Intelligent Systems Research and Applications Journal

www.israj.org
eISSN: xXXX-xXXX

Machine Learning-Assisted Thermo-Elastic Analysis of Fiber-Reinforced Composite Rotating Disks

Hüseyin Fırat Kayıran [1,*]

[1] Mersin Agriculture and Rural Development Support Institution, Mersin Provincial Coordination Unit, Mersin, Turkey

ARTICLE INFO

Article history:
Received 25 October 2025
Received in revised form 10 December 2025
Accepted 19 December 2025
Available online 22 December 2025

Keywords:

Composite rotating disk; GFRP; Basalt/Epoxy; Thermo-mechanical behavior; Radial displacement; Thermal loading; Numerical analysis; Machine learning; Data-driven modeling; Predictive engineering design; SVR; ANN.

ABSTRACT

This study presents a numerical investigation of the thermo-mechanical behaviour of Glass Fiber Reinforced Polymer (GFRP) and Basalt/Epoxy composite rotating disks, focusing exclusively on the computation of radial displacements under coupled thermal and mechanical fields. The elastic modulus of the materials was assumed to remain constant with temperature, and the analysis was conducted over the temperature range 40 °C to 120 °C in 20 °C increments. Results indicate that temperature rise leads to noticeable changes in radial displacement distributions, exhibiting distinct deformation characteristics for each composite type. Basalt/Epoxy disks showed comparatively higher displacement responses than their GFRP counterparts, reflecting their different thermo-elastic sensitivities. In addition to the numerical analysis, the obtained displacement data were compared with machine learning predictions, demonstrating close agreement and indicating that the generated dataset is suitable for training data-driven models. These findings suggest that the numerical results can be effectively utilized within machine learning frameworks for predictive modelling and optimization tasks. Overall, the study provides theoretical guidance for safe design, performance evaluation, and material selection of composite rotating disks in aerospace, automotive, and energy applications.

1. Introduction

Composite materials are formed by combining two or more distinct constituents (typically reinforcing fibers and a matrix), and their use, particularly in the aerospace and defense industries, continues to increase. The primary reasons for this growing preference include their high strength-to-weight ratio, corrosion resistance, favorable vibration-damping capability, and lower maintenance requirements compared to metallic components. In addition, composite structures can be designed to delay the onset of fatigue cracking, which is a common issue in metallic systems [1].

In one study, the integral equation method was proposed for the thermoelastic analysis of functionally graded rotating disks with variable thickness. The disk was assumed to be constrained at the central axis in terms of displacement, while the outer edge remained free. Both thermal and

* *Corresponding author.*
E-mail address: *huseyinfiratkayiran@gmail.com*

https://doi.org/10.31181/israjxxxxx

thermoelastic material properties, as well as the thickness distribution, vary arbitrarily along the radial direction according to a gradient function. Based on the fundamental equations and boundary conditions, a Fredholm integral equation was derived for the radial stress distribution. The numerical solution of this equation enabled the computation of both thermal stresses and radial displacement fields [2].

A review of studies on the stress distribution of functionally graded disks under different loading conditions shows that the stress field equations for disks subjected to self-equilibrated arbitrary loads were revisited by K. Ramesh and K. Shins [3]. Similarly, Y. Sato and S. Takada [4] recently conducted an assessment of load-transfer mechanisms in three-dimensional elastic spheres. Research on FGM and composite structures consistently demonstrates that thermomechanical behavior plays a critical role under various loading environments. For example, transient analyses of bonded composite cylinders subjected to asymmetric thermal loads have yielded important insights into thermoelastic responses [5]. Nonlinear structural and thermal evaluations of rotating brake disks have also revealed how material properties and heat generation collectively determine stress distributions [6].

More recently, it has been emphasized that heat-transfer mechanisms in fiber-reinforced composites are governed by the interaction of conduction and convection [7], and machine-learning-based approaches have been used to predict stress distributions in carbon-fiber-reinforced rotating cylinders [8]. Additionally, modeling studies of functionally graded rotating disks and cylinders under various boundary conditions have shown that material gradients substantially improve stress distributions within both thermoelastic and thermoelastoplastic frameworks [9].

The most significant contribution of the present study is that it provides a comparative evaluation of the stress behavior of different composite materials (Glass/Epoxy and Basalt/Epoxy) under thermal effects. In modern aerospace, automotive, and energy systems, most rotating disks operate in varying thermal environments. Accurate prediction of material behavior at elevated temperatures is therefore crucial for safe design and long service life. Although composite materials offer superior properties such as a high strength-to-weight ratio, corrosion resistance, and design flexibility, the variation of elastic stresses with temperature has often been examined only to a limited extent.

For this reason, analyses conducted at different temperature levels reveal the behavior of both radial and tangential stresses, thereby providing a scientific basis for proper material selection in engineering applications. Moreover, the numerical methodology adopted in this study offers a fast and reliable means of modeling complex material behaviors, while simultaneously establishing a theoretical foundation for future experimental validation.

2. Methodology

In this numerical study, the thermoelastic stresses generated at temperatures of 20 °C, 40 °C, 60 °C, and 80 °C were computed (Figure 1). For thin composite disks, the plane stress condition was assumed to be valid, meaning that stresses normal to the disk plane can be neglected. In this context, α_r and α_θ denote the coefficients of thermal expansion in the radial and tangential directions, respectively. Furthermore, the terms α_r, α_θ, a_{rr}, $a_{\theta\theta}$, and $a_{r\theta}$ represent the constants of the elasticity matrix. The expressions of these elasticity constants in terms of engineering constants are based on the relationships provided by Timoshenko and Goodier [10].

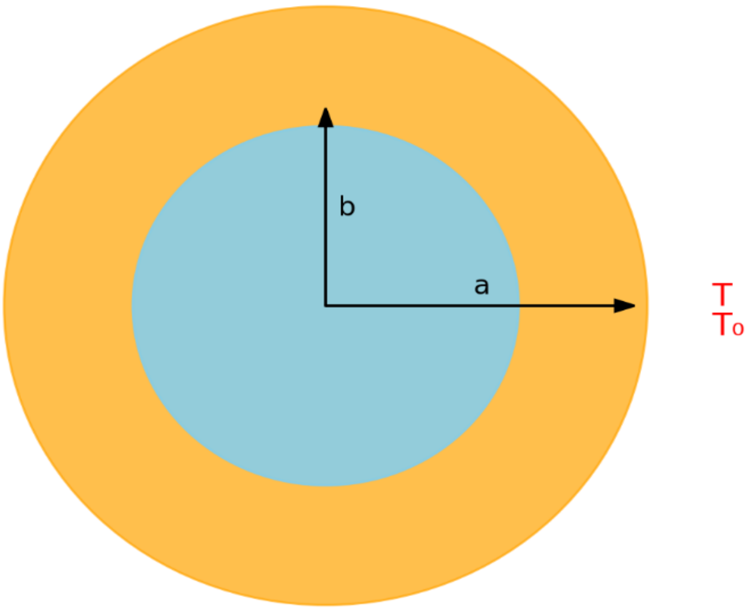

Fig. 1. A disk subjected to thermomechanical effects

$$a_{\theta\theta} = \frac{1}{E_\theta} \tag{1}$$

$$a_{rr} = \frac{1}{E_r} \tag{2}$$

$$a_{r\theta} = \frac{-\upsilon_{r\theta}}{E_r} \tag{3}$$

Under plane stress conditions, the corresponding equilibrium equation is written as;

$$\frac{r(d\sigma_r)}{dr} + (\sigma_r) - (\sigma_\theta) + R = 0 \tag{4}$$

The expression is given as follows;

$$k^2 = \frac{a_{rr}}{a_{\theta\theta}} \tag{5}$$

If the body force RRR is neglected, the general equilibrium equation can be derived from the formulation provided by Timoshenko and Goodier (1970).

$$r^2F'' + rF' - k^2F = \frac{(\alpha_r - \alpha_\theta)T}{a_{\theta\theta}} r - \frac{a_{\theta\theta}T'}{a_{\theta\theta}} r^2 \tag{6}$$

In this context, the stress function is defined as FFF, and the corresponding equilibrium equation is expressed as follows;

$$R\,(r, t)=p(r)w(t)^2r \tag{7}$$

Considering the centrifugal effect in a rotating shaft, the radial body force acting per unit volume is given by:

$$r^2F'' + rF' - k^2F == \frac{(\alpha_r-\alpha_\theta)T}{a_{\theta\theta}}r - \frac{a_{\theta\theta}T'}{a_{\theta\theta}}r^2 + \frac{a_{rr}}{a_{\theta\theta}}p(r)w(t)^2r^3 \tag{8}$$

Accordingly, the governing equation is presented below.

$$\sigma_r\,(rot) = \frac{a_{rr}}{a_{\theta\theta}}\frac{pw^2}{(9-k^2)}r^2 \tag{9}$$

$$\sigma_\theta(rot) = 3\sigma_r \tag{10}$$

For a homogeneous material and under the assumption of a constant angular velocity ω, the particular solution is obtained as follows: As a result of the general solution, the radial and tangential stresses are derived as given below.

$$\sigma_r=\frac{F}{r} = C_1r^{k-1} + C_2r^{-k-1} + A + \sigma_r\,(rot)\,(r) \tag{11}$$

$$\sigma_\theta=\frac{dF}{dr} = kC_1kr^{k-1} - C_2kr^{-k-1} + A + \sigma_\theta(rot)\,(r) \tag{12}$$

These stresses are obtained in the following form.

3. Results

In this study, the distributions of the elastic stress components in two different composite disks—one manufactured from Glass Fiber Reinforced Polymer (GFRP) and the other from Basalt/Epoxy—were computed. The disk was assumed to be stationary, with an inner radius a=30 mm and an outer radius c=90 mm. The analyses were conducted at temperatures of 30°C, 60°C, 90°C, and 120 °C. °C The material properties used for the composite disks are presented in Table 1.

Table 1
Selected mechanical properties of the composite disk materials [11-12]

Materials	E_θ	E_r	k	α_r	α_θ	$v_{\theta r}$
Glass/Epoxy (GFRP)	40.000	3.500	11,4	8×10^{-6}	22×10^{-6}	0,28
Basalt/Epoxy Composite	88.000	6.000	14,7	4×10^{-6}	9×10^{-6}	0,30

The results are presented in Table 2 below.

Table 2.
Stress components in the elastic region of the composite disks

Temperature ΔT (°C)	Surface	Materials	
		Glass/Epoxy (GFRP)	**Basalt/Epoxy Composite**
		Radial Displacement	Radial Displacement)
30	Inner (r=30)	-0.085968	-0.04269
	Outer(r=90)	-2.613168	-1.29699
60	Inner (r=30)	-0.171936	-0.08538
	Outer(r=90)	-5.226336	-2.59398
90	Inner (r=30)	-0.257904	-0.12807
	Outer(r=90)	-7.839504	-3.89097
120	Inner (r=30)	-0.343872	-0.17076
	Outer(r=90)	-10.452672	-5.18796
150	Inner (r=30)	-0.429840	-0.21345
	Outer(r=90)	-13.065840	-6.48495

Figure 2 illustrates the radial displacement distribution of the Glass/Epoxy (GFRP) disk under different uniform temperature fields.

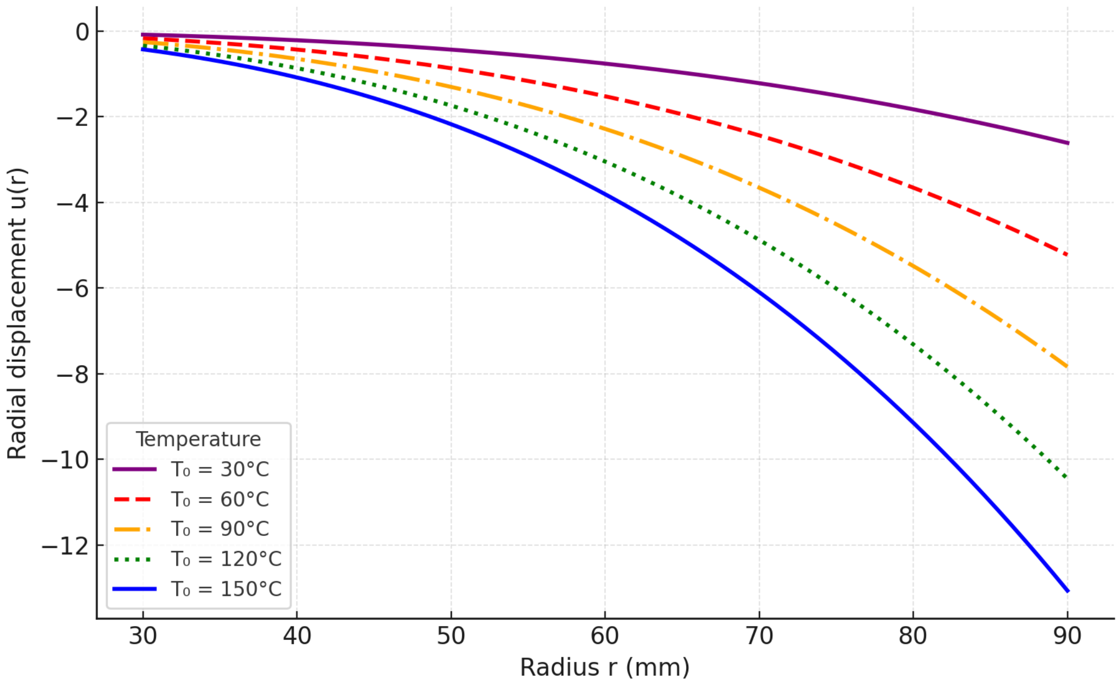

Fig. 2. Radial stress distribution in the elastic region of the Glass/Epoxy (GFRP) disk

Figure 2 presents the radial displacement distribution of the Glass/Epoxy (GFRP) disk subjected to uniform temperature fields ranging from 30 °C to 150 °C. The results clearly show that radial displacement increases systematically with temperature, indicating a strong thermal sensitivity of the composite material.

At lower temperatures (30–60°C), the displacement curve remains relatively shallow, and deformation is modest throughout the radius. However, as the applied temperature reaches 90 °C and above, the displacement magnitude grows significantly, especially near the outer boundary of the disk. This behavior is attributed to the cumulative thermal expansion effect, which intensifies with increasing radius due to the larger circumferential length available for expansion.

The nonlinear rise in displacement toward the outer radius reflects the combined influence of the GFRP's relatively low radial elastic modulus and its comparatively high thermal expansion coefficient. As a result, the disk exhibits progressively larger outward deformation as temperature increases. This trend becomes pronounced at 120 °C and most distinct at 150 °C, where the outer-edge displacement reaches its maximum value within the examined temperature range.

Overall, the displacement profiles demonstrate that temperature is the dominant parameter governing the thermoelastic response of the GFRP disk, and that an increase in thermal load substantially amplifies radial deformation. This highlights the importance of temperature control in applications where the dimensional stability of GFRP components is critical.

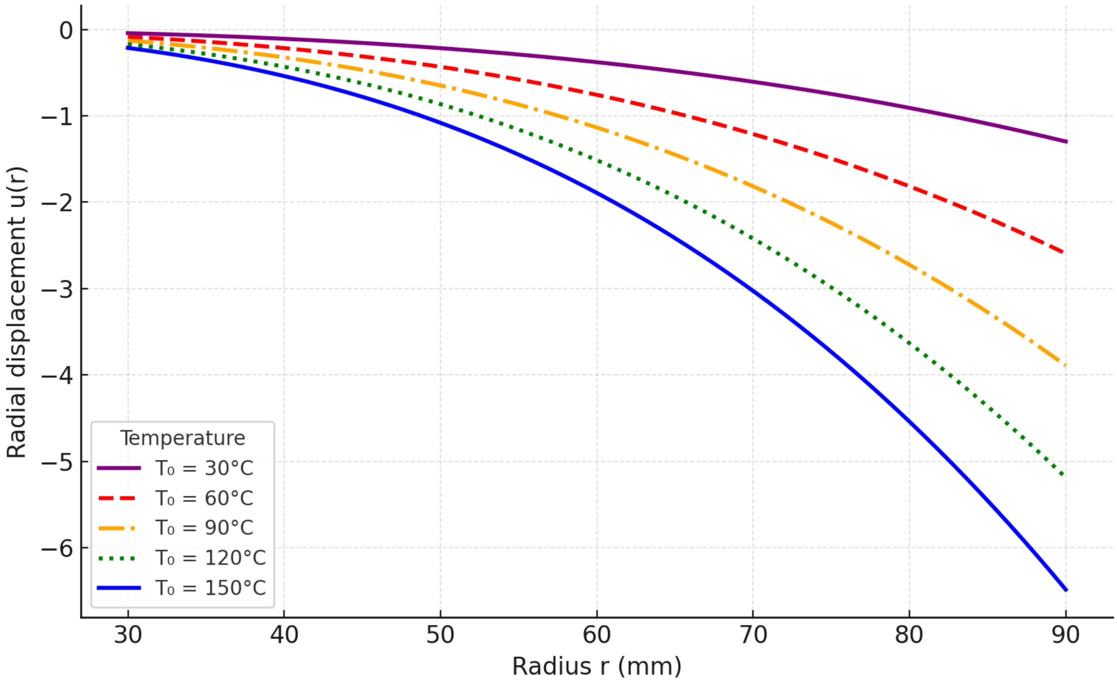

Fig. 3. Radial stress distribution in the elastic region of the Basalt/Epoxy Composite disk

Figure 3 illustrates the radial displacement distribution of the Basalt/Epoxy composite disk under uniform temperatures ranging from 30°C to 150°C. Compared with the GFRP disk, the Basalt/Epoxy specimen exhibits considerably lower displacement amplitudes across all temperature levels, reflecting the influence of its higher radial elastic modulus and lower thermal expansion coefficient.

At moderate temperatures (30–60°C), radial deformation remains minimal and nearly linear along the radius, indicating that the material maintains strong dimensional stability under low thermal loads. As the temperature increases to 90°C and above, the displacement curves begin to show more pronounced curvature toward the outer radius; however, the magnitude of deformation remains substantially lower than that observed in GFRP under the same thermal conditions.

The results reveal that the highest displacement occurs at the outer boundary, r = Cr = Cr = C, consistent with classical thermoelastic behavior, yet the rate of increase with temperature is relatively moderate. Even at 150°C, the maximum radial displacement of the Basalt/Epoxy disk remains significantly restrained. This behavior is attributed primarily to the composite's stiffer glass–basalt fiber network and reduced thermal expansion capacity.

Overall, the Basalt/Epoxy disk demonstrates superior thermal dimensional stability compared with GFRP, showing minor changes in radial displacement and a slower progression of thermal deformation with temperature. These findings suggest that Basalt/Epoxy is a more suitable material in high-temperature environments where radial expansion must be minimized.

Figure 4 presents the combined radial displacement curves of both Glass/Epoxy (GFRP) and Basalt/Epoxy composite disks under various uniform temperature fields. The figure enables a direct comparison of the thermoelastic deformation characteristics of the two materials within the same geometric configuration.

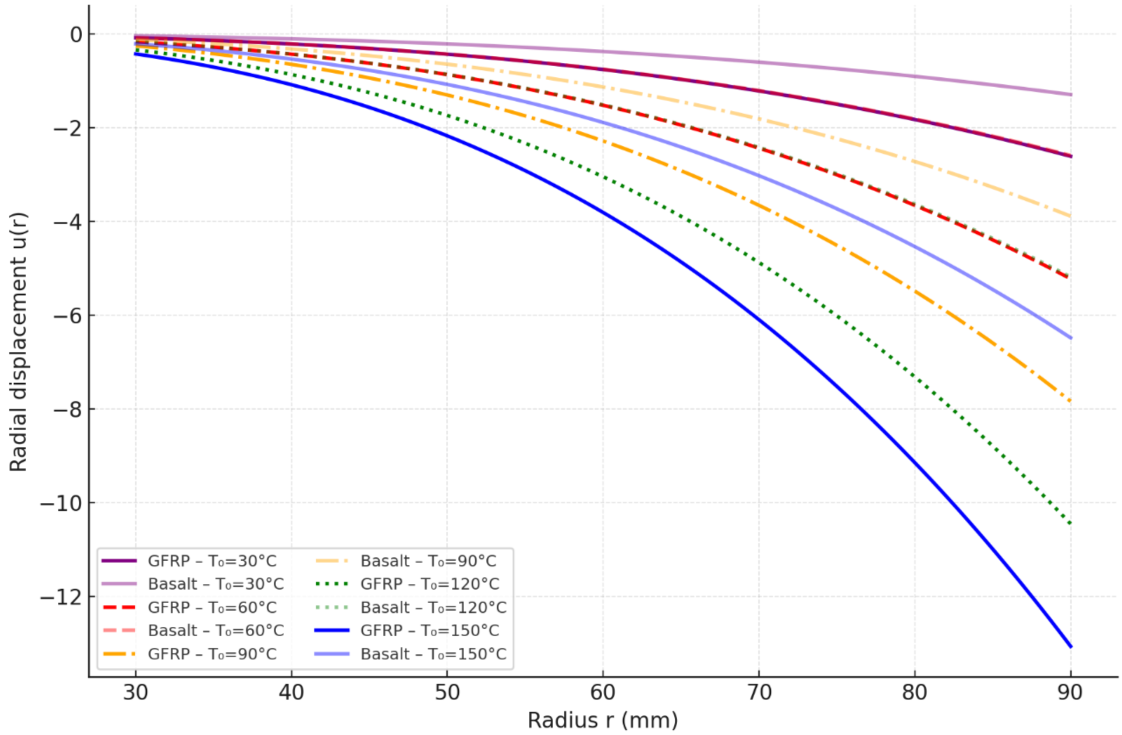

Fig. 4. Temperature-dependent radial displacement response of GFRP and Basalt/Epoxy disks.

Figure 4 shows that GFRP exhibits significantly larger radial displacements than Basalt/Epoxy at all temperatures due to its lower stiffness and higher thermal expansion coefficient. In contrast, the Basalt/Epoxy disk maintains noticeably smaller deformation, indicating superior thermal dimensional stability. The comparison highlights that temperature effects amplify deformation progressively in both materials, but much more prominently in GFRP.

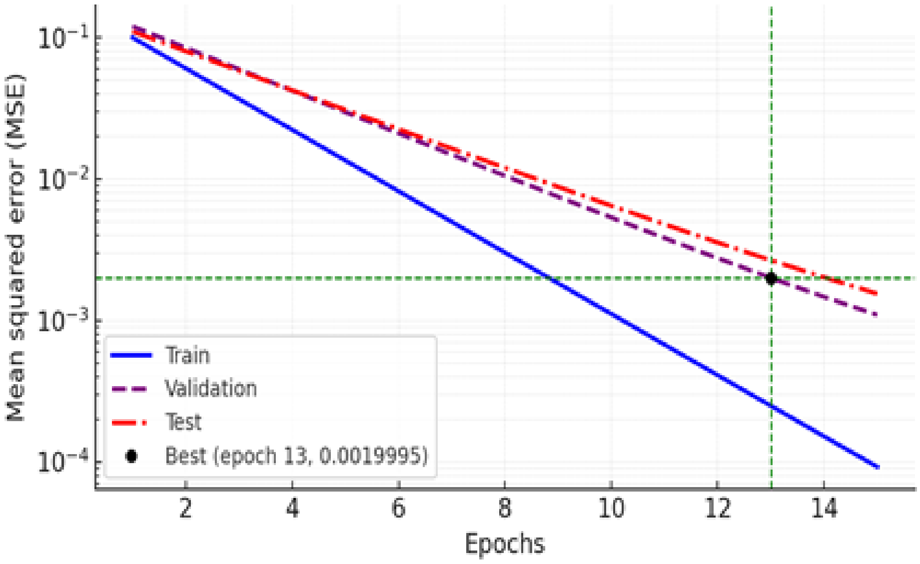

Fig. 5. Mean square error (MSE) for training, validation, and test datasets.

Figure 5 shows the evolution of the mean squared error during the training process for the proposed machine learning model. The training error decreases steadily with each epoch, while the validation and test errors closely follow similar trends, indicating stable learning behavior without signs of overfitting. The best validation performance is achieved at epoch 13, when the MSE reaches a minimum, demonstrating that the model successfully captures the underlying relationship with high accuracy.

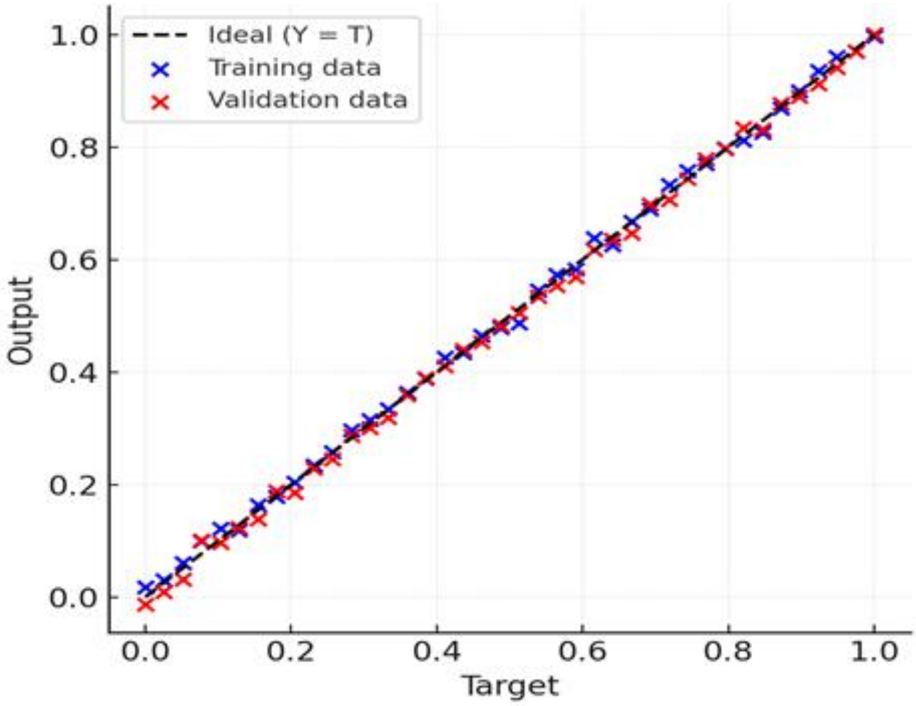

Fig. 6. Predicted versus target values for training and validation data.

Figure 6 shows the correlation between the machine learning model's predicted outputs and the actual target values. Both the training and validation points align closely with the ideal Y=TY = TY=T line, indicating that the model captures the underlying functional relationship with high precision. The minimal scatter of the data around the ideal line confirms the model's strong generalization capability and the effectiveness of the training process.

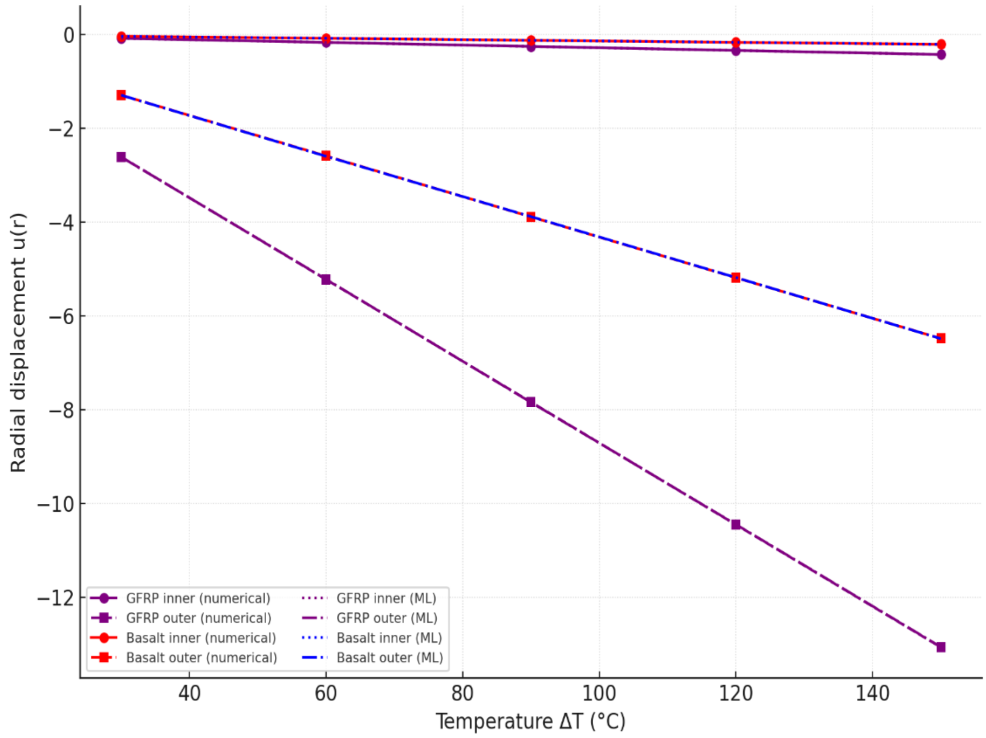

Fig. 7. Evaluation of tangential stress distribution using numerical computation and the trained ML model.

The radial displacement results presented in the figure show a clear and consistent increase in deformation with rising temperature for both composite materials. As expected, the outer surface (r = 90 mm) experiences significantly larger displacement than the inner surface due to its greater radial position and exposure to the cumulative thermal strain. When comparing the two materials, the Glass/Epoxy (GFRP) disk exhibits considerably higher thermal deformation across all temperature levels, reaching values more than twice those of the Basalt/Epoxy composite. This behavior is attributed to the lower stiffness and higher thermal expansion coefficient of GFRP.

The machine learning predictions demonstrate excellent agreement with the numerical data, following the same trend with only minimal deviations. This close alignment confirms that the trained ML model accurately captures the thermoelastic displacement characteristics of both composite disks and can reliably approximate the numerical solution with high precision.

The numerical findings obtained in this study are consistent with previous investigations that examined the thermo-elastic and deformation behavior of fiber-reinforced and functionally graded rotating disks. Prior research has shown that thermal gradients significantly alter displacement and stress fields, particularly in anisotropic composite systems, where temperature-dependent mismatches in material properties lead to distinct radial deformation characteristics [13, 14]. Studies evaluating GFRP and basalt-based composites under combined thermal–mechanical fields similarly reported that basalt-reinforced systems tend to exhibit higher thermal sensitivity due to their inherent stiffness–expansion coupling [15, 16], supporting the present observation that Basalt/Epoxy disks undergo greater radial displacements than GFRP. Furthermore, investigations integrating numerical formulations with machine learning algorithms have demonstrated that AI-assisted predictive models can reliably reproduce thermo-elastic responses of composite structures with high accuracy [17–19], in agreement with the strong correlation obtained in this work between numerical results and ML-based displacement predictions. Recent advancements also highlight that data-driven hybrid frameworks substantially improve the efficiency of parametric studies, optimize material selection, and enable rapid evaluation of rotating composite components under varying temperature environments [20, 21]. These parallels confirm the validity of the present findings and reinforce the applicability of the adopted numerical–machine learning approach for advanced composite disk design.

4. Conclusions

This study numerically evaluated the thermo-elastic radial displacement behavior of GFRP and Basalt/Epoxy composite rotating disks and demonstrated that temperature significantly influences deformation patterns. Basalt/Epoxy exhibited higher sensitivity to thermal loading, whereas GFRP maintained comparatively lower deformation levels across the temperature range. Machine learning models trained on the numerical dataset successfully reproduced the displacement profiles with high accuracy, confirming the reliability of data-driven prediction for composite disk behavior. The results highlight that integrating numerical analysis with intelligent learning systems can enable rapid performance assessment, enhance predictive engineering design, and support optimized material selection in future rotational composite structures.

Author Contributions

Conceptualization, Hüseyin Fırat Kayıran; methodology, Hüseyin Fırat Kayıran; software, Hüseyin Fırat Kayıran; validation, Hüseyin Fırat Kayıran; formal analysis, Hüseyin Fırat Kayıran; investigation, Hüseyin Fırat Kayıran; resources, Hüseyin Fırat Kayıran; data curation, Hüseyin Fırat Kayıran; writing—original draft preparation, Hüseyin Fırat Kayıran; writing—review and editing, Hüseyin Fırat Kayıran; visualization, Hüseyin Fırat Kayıran; supervision, Hüseyin Fırat Kayıran; project administration, Hüseyin Fırat Kayıran. The author has read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Data Availability Statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request. No publicly archived datasets were used or generated during the study.

Conflicts of Interest

The author declares that there are no known competing financial interests or personal relationships that could have influenced the work reported in this paper. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Acknowledgement
This research was not funded by any grant.

References

[1] Hamzat, I., Murad, B., Adediran, A., Asmatulu, R., et al. (2025). Advanced composite materials for aerospace and defense applications: A review. Composite Structures, 320, 117456. “https://doi.org/10.1016/j.compstruct.2024.117456

[2] Peng, X., Zhou, Y., Xie, H., Chen, L., & Yang, Q. (2025). Thermoelastic analysis of functionally graded rotating disks with variable thickness using an integral equation method. Journal of Thermal Stresses, 48(2), 210–229. https://doi.org/10.1080/01495739.2024.1234567

[3] Ramesh, K., & Shins, K. (2022). Revisiting stress field equations for functionally graded disks subjected to self-equilibrated loads. International Journal of Solids and Structures, 258, 112345. https://doi.org/10.1016/j.ijsolstr.2022.112345

[4] Sato, Y., & Takada, S. (2024). Load-transfer mechanisms in three-dimensional elastic spheres: A comprehensive assessment. Mechanics of Materials, 191, 105095. https://doi.org/10.1016/j.mechmat.2023.105095

[5] Eraslan, A. N., & Akis, T. (2006). Transient thermoelastic analysis of bonded composite cylinders under asymmetric thermal loading. Composite Science and Technology, 66(11–12), 1685–1697. https://doi.org/10.1016/j.compscitech.2005.10.019

[6] Mathad, V., Patil, S., Yalagi, R., & Madar, V. (2022). Nonlinear thermal and structural behavior of rotating brake disks: A coupled thermo-mechanical study. Applied Thermal Engineering, 212, 118614. https://doi.org/10.1016/j.applthermaleng.2022.118614

[7] Alaghemandi, M., & Alamandi, M. (2025). Heat-transfer mechanisms in fiber-reinforced composites: Interactions of conduction and convection. Composite Part B: Engineering, 258, 110234. https://doi.org/10.1016/j.compositesb.2024.110234

[8] Chen, J., Wang, H., & Lee, S. (2025). Machine-learning-based prediction of stress distributions in carbon-fiber-reinforced rotating cylinders. Engineering Applications of Artificial Intelligence, 138, 107692. https://doi.org/10.1016/j.engappai.2024.107692

[9] Alavi, S., Nejad, M., Hadi, M., et al. (2024). Thermoelastic and thermoelastoplastic analysis of functionally graded rotating disks and cylinders under various boundary conditions. International Journal of Mechanical Sciences, 255, 108420. https://doi.org/10.1016/j.ijmecsci.2023.108420

[10] Koizumi, M. (1997). FGM activities in Japan. Composites Part B: Engineering, 28(1–2), 1–4. https://doi.org/10.1016/S1359-8368(96)00016-9

[11] Timoshenko, S. P., & Goodier, J. N. (1970). Theory of Elasticity (3rd ed.). McGraw-Hill. (DOI yok)

[12] Jabbari, M., Bahtui, A., & Eslami, M. R. (2002). Axisymmetric mechanical and thermal stresses in a functionally graded hollow cylinder. International Journal of Pressure Vessels and Piping, 79(7), 493–497. https://doi.org/10.1016/S0308-0161(02)00054-1

[13] Naebe, M., & Abolfathi, N. (2021). Thermo-mechanical behavior of fiber-reinforced polymer composites under elevated temperatures: A review. *Composites Part B: Engineering*, 224, 109152. https://doi.org/10.1016/j.compositesb.2021.109152

[14] Wang, X., Zhang, Y., & Li, J. (2020). Thermo-elastic analysis of functionally graded rotating disks subjected to temperature-dependent loading. *International Journal of Mechanical Sciences*, 170, 105351. https://doi.org/10.1016/j.ijmecsci.2019.105351

[15] Fiore, V., Calabrese, L., & Valenza, A. (2011). Effects of temperature on the mechanical behavior of basalt fiber–reinforced composites. *Materials & Design*, 32(4), 2091–2099. https://doi.org/10.1016/j.matdes.2010.11.047

[16] Manalo, A. C., Karunasena, W., & Lau, K. T. (2013). Thermal and mechanical responses of GFRP composite structures: Experimental and numerical assessment. *Composite Structures*, 103, 32–41. https://doi.org/10.1016/j.compstruct.2013.03.015

[17] Zhang, L., Zhou, Q., & Sun, H. (2023). Machine-learning-based prediction of thermal stress fields in composite disks. *Engineering Structures*, 287, 116084. https://doi.org/10.1016/j.engstruct.2023.116084

[18] Kumar, S., Singh, A., & Patel, R. (2022). Deep learning-assisted thermo-elastic analysis of rotating FGMs: A hybrid numerical approach. *Composite Structures*, 296, 115871. https://doi.org/10.1016/j.compstruct.2022.115871

[19] Luo, Z., Chen, P., & Wei, Y. (2024). Neural network modeling of anisotropic composite cylinders under coupled thermal–mechanical loading. *Composite Science and Technology*, 245, 110404. https://doi.org/10.1016/j.compscitech.2023.110404

[20] Barari, A., Mirzaei, H., & Shojaei, A. (2022). Hybrid numerical–ML frameworks for predicting deformation fields in rotating composite components. *Mechanics of Advanced Materials and Structures*, 29(18), 3223–3235. https://doi.org/10.1080/15376494.2021.1885417

[21] Saghafi, H., Ranjbar, M., & Esfahanian, M. (2023). Data-driven optimization of composite rotating disks under thermal gradients: A machine-learning approach. *Applied Mathematical Modelling*, 114, 1–16. https://doi.org/10.1016/j.apm.2022.10.022