization

Drag the mouse in a viewport to pan the view

Figure 7. Axisymmetric model built in simulation software.



Edit Section

Name: Rebar1

Type: Membrane

Material: Rubber

Thickness

Membrane thickness: ● Value: 0.5

○ Element distribution:

Section Poisson's ratio: ● Use analysis default

○ Specify value:

Options:

Rebar Layers

Rebar geometry: ○ Constant ○ Angular ● Lift equation-based

Layer Name	Material	Area per Bar	Spacing	Orientation Angle	Extension Ratio	Radius
Belt1	Rebar	2	1	-65	0	293.632

Note: A cylindrical orientation system must be defined if this option is used with three-dimensional membrane, shell, or surface elements.

Figure 8. Rebar function for modelling reinforcement in plies.

element types CGAX4 and CGAX3 are used for modelling carcass-sidewall-apex assembly. This allows to capture in-plane stress distributions and structural deformations. For the belt section to have flexibility with twisting, they are meshed using axisymmetric membrane elements with twist (MGAX1), as shown in Figures 9 and 10. Element length of 8 mm is used for meshing carcass, whereas the apex and sidewall regions are meshed with more finer mesh size of 4 mm to capture the localized stress distributions more accurately. Similarly, the plies are also meshed with a 4 mm element size. The finite element model consists of a total of 390 nodes and 367 elements. Among these, 181 elements

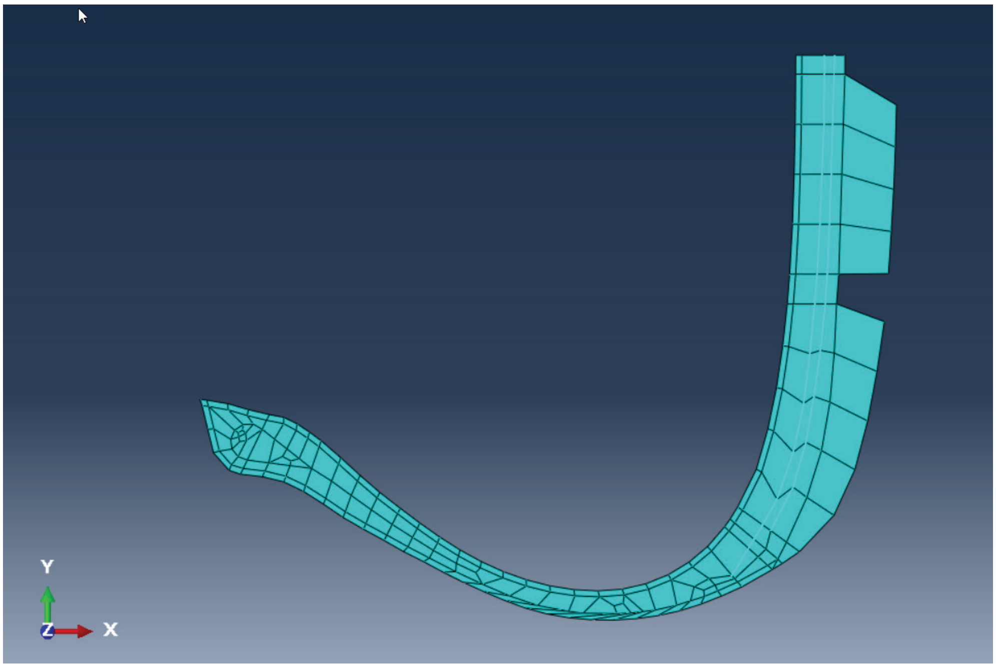


Figure 9. Carcass, sidewall, and apex meshing with suitable element types.

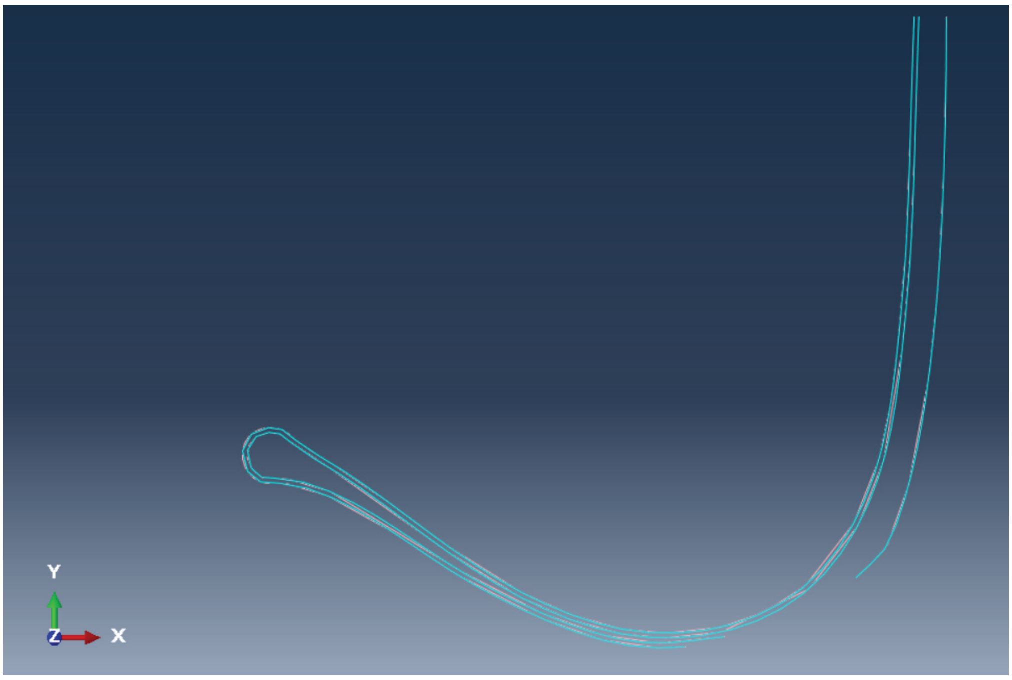


Figure 10. 1D Meshing of plies.

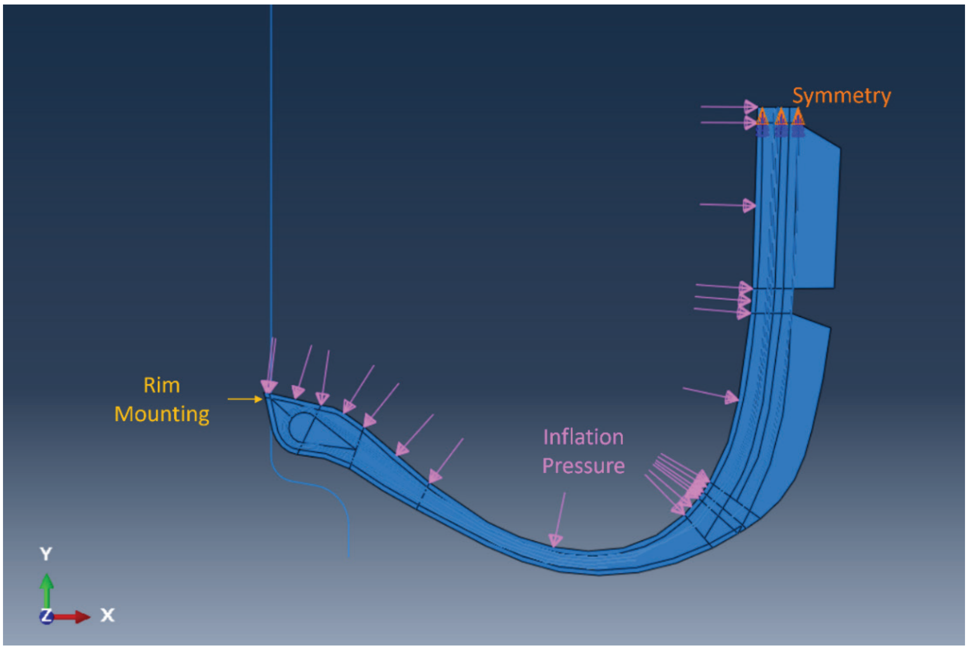


Figure 11. Visualization of boundary condition of an inflated tire.

are of type MGAX1, 184 elements are of type CGAX4, and 2 elements are of type CGAX3. The mesh quality check is performed before carrying out the simulation to ensure all elements pass the test.

Boundary conditions are applied as shown in Figure 11. The displacement boundary condition on the rim constrains all degrees of freedom except the axial direction. Inflation pressure is applied as an internal load of 3.5.

In the post-processing, specific field output requests such as deformation, max stress and reaction force at rebar are added based on the requirements of the simulation.

RESULTS AND DISCUSSION

The behavior of the tire under an inflation pressure of 3.5 Bar is obtained through simulations conducted in ABAQUS. The rubber components are represented using both Neo-Hookean and Mooney-Rivlin hyperelastic material models in the simulations. The stress analysis shows significant stress concentration around the belts edges and sidewalls. These are expected high strain aras in tire structure under inflation. The simulation results provided in Figure 12 show maximum stress reaching 319 MPa in the bead wire.

The stress level as shown is within acceptable limit. The material for bead wire is steel. This ensures its structural reliability for acting load. The significant expansion is observed in the sidewalls and contact patch areas. It is obvious as all degrees of freedom are constrained in simulation except the axial one to mimic real-world mounting conditions.

The energy stored in the material during deformation can be obtained using the strain energy density function, derived from the hyperelastic models. It will be maximum in the areas subjected to substantial strains. In this sense, the hyperelastic properties play a vital role in capturing tire

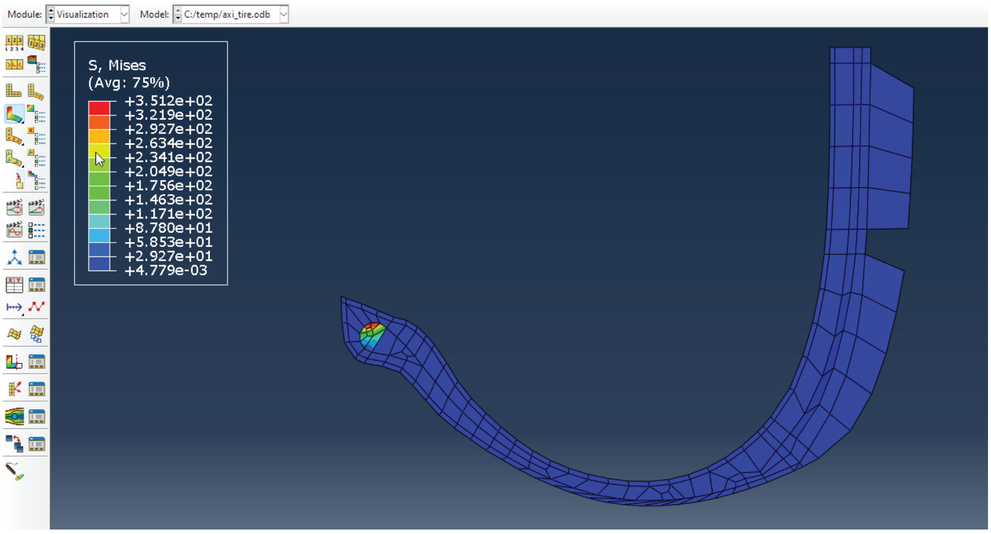


Figure 12. S-misses stress analysis.

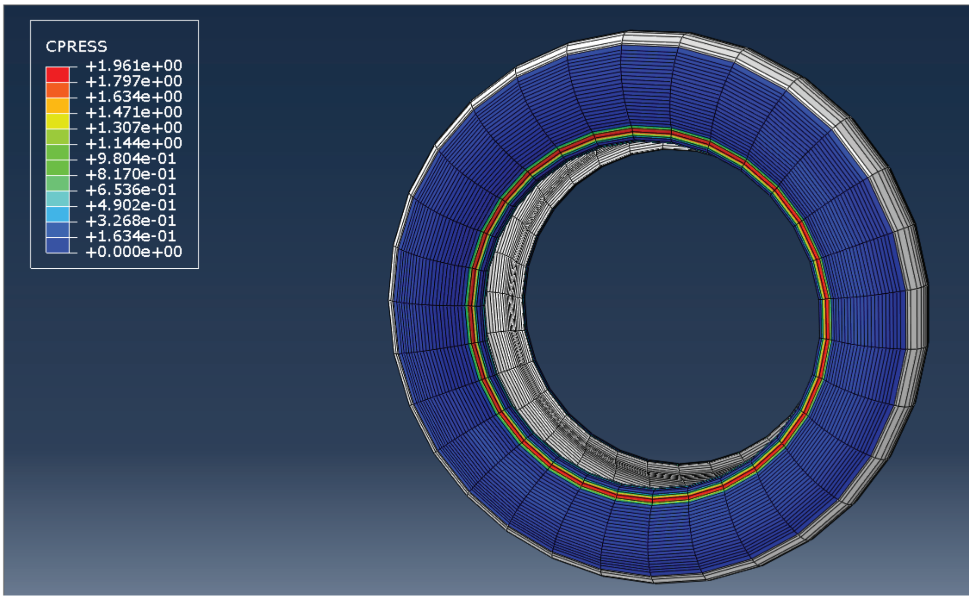


Figure 13. Contact pressure analysis.

material response under loading. The rebar layer function used to model the belt reinforcement mitigates stress and limiting deformation, particularly within the tread area. This reinforcing effect highlights the significance of reinforcement layers in tire performance and can increase durability and safety. Despite being computationally simple, the Neo-Hookean model exhibited limitations at higher strain levels when compred with the Mooney-Rivlin model. The Mooney-Rivlin model offers a more accurate depiction of the material behavior under considerable deformation as it incorporates an extra strain invariant. Therefore, it is concluded that the Mooney-Rivlin model is more suitable for forecasting tire performance in high-stress scenarios.

The details information about the forces acting on contacting surfaces can be derived through CPRESS analysis (contact pressure analysis). This analysis is also able to identify potential failure points and optimizing the designs for load distribution. It can also be used to ensure structural integrity, under situations where high contact pressures could lead to wear, deformation, or component failure. The results obtained by Contact Pressure analysis are provided in Figure 13.

The accuracy of the simulation depends on the factors like selected boundary conditions, the meshing techniques, etc. In the current analysis the meshing is carried out using quadrilateral surface elements and special attention is given to the aeas like sidewall and carcass regions in order to capture detailed deformation and stress gradients accuately. The boundary conditions and loadings applied during simulation study replicate real-world sinarios in order to get realistic insights into tire behavior under inflation. Additionally, the use of 2D elements used in the analysis helps in better visualization of the deformation patterns when swept applied as per need.

The importance of the non linear material properties and reinforcement structures in tire design is successfully underlined in the current research work by simulating the tire response subjected to inflation pressure. It is observed that the durability of the tire can be improved by optimizing the material properties and structural design specially in in high-stress regions. Future research in this area could focus on exploring advanced material models which can take into account thermal effects and investigating alternative reinforcement configurations to develop more safe and durable tires.

The behaviour of the tire rubber is investigated using Neo-Hookean and Mooney-Rivlin hyperelastic models in the current simulations. It is observed that the Mooney-Rivlin model is more accurate at higher strains. This observation is inline with the earlier researchers Gudsoorkar et al. [32] and Hernandez & Al-Qadi [10], who also considered Yeoh and Arruda-Boyce hyperelastic models additionally for tire rubber. The observations in the current study also highlight the limitations of the Neo-Hookean model at high strain levels as reported by Hernandez & Al-Qadi [10].

The stress analysis results show high stress concentration values around 319 MPa in the regions like the bead wire, belt edges, and sidewalls. Similar findings are reported by Zhang et al. [5], while Rugsaj & Suvanjumrat [11], emphasized on the role of reinforcement layers in stress mitigation. The tread stability can be improved using the rebar layer function for belt reinforcements which redirtibutes the stress. Rugsaj & Suvanjumrat [11] employed rebar elements in non-pneumatic tires (NPTs) for load distribution and stress reduction.

The realistic mounting conditions are achieved by constraining all degrees of freedom except axial one in the simulation study. The computational efficiency is ensured with the use of axisymmetric meshing with quadrilateral elements without sacrificing accuracy. Hernandez & Al-Qadi [10] validated boundary conditions using contact area and deflection measurements, while Zhang et al. [31] validated tire models subjected to inflation and normal loading. Similar approach is implemented in the current simulation study.

CONCLUSION

- The paper discusses FE analysis of tire with particular focus on structural configuration and modelling, material properties, and simulation methodology to evaluate its deformation behavior under different loading conditions. The FE simulation results demonstrated that accurate material modelling of the reinforcement layers plays an important role in predicting tyre deformation performance.
- The boundary conditions were applied to represent actual rim mounting conditions. The model was constrained such that movement was allowed only in the axial direction, while all other degrees of freedom (DOFs) were restricted. An axisymmetric mesh with quad elements was used. This reduces the overall computational time without compromising the accuracy of the results.
- The Neo-Hookean and Mooney–Rivlin hyperelastic material models were used to simulate the nonlinear stress–strain characteristics of rubber components and their results are compared. It was observed that the Neo-Hookean model provides good predictions at lower strain levels whereas the Mooney–Rivlin model gives better accuracy at higher strains. Strain energy density was found to be maximum in areas where there was large deformation. This confirms the significance of hyperelastic material modelling in tyre simulations. The comparison further shows the limitations of the Neo-Hookean approach at higher strain levels and can be concluded that the Mooney–Rivlin model stands out a more reliable option for analysing complex tyre behaviour.
- The FE simulations identified critical stress concentration zones, especially in regions such as the bead wire (approximately 320 MPa), belt edges, and sidewalls. These areas are structurally significant under an inflation pressure of 3.5 bar, as they directly contribute to

maintain tyre integrity and prevents the failure. The successful implemntation of rebar layer function to simulate belt reinforcements resulted in uniform distribution of stresses and enhanced tread stability. This is imporatnt for improving tire performance and safety.

- The overall study carried out here indicates the need for proper optimisation of structural design and material parameters to strengthen high-stress regions and improve tyre durability. Future work can extend this simulation by incorporating dynamic loading conditions, thermal effects due to rolling resistance, and alternative reinforcement configurations to develop a more comprehensive and realistic tyre model. The outcomes of this study provide a useful foundation for designing advanced tyres with improved safety, fuel efficiency, and longer service life.

ACKNOWLEDGEMENT

We extend our sincere appreciation to Dassault Systèmes for their support. Their generous support significantly elevated the quality and efficiency of our work.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

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