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**Dragan Čukanović[1]**
**Gordana Bogdanović[2]**
**Aleksandar Radaković[3]**
**Petar Knežević[4]**

# APPLICATION, MODELLING AND BENDING ANALYSIS OF COMPOSITE LAMINATES IN MODERN VEHICLES

**ABSTRACT:** The paper highlights the importance of the continuous development of composite materials as one of the key trends in the modern automotive industry. Particular attention is devoted to the advantages offered by composite materials in terms of vehicle weight reduction, improved energy efficiency, and enhanced mechanical performance of structural components. In addition, various mathematical models developed for describing the behaviour of laminated composite plates are considered. Based on the adopted mathematical formulations, a static bending analysis of these structural elements subjected to transverse loading was carried out. The obtained results are presented and analysed with the aim of providing a comprehensive insight into the potential applications of composite materials and their more efficient integration into the structures of modern electric vehicles.

**KEYWORDS:** modern automotive vehicles, composite materials, mathematical models of composite plates, elastic foundations, static analysis

# PRIMENA, MODELIRANJE I ANALIZA SAVIJANJA KOMPOZITNIH LAMINATA U SAVREMENIM VOZILIMA

**REZIME:** U radu je istaknut značaj kontinuiranog razvoja kompozitnih materijala kao jednog od ključnih trendova u savremenoj automobilskoj industriji. Posebna pažnja posvećena je prednostima koje kompozitni materijali pružaju u pogledu smanjenja mase vozila, povećanja energetske efikasnosti i unapređenja mehaničkih performansi konstrukcionih elemenata. Takođe, razmatrani su različiti matematički modeli namenjeni opisu ponašanja laminatnih kompozitnih ploča. Na osnovu usvojenih matematičkih formulacija sprovedena je statička analiza savijanja

[1] *Dragan Čukanović, University of Priština, Faculty of Technical Sciences, Knjaza Miloša 7, 38220 Kosovska Mitrovica, dragan.cukanovic@pr.ac.rs, https://orcid.org/0000-0001-8370-748X*
[2] *Gordana Bogdanović, University of Kragujevac, Faculty of Engineering, Sestre Janjić 6, 34000 Kragujevac, gocab@kg.ac.rs, https://orcid.org/0000-0001-7231-7400*
[3] *Aleksandar Radaković, Institute for Information Technologies Kragujevac, Jovana Cvijića bb, 34000 Kragujevac, Serbia, aradakovic@uni.kg.ac.rs, https://orcid.org/0000-0002-7355-7403*
[4] *Petar Knežević, University of Priština, Faculty of Technical Sciences, Knjaza Miloša 7, 38220 Kosovska Mitrovica, petar.knezevic@pr.ac.rs, https://orcid.org/0000-0003-4187-2879*

navedenih konstrukcionih elemenata pod dejstvom poprečnog opterećenja. Dobijeni rezultati su prikazani i analizirani u cilju sagledavanja mogućnosti primene kompozitnih materijala i njihove efikasnije integracije u konstrukcije savremenih električnih vozila.

**KLJUČNE REČI:** savremena motorna vozila, kompozitni materijali, matematički modeli kompozitnih ploča, elastična podloga, statička analiza

# INTRODUCTION

The development of electric vehicles represents one of the most significant directions in the ongoing transformation of the automotive sector, primarily driven by the need to reduce greenhouse gas emissions, improve energy efficiency and enhance the sustainability and performance of electric vehicle technologies. Modern vehicles require structures capable of simultaneously providing low weight, high stiffness and strength, impact and fatigue resistance as well as adequate thermal and electrical protection. A particular challenge arises from the fact that the battery system represents a significant proportion of the total mass of an electric vehicle. Therefore, reducing the mass of other structural components represents one of the key directions in the development of electric vehicles. According to available research, a reduction in vehicle mass of approximately 10% can result in a reduction in energy consumption of about 6–8%, although the actual effect depends on the vehicle type, driving conditions, and characteristics of the propulsion system. Wazeer, A. et al. (2023), Kumar, S. and Bharj, R. S. (2018), and Khan, F. et al. (2025) highlight the significant potential of composite materials for reducing vehicle mass while maintaining the required mechanical performance and structural integrity.

In this context, composite laminates represent a particularly important class of materials. Unlike conventional metallic materials, whose mechanical properties are generally isotropic, the properties of composite laminates can be tailored by selecting the type of fibres and matrix, reinforcement content, thickness of individual plies, and, in particular, the orientation and stacking sequence of the plies. This design flexibility represents one of the major advantages of laminated composites over conventional materials and enables the development of structures tailored to the specific requirements of modern automotive vehicles.

Accordingly, carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP) laminates are among the most commonly considered composite materials for vehicle structural components. CFRP laminates exhibit a particularly favourable stiffness- and strength-to-weight ratio, making them an attractive solution for components where weight reduction is a primary requirement. GFRP laminates are characterized by lower cost and good mechanical properties and can therefore represent a more economical alternative to CFRP. In addition, hybrid laminates combining different types of fibres, as well as thermoplastic composite laminates and sandwich structures, are being increasingly investigated as reported by Bazan, P. et al. (2026).

Under operating conditions vehicle and their structural components are subjected to various static and dynamic loading conditions, including vibration, impact, and cyclic loading associated with material fatigue. These loading conditions require adequate strength, stiffness, and durability of structural components, particularly when they are manufactured from composite materials. Consequently, mathematical modelling of composite laminates, together with their static and dynamic analysis, is becoming increasingly important in the modern design of vehicle structures. Lin, Y. et al. (2025) emphasize the importance of structural integrity and mechanical performance of composite materials under various loading conditions, while Atallah, K. E. et al. (2025) demonstrate the application of advanced numerical models for the static, free vibration, and buckling analysis of laminated composite plates. Numerous studies have therefore focused on the development and application of numerical models for predicting the mechanical response of composite structures under different loading conditions.

# APPLICATIONS OF COMPOSITE LAMINATES

In the development and design of modern electric vehicles, composite materials are increasingly being used not only for body components but also for chassis and load-bearing structures, protective elements, battery pack enclosures, and other functional components.

One of the most significant application areas of composite laminates is battery pack enclosures. These structures perform multiple functions: they support the battery modules, protect the cells from external mechanical loads, transfer loads to the vehicle structure, and provide adequate protection in the event of a crash. At the same time, the enclosure must withstand vibrations, temperature variations, moisture, and corrosive environments. Consequently, CFRP and GFRP laminates are increasingly being investigated as alternatives to steel and aluminium battery enclosures.

The application of composite laminates in battery enclosures is particularly important from the perspective of impact protection and crashworthiness. Unlike ductile metals, in which energy is absorbed primarily through plastic deformation, composite laminates absorb energy through a combination of different damage mechanisms, including fibre fracture, matrix cracking, delamination, and local crushing. Through appropriate laminate stacking-sequence design, progressive damage and controlled energy absorption can be achieved. This is particularly important in electric vehicles because mechanical damage to the battery enclosure can result in deformation or damage to the battery cells themselves. Research by Isaac, C. W. and Ezekwem, C. (2021) and Capretti, M. et al. (2024) on the crashworthiness of composite structures indicates that material selection, geometry, and stacking sequence must be considered simultaneously, as even a small change in laminate configuration can significantly alter the failure mechanism and the total amount of absorbed energy. Therefore, composite laminates have significant potential for application in electric vehicles, particularly in battery enclosures and battery pack covers, where they can provide low weight combined with the required stiffness, mechanical protection, impact resistance and the possibility of tailoring material properties through changes in ply orientation, as discussed by Liu, Y. et al. (2026).

In load-bearing vehicle structures, including the vehicle floor structure, chassis components, and structural supports, composite laminates enable weight reduction while maintaining adequate load-carrying capacity and stiffness. In addition, the fibre direction can be oriented according to the predominant loading directions. In body components, such as roof, floor, and door panels, composite laminates enable vehicle weight reduction while providing sufficient stiffness and flexibility for manufacturing components with complex geometries. Composite laminates are also applied in bumpers, supports, and other components designed for controlled energy absorption, where their progressive damage behaviour can be exploited to improve the crashworthiness characteristics of the vehicle.

# MODELLING COMPOSITE LAMINATES ON ELASTIC FOUNDATION

The static analysis of composite laminates is based on different plate theories. For thin laminated plates, the classical plate theory (CPT) is applied, whereas the first-order shear deformation theory (FSDT) is most commonly used for moderately thick plates, accounting for the effect of transverse shear deformation. For thicker laminated plates, higher-order shear deformation theories (HSDT) are employed, providing a more accurate description of the deformation and stress states through the plate thickness. An additional level of model complexity can be achieved by incorporating an elastic foundation, such as the Winkler, Pasternak, or Kerr models, which enables the analysis of the interaction between the composite laminate and the supporting foundation, as demonstrated by Akavci, S. S. (2005).

In this paper, the mechanical behaviour of composite laminates resting on elastic foundations is investigated using the higher-order shear deformation theory (HSDT), which accounts for transverse shear deformation without requiring an additional shear correction factor and provides an appropriate framework for the analysis of moderately thick laminated plates. The interaction between the composite laminate and the supporting medium is modelled using three commonly adopted elastic foundation models, namely the Winkler, Pasternak, and Kerr models. The Winkler model represents the foundation as a set of independent vertical springs and therefore considers only the local transverse response of the foundation (Figure 1a). In contrast, the Pasternak model introduces an additional shear layer that establishes interaction between neighbouring foundation points and consequently accounts for the transverse shear interaction within the supporting medium (Figure 1b). The Kerr foundation model further extends this concept by incorporating two independent layers of elastic springs connected through a shear layer, enabling a more flexible representation of the foundation response (Figure 1c).

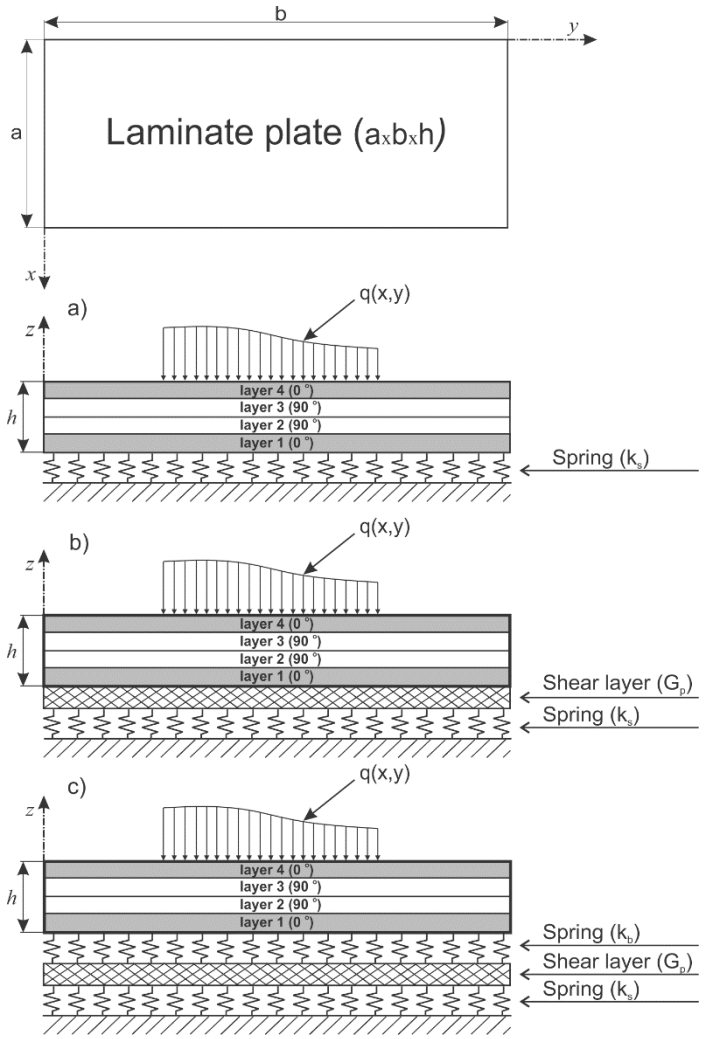
Within the framework of the higher-order shear deformation theory the kinematic relationships between the displacement and strain fields are established by introducing appropriate assumptions for the displacement components:

$$u = u_0(x,y) - zw_{0,x} + f(z)\theta_x, \quad v = v_0(x,y) - zw_{0,y} + f(z)\theta_y, \quad w = w_0(x,y), \tag{1}$$

where are:

- $u_0(x,y), v_0(x,y), w_0(x,y)$ - displacements of the mid-surface in the $x$, $y$ and $z$ directions, respectively;
- $w_{0,x}, w_{0,y}$ - rotations of transverse cross-sections about the $y$ and $x$ axes, respectively;
- $\theta_x, \theta_y$ - higher-order terms which, in combination with the shape function $f(z)$, enable the interpolation of shear deformation across the plate thickness;
- $f(z)$ - shape function proposed by authors in the follow form:

$$f(z) = -\left( \frac{z^2 \sinh\left(\frac{z}{h}\right)}{h} - 0{,}8z \right) \tag{2}$$




$q_e(x,y)$ - foundation reaction

$U_e$ - strain energy of the elastic foundation

$$q_e^{Winkler} = k_s w$$

$$U_e^{Winkler} = \int_A \frac{1}{2} k_s w^2 dA$$

$$q_e^{Pasternak} = k_s w - G_p \nabla^2 w\,, \qquad \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$$

$$U_e^{Pasternak} = \frac{1}{2}\int_A \left\{ k_s w^2 + G_p \left[ \left(\frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial y}\right)^2 \right] \right\} dA$$

$$q_e^{Kerr} = \frac{k_s k_b}{k_s + k_b} w - \frac{G_p k_b}{k_s + k_b} \nabla^2 w$$

$$U_e^{Kerr} = \frac{1}{2}\int_A \left\{ \frac{k_s k_b}{k_s + k_b} w^2 + \frac{G_p k_b}{k_s + k_b} \left[ \left(\frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial w}{\partial x}\right)^2 \right] \right\} dA$$

***Figure 1*** The geometry of composite laminate plate on elastic foundation: a) Winkler foundation, b) Pasternak foundation, c) Kerr foundation

The determination of the unit-load components requires the application of the displacement–strain relationships within the framework of linear elasticity. Accordingly, the constitutive equations describing the elastic behaviour of anisotropic materials can be expressed as follows:

$$\sigma_{ij} = C_{ijkl} \varepsilon_{kl} \tag{3}$$

where:

- $\sigma_{ij}$ are the stress components in different directions;
- $C_{ijkl}$ is the material elasticity tensor;
- $\varepsilon_{kl}$ are the strain components.

In order to apply the principle of minimum potential energy:

$$\delta U + \delta V + \delta U_e = \delta\left(U + V + U_e\right) \equiv \delta \Pi = 0 \tag{4}$$

it is necessary to define work under external load V for the plate bending problem subjected to a sinusoidal transverse load q(x,y):

$$V = -\frac{1}{2}\int_A qw dA, \quad \text{where is} \quad q(x,y) = q_0 \sin\left(\frac{\pi x}{a}\right)\sin\left(\frac{\pi y}{b}\right) \tag{5}$$

as well as plate strain energy deformation *U* in the follow form:

$$U = \int_A (N_{xx}\varepsilon_{xx}^{(0)} + N_{yy}\varepsilon_{yy}^{(0)} + N_{xy}\gamma_{xy}^{(0)} + M_{xx}k_{xx}^{(0)} + M_{yy}k_{yy}^{(0)} + M_{xy}k_{xy}^{(0)} + P_{xx}k_{xx}^{(1)} + P_{yy}k_{yy}^{(1)} + P_{xy}k_{xy}^{(1)} + R_x k_{xz}^{(2)} + R_y k_{yz}^{(2)})dA \tag{6}$$

while strain energy of the elastic foundation Ue is already defined according figure 2, depending on the particular foundation model considered.

Upon substitution of the strain components into the governing formulation and application of the variational principle, the corresponding equilibrium equations are obtained as follows:

$$\begin{aligned}
&\delta u_0: \quad N_{xx,x} + N_{xy,y} = 0 \\
&\delta v_0: \quad N_{yy,y} + N_{xy,x} = 0 \\
&\delta w_0: \quad M_{xx,xx} + 2M_{xy,xy} + M_{yy,yy} + N_{xx}w_{0,xx} + 2N_{xy}w_{0,xy} + N_{yy}w_{0,yy} + q - \frac{k_s k_b}{k_s + k_b}w_0 + \frac{G_p k_b}{k_s + k_b}\left(w_{0,xx} + w_{0,yy}\right) = 0 \\
&\delta\theta_x: \quad P_{xx,x} + P_{xy,y} - R_x = 0 \\
&\delta\theta_y: \quad P_{xy,x} + P_{yy,y} - R_y = 0
\end{aligned} \tag{7}$$

where:

$$\mathbf{N}=\left\{N_{xx} \quad N_{yy} \quad N_{xy}\right\}^T, \mathbf{M}=\left\{M_{xx} \quad M_{yy} \quad M_{xy}\right\}^T, \mathbf{P}=\left\{P_{xx} \quad P_{yy} \quad P_{xy}\right\}^T, \mathbf{R}=\left\{R_x \quad R_y\right\}^T \tag{8}$$

represents the force, moments and higher order moment resultants.

Equilibrium equations (7) correspond to the model of a composite laminate plate resting on Kerr's type of elastic foundation.

In the case of the Pasternak type of elastic foundation, the third equation has the form:

$$\delta w_0: \quad M_{xx,xx} + 2M_{xy,xy} + M_{yy,yy} + N_{xx}w_{0,xx} + 2N_{xy}w_{0,xy} + N_{yy}w_{0,yy} + q - k_s w_0 + G_p\left(w_{0,xx} + w_{0,yy}\right) = 0 \tag{9}$$

and finally, for the simplest Winkler-type elastic foundation:

$$\delta w_0: \quad M_{xx,xx} + 2M_{xy,xy} + M_{yy,yy} + N_{xx}w_{0,xx} + 2N_{xy}w_{0,xy} + N_{yy}w_{0,yy} + q - k_s w_0 = 0 \tag{10}$$

For the analytical solution of the system of equations (7), appropriate displacement fields and boundary conditions are assumed in accordance with Navier's solution, as described by Čukanović, D. et al. (2018).

# NUMERICAL EXAMPLES

The numerical examples presented in this section are conducted to verify the theoretical formulation developed in the previous sections and to demonstrate its applicability to the analysis of composite laminated plates. A symmetric cross-ply square laminate [0°/90°/90°/0°] resting on different type of elastic foundation is considered as the reference model. The plate is subjected to a sinusoidally distributed transverse load, while the material properties of the individual orthotropic layers are defined by their prescribed engineering constants:

$$E_1 / E_2 = 25, \quad G_{12} / E_2 = 0.6, \quad G_{13} / E_2 = 0.6, \quad G_{23} / E_2 = 0.5, \quad \nu_{12} = \nu_{13} = \nu_{23} = 0.25 \tag{11}$$

The numerical procedure is implemented to determine the mechanical response of the laminated plate under the considered loading and boundary conditions. The obtained results provide a basis for verifying the theoretical predictions and for further examining the influence of the considered elastic foundation models on the response of the composite plate. The numerical examples was performed by using MATLAB program package. The obtained numerical values were subsequently processed and normalized to facilitate their presentation and comparison:

$$\bar{w} = \frac{100E_2h^3}{q_0a^4}w\left(\frac{a}{2},\frac{b}{2},0\right); \quad \bar{\sigma}_{xx} = \frac{h^2}{qb^2}\sigma_{xx}\left(\frac{a}{2},\frac{b}{2},\frac{h}{2}\right)$$
$$\bar{\sigma}_{yy} = \frac{h^2}{q_0b^2}\sigma_{yy}\left(\frac{a}{2},\frac{b}{2},\frac{h}{4}\right); \quad \bar{\tau}_{xy} = \frac{h^2}{q_0b^2}\sigma_{xy}\left(0,0,\frac{h}{2}\right) \tag{12}$$
$$\bar{\tau}_{yz} = \frac{h}{q_0b}\sigma_{yz}\left(\frac{a}{2},0,0\right); \quad \bar{\tau}_{xz} = \frac{h}{q_0b}\sigma_{xz}\left(0,\frac{b}{2},0\right)$$

Based on the presented results in table 1, it can be observed that the selection of the elastic foundation model has a significant effect on the mechanical response of the laminated plate, particularly in terms of the normalized maximum displacement and the distribution of stress components. For the Winkler foundation, which represents the simplest model of the plate–foundation interaction, the normalized maximum displacement is 1.1189 for the geometric ratio a/h=4 and 0.4272 for a/h=20. This result indicates a pronounced influence of the geometric characteristics of the plate on its global deformation response. By introducing shear stiffness through the Pasternak model, the normalized displacement is reduced compared with the Winkler model, while the Kerr model, owing to the additional consideration of shear and local interaction characteristics, exhibits an even greater restriction of deformation. A similar dependence can be observed for the normalized normal stresses, with the Winkler foundation generally producing higher values of the stress response, whereas the additional stiffness parameters of the Pasternak and Kerr foundations contribute to its reduction. The change in the elastic foundation model also affects the values of the shear stresses, indicating that the characteristics of the foundation influence not only the global deformation of the plate but also the local distribution of stresses through the laminate thickness. Overall, the results demonstrate that the application of the Pasternak and Kerr foundation models enables a more detailed description of the interaction between the laminated plate and the elastic foundation compared with the Winkler model, while an increase in the effective stiffness of the system results in a reduction in both the deformation and, to a certain extent, the stress response of the plate.

***Table 1*** Normalized values of displacement and stresses of symmetric cross-ply square laminate [0°/90°/90°/0°] resting on different type of elastic foundation

| Theory | $k_s$ | $G_p$ | $k_b$ | a/h | $\bar{w}$ | $\bar{\sigma}_{xx}$ | $\bar{\sigma}_{yy}$ | $\bar{\tau}_{xy}$ | $\bar{\tau}_{yz}$ | $\bar{\tau}_{xz}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| *Winkler* | 100 | | | 4 | 1.1189 | 0.3997 | 0.3682 | 0.0266 | 0.1492 | 0.1292 |
| | | | | 20 | 0.4272 | 0.4561 | 0.2623 | 0.0195 | 0.1082 | 0.2552 |
| *Pasternak* | 100 | 30 | | 4 | 0.3313 | 0.1203 | 0.1103 | 0.0079 | 0.0456 | 0.0389 |
| | | | | 20 | 0.2292 | 0.2463 | 0.1396 | 0.0109 | 0.0589 | 0.1354 |
| *Kerr* | 100 | 100 | 100 | 4 | 0.2376 | 0.0892 | 0.0784 | 0.0059 | 0.0345 | 0.0276 |
| | | | | 20 | 0.1788 | 0.1965 | 0.1106 | 0.0081 | 0.0463 | 0.1060 |

By analysing the normalized displacement values shown in Figure 2, with the change of the ratio a/h=4 to 20, the following can be concluded:

- Winkler foundation - the normalized displacement changes by about 2.6 times,
- Pasternak foundation - the normalized displacement changes approximately 1.45 times,
- Kerr foundation - the normalized displacement changes approximately 1.3 times.

Thus, the normalized displacement is most sensitive to changes in the a/h ratio for the Winkler foundation and least sensitive for the Kerr foundation.

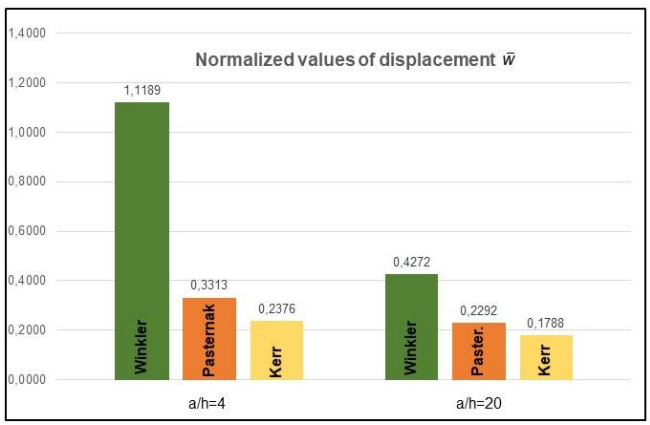



***Figure 2*** Comparative results of normalized displacement values for plates with length to thickness ratio of a/h=4 and a/h=20

# CONCLUSIONS

The presented paper confirms the significant potential of composite materials for application in modern automotive and electric vehicle structures, particularly due to their favourable mechanical performance and potential for weight reduction. The developed theoretical formulation for the static analysis of laminated composite plates provides an effective framework for investigating their response under transverse loading and was verified through the presented numerical examples. The results demonstrate that the elastic foundation model has a pronounced influence on the deformation and stress response of the laminated plate, with the Pasternak and Kerr models providing a more comprehensive representation of plate–foundation interaction than the Winkler model. An increase in the length-to-thickness ratio generally leads to changes in normalized displacement and stresses components, highlighting the importance of plate geometry in the structural analysis. Overall, the obtained results demonstrate that an appropriate combination of laminate configuration, material properties, geometric parameters, and elastic foundation characteristics can significantly influence the mechanical behaviour of composite plates.

As a direction for future research, the developed model could be extended to asymmetric laminated plates in order to assess its applicability and accuracy for more complex laminated plate configurations. Particular attention could be devoted to investigating the influence of different layer arrangements and orientations on the deformation and stress response. Further research could also focus on the optimization of the laminate structure and elastic foundation parameters with respect to predefined criteria, such as minimum displacement, maximum allowable stress, or the simultaneous minimization of mass and deformation.

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