





## Research Article

# Enhancing the mechanical performance of perforated steel plates through fiber-reinforced composite reinforcement: A finite element analysis study

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## ABSTRACT

Reinforced concrete and steel plates are widely used in civil engineering and are important components of many structural systems and ground reinforcement projects. These plates effectively carry different loads, enhance ground support, and improve the durability of structures. Moreover, the proper selection and use of these materials during the design and planning stages of construction projects have a direct impact on cost and time efficiency. In addition to their structural contributions, the effective use of reinforced concrete and steel plates is critical for the safety and success of construction projects. In order to transfer loads to the frame system, reinforced concrete plates serve as horizontal load-carrying components. Load-bearing capacity, stiffness, fire resistance, and sound insulation are important properties of reinforced concrete plates. Perforated plates are widely used in structural applications but suffer from stress concentration around openings, reducing their mechanical performance. This study investigates the reinforcement of perforated steel plates using fiber-reinforced polymer (FRP) composites around holes to enhance structural integrity. The research employs finite element analysis (FEA) to assess the effects of different reinforcement widths under varying loads. A detailed comparison of stress and deformation distributions before and after reinforcement is presented. The findings indicate that FRP reinforcement significantly reduces stress concentration and improves the load-bearing capacity of perforated plates, providing practical insights for industrial and construction applications.

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## 1. Introduction

Plates are structural elements characterized by their two-dimensional geometry, where their thickness is small relative to their other dimensions. They play critical roles in enhancing structural integrity in architectural applications, reinforced concrete and steel structures, the automotive industry, and various industrial sectors.

Perforated plates are widely used in engineering projects (Zhou 2016). These plates are components made of

metals, plastics, or fiber-reinforced composites with regularly or irregularly arranged holes on their surfaces.

Steel is one of the most commonly used metallic materials for perforated plates due to its strength, durability, and cost-effectiveness. Steel perforated plates are resistant to impact, abrasion, and harsh environmental conditions, making them suitable for demanding applications in industries such as construction, automotive, and manufacturing. The high tensile strength of steel allows for the creation of plates with various hole sizes and patterns without compromising structural integrity. Moreo-

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ver, steel is easily formable and manufacturable, enabling customization to meet specific design requirements.

Composite structures are often used in many areas due to their lightweight nature and adaptability to changing mechanical conditions (Demir 2024; Sunar and Uysal 2024). Using composites called fiber-reinforced polymers, obtained by combining fibers with high-strength proper-ties with the help of epoxy resin, has become widespread in the last twenty years. Carbon fiber is a lightweight and high-strength reinforcement material commonly used in advanced composite materials. Carbon fiber composites exhibit exceptional strength-to-weight ratios, stiffness, and resistance to temperature variations (Hou et al. 2025). Compared to traditional materials such as steel or aluminum, these composites offer superior mechanical properties. Carbon fiber is widely utilized in industries such as aerospace, automotive, wind energy, sports equipment, and high-performance engineering. The use of carbon fiber composites helps reduce the weight of structures without compromising strength, making them an ideal choice for applications where weight reduction is critical (Tarhan et al. 2025; Xie et al. 2020).

Durability is a critical factor to consider when selecting perforated plates. The strength of a plate determines its ability to withstand loads and forces without deformation or failure. Plates with higher strength can support heavier loads and provide increased structural stability, making them suitable for demanding applications. The strength of a plate depends on various factors such as material composition, thickness, and manufacturing processes. To effectively meet the requirements of an application, careful attention must be given to the anticipated loads and forces the plate will encounter, ensuring the selection of a plate with adequate strength.

Reinforced concrete plates are structural elements that act as horizontal load-carrying components, transferring loads to the frame system. Key characteristics of reinforced concrete plates include load-bearing capacity, rigidity, fire resistance, and sound insulation. These plates are particularly suitable for spanning large distances and allow for the addition of extra layers to structures (Baş 2024).

Reinforced concrete plates are widely used in building floors. Additionally, they are frequently preferred in industrial facilities, bridge structures, water structures, and infrastructure projects. Due to their high strength and durability, they provide excellent solutions for spanning large distances and meeting various structural needs.

Steel plates are often made of high-strength steel alloys and are available in various thicknesses. These plates can be composed of carbon steel, stainless steel, or alloy steel, offering durability, high strength, and flexibility. These characteristics make steel plates widely applicable in civil engineering.

Steel plates are commonly used in load-bearing systems of large-span structures in civil engineering. Additionally, they are preferred for industrial facilities, infrastructure projects, bridges, viaducts, warehouses, crane beams, and high-rise buildings. Steel plates are also extensively applied in vehicle and train passageways (Demirel 2023).

Perforated plates, often made of steel, are structural components with regularly spaced holes that significantly reduce weight while maintaining flexibility and durability. These advantageous features make perforated plates highly effective and widely used in large-span structural elements and ground reinforcement applications. They are preferred in engineering designs for their combination of robustness and economic efficiency, contributing significantly to the construction industry (Caştur 2021).

Perforated plates are frequently used in ground reinforcement applications and large-span structural elements. They are also commonly applied in bridges, buildings, crane beams, and platforms that carry heavy loads. By reducing weight, they provide significant cost savings and offer greater flexibility and load-bearing capacity compared to solid steel plates. Their versatility, durability, and adaptability to various projects have made perforated plates indispensable in structural engineering (Yücesoy 2021).

This paper is prepared to examine the benefits of using fiber-reinforced composites, an innovative reinforcement method, to improve the strength of perforated plates. The goal is to enhance the performance of these plates and provide engineers and designers with more innovative and effective solutions for construction and industrial applications. Within this scope, a steel plate with a central hole was reinforced around the hole using fiber-reinforced polymer (FRP) composites of varying widths. The study investigates the effectiveness of these reinforcements made with composite materials to achieve higher performance in structural applications.

## 2. Materials and Method

Reinforced concrete and steel plates are commonly utilized in civil engineering and play significant roles in various structural systems and ground reinforcement works. In addition to their structural contributions, the effective use of reinforced concrete and steel plates is critical for the safety and success of construction projects. Their flexibility in engineering applications, as well as their adaptability to various climatic conditions and subsurface environments, make these materials invaluable in the field of engineering. The wide range of applications, the improvement in labor efficiency, and the acceleration of construction processes further highlight their significance (Seçkin 2022).

### 2.1. Composite materials

Composite materials have been gaining increasing popularity in both the industrial and construction sectors, a trend that continues to strengthen each year. Owing to their unique advantages and distinctive properties, many industries have started to favor the use of such materials. Composites, created by combining materials with different characteristics, are particularly notable for being lighter than metals and plastics. This quality enables composite materials to stand out in various applications.

Detailed investigations address topics such as the definition, properties, types, classification, advantages, and disadvantages of composites, supported by comprehensive research. These studies aim to provide extensive knowledge on how to utilize these materials most effectively in both theoretical and practical fields. For instance, composites are widely used in applications where both strength and lightness are required simultaneously. Therefore, their application in construction projects and engineering designs contributes to improving processes and final outcomes, enhancing safety standards, and significantly supporting the overall efficiency of projects.

Composite materials represent a type of material created through the combination of different components to produce a stronger and more durable result. They typically consist of a matrix material reinforced with a secondary material. The harmonious integration of these two components endows composite materials with superior characteristics, such as high strength, lightness, flexibility, and chemical resistance. These unique attributes make composites widely utilized across various sectors, including construction, aerospace, automotive, and sports. As a result, composite materials play a significant role in modern engineering designs and excel in diverse applications (Yilmaz and Vural 2018).

## 2.2. Strengthening of plates

Extensive research conducted in the fields of structural engineering and materials science on plate strengthening holds significant importance. Considering that enhancing the resistance and durability of structures substantially contributes to structural safety and extends their service life, this subject is of critical relevance. Such studies aim to develop various methods and techniques for reinforcing plates. Therefore, in-depth investigations into plate strengthening have the potential to improve the safety and longevity of structures while enriching the existing body of knowledge. These efforts are valuable not only in the field of engineering but also for offering environmentally sustainable outcomes.

The increasing number of studies on plate strengthening is enabling structures to become more resilient. This trend holds great importance not only in academic circles but also in industrial and practical applications. The results obtained from strengthening plates in engineering projects form the basis for the reliable and efficient performance of numerous structures. In this context, the development of innovative techniques and the improvement of existing methods for plate strengthening offer significant contributions to researchers and engineering professionals alike. As a result, projects aimed at enhancing structural durability and safety can be further advanced, laying the groundwork for sustainable engineering approaches.

Furthermore, the discovery of innovative methods in this domain serves the development of the construction sector, thereby paving the way for a healthier future from both economic and environmental perspectives. The strengthening of plates will remain a noteworthy field of research and application both now and in the future.

Plates, one of the fundamental components of a structure, are horizontal structural elements that bear and transmit loads. Proper support and reinforcement of plates are essential for ensuring structural integrity and durability. Since their primary function is to transmit and bear vertical loads, strengthening plates can enhance the long-term stability and performance of structures. The definition and importance of plates are fundamental topics for professionals in structural engineering and the construction sector, playing a critical role in effectively planning and implementing strengthening projects.

Strengthening plates offers numerous structural and economic advantages. Structural benefits include increased durability, enhanced resistance to earthquakes, and extended service life of structures. These advantages improve the safety of buildings and other structures, ensuring longer-lasting performance.

## 2.3. Numerical modelling

Finite element analysis (FEA) is a computerized method used to predict how a product reacts to real-world forces, such as mechanical stresses, vibrations, thermal fluctuations, fluid flow dynamics, and other physical effects. FEA enables engineers to simulate the behavior of complex structures and systems by creating a virtual model composed of finite elements. By applying loads, constraints, and boundary conditions, engineers can observe and analyze the impacts on a product's performance and durability. Over the years, FEA has proven to be an invaluable tool in the design and development of a wide range of products, including perforated trays, sieves, and gas-preventing mats. Its industry-specific and application-focused approach has revolutionized the way engineers address engineering challenges, providing efficient and optimized designs for various sectors (Chen et al. 2022; Abualigah et al. 2022).

In this study, a steel plate with a central hole was analyzed under three different force values: 1.5 kN, 2.0 kN, and 3.0 kN. The study considered both unreinforced and reinforced scenarios, with FRP layers of varying widths (40 mm, 50 mm, and 60 mm) applied symmetrically around the hole.

An advanced finite element method based software ANSYS were used to create and analyse the models. The material properties used in the numerical model are presented in Table 1. Determining the mesh size, Cheng and Zhao (2010) and Singh and Singh (2021) were taken into account and the similar modeling procedure in these studies was followed. Finite element analysis was performed to simulate the behavior of perforated steel plates under static loading.

## 3. Results and Discussion

In perforated plates, lateral buckling and stress accumulation are commonly observed problems. These issues reduce the load-carrying capacity of the plates and shorten their service life. Additionally, significant stress concentrations occur around the perforations. Reinforcement is critically important to address these weaknesses.

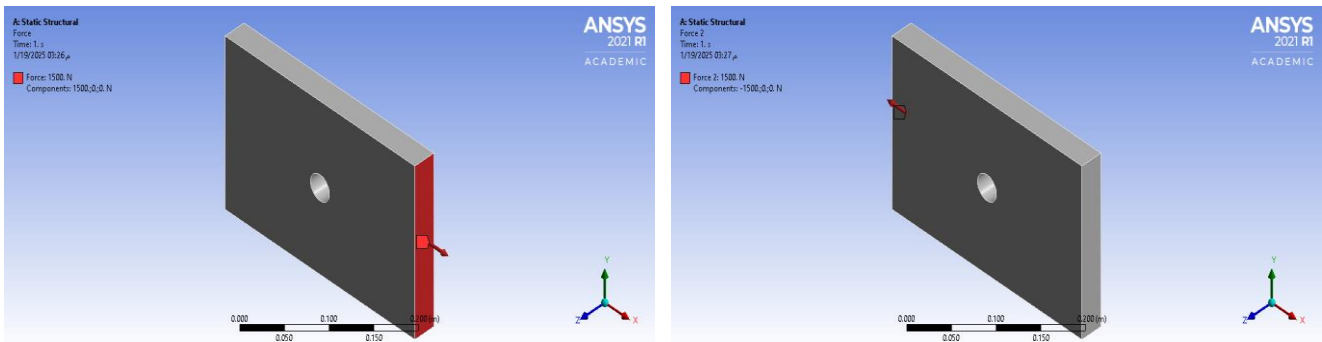
In this study, the effects of using fiber materials to enhance the mechanical strength of perforated plates were analyzed in detail. The analyses were conducted using the advanced finite element method (FEM)-based ANSYS software, evaluating critical mechanical parameters such as total deformation, equivalent stress (von-Mises stress). The primary objective of this study was to systematically investigate the extent to which the fiber material added around the perforation could improve the overall strength of the plate.

During the modeling process, the perforated plate was designed as a simple rectangular geometry with a length of 300 mm, a height of 200 mm, and a width of 30 mm. At the center of the plate, a circular perforation with a diameter of 30 mm was included.

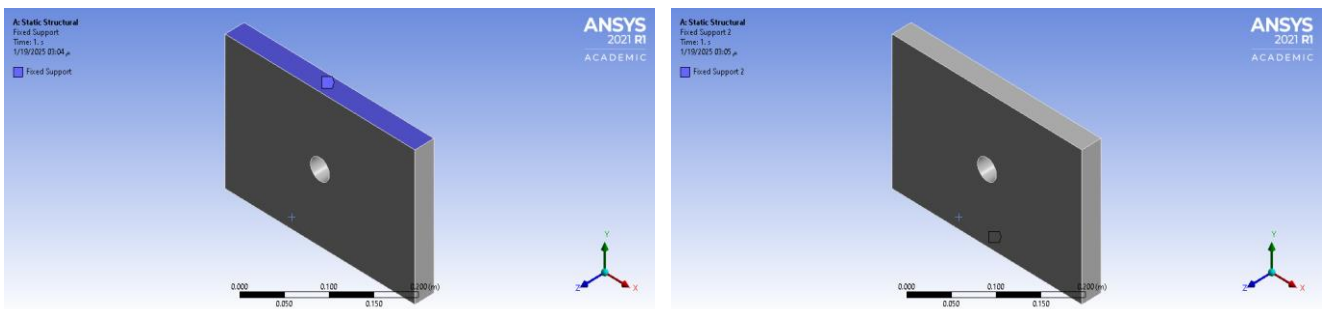
In the first stage, the behavior of the plate was analyzed before adding the composite material using three different forces 1.5, 2.0, and 3.0 kN as shown in Fig. 1. The plate was fixed from the top and bottom with a fixed support as shown in Fig. 2, and the analysis results obtained for each load value are given in Figs. 3–5, respectively.

**Table 1.** Material parameters used in modelling.

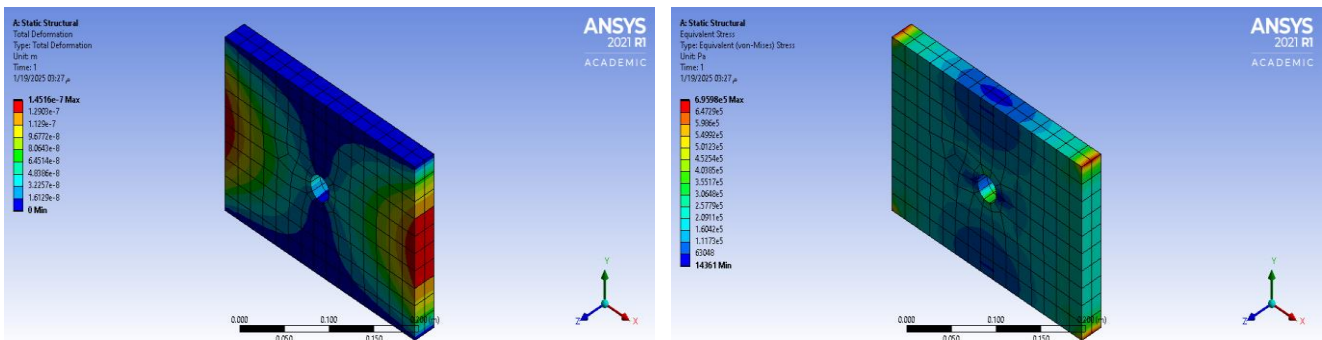
Material	Unit volume weight (kg/m <sup>3</sup> )	Modulus of elasticity (Pa)	Poisson's ratio (-)
FRP composites	1600	2.30e+11	0.30
Structural steel	7850	2.00e+11	0.28



**Fig. 1.** Force applied from the right and left sides (1.5, 2.0 and 3.0 kN applied respectively).



**Fig. 2.** Fixed support at the top and lower sides.



**Fig. 3.** Total deformation and equivalent stress distribution (1.5 kN).

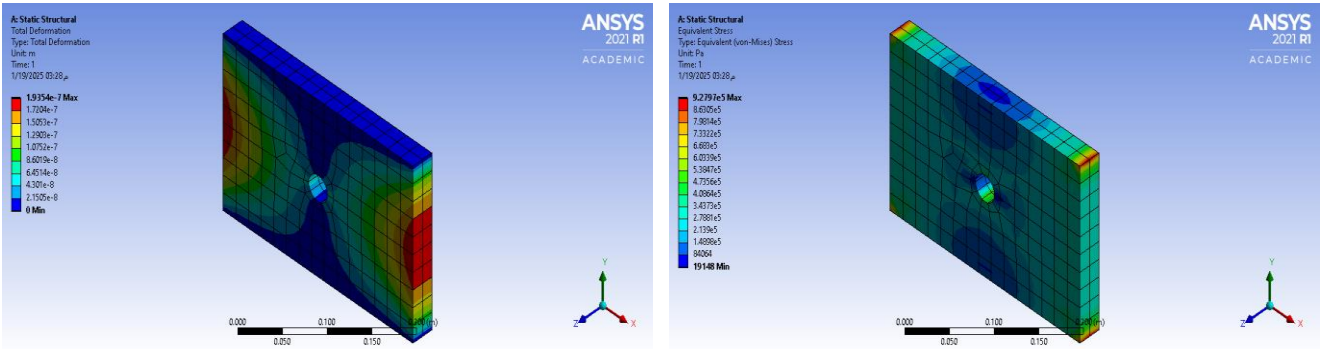


Fig. 4. Total deformation and equivalent stress distribution (2.0 kN).

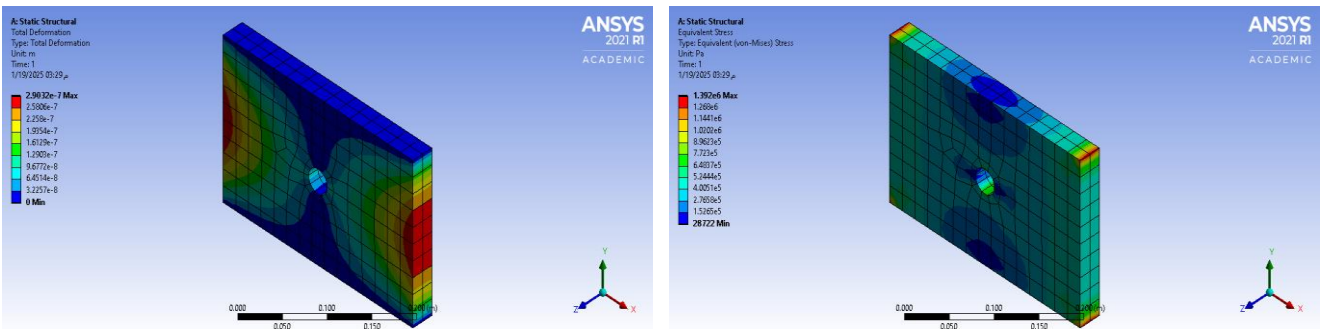


Fig. 5. Total deformation and equivalent stress distribution (3.0 kN).

In second case, carbon fiber reinforced composite material in varying widths was used for the plate ( $40 \times 200 \text{ mm}^2$ ,  $50 \times 200 \text{ mm}^2$  and  $60 \times 200 \text{ mm}^2$ ). Loads of 1.5, 2.0, and 3.0 kN were applied to both the right and left edges, respectively. Loads of 1.5, 2.0, and 3.0 kN were applied to both the right and left edges, respectively as shown in

Fig. 6, and a fixed support was added to the upper and lower edges as shown in Fig. 7.

The results were obtained by linear static analysis using ANSYS software. The total deformation and equivalent stress (von Mises) distribution resulting from the analysis are shown in Figs. 8–16.

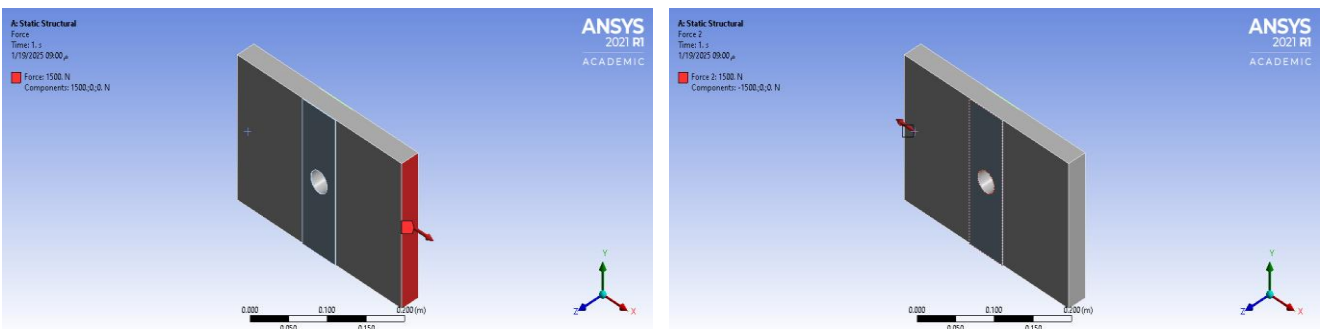


Fig. 6. Force applied from the right and left sides (1.5 kN).

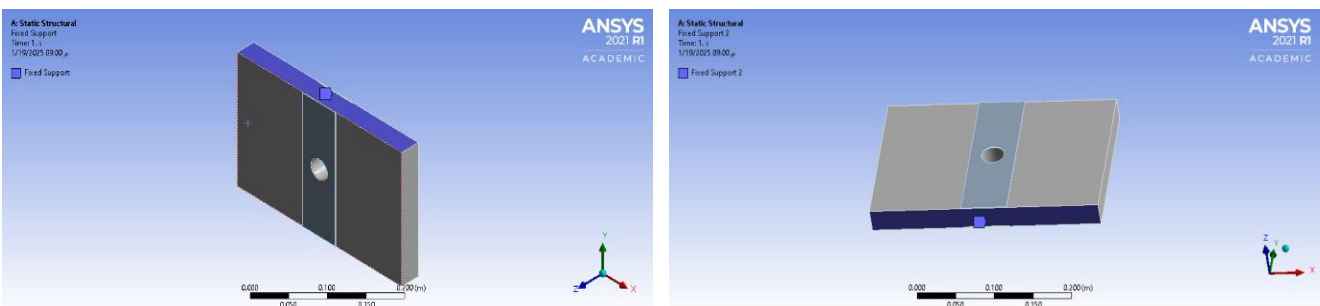


Fig. 7. Fixed support at the top and lower sides.

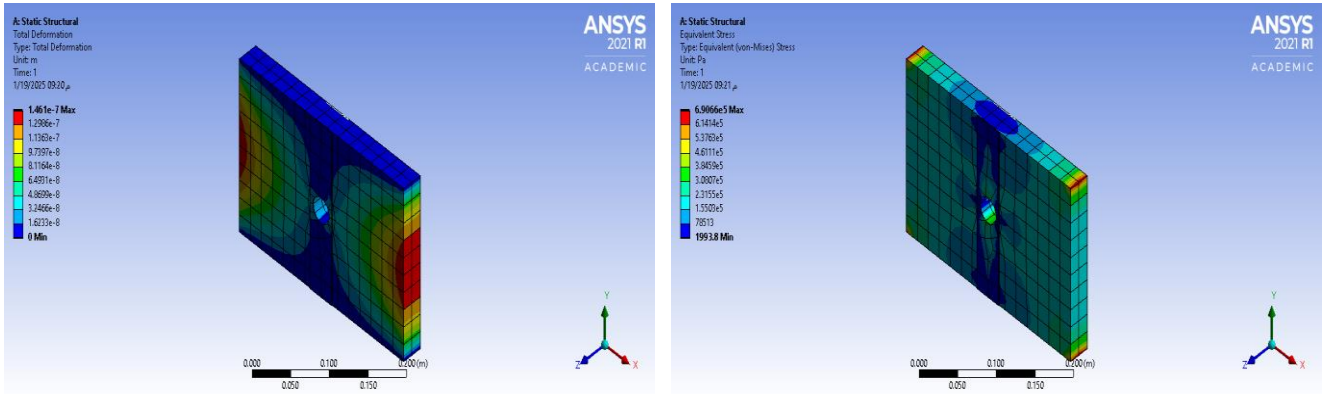


Fig. 8. Total deformation and equivalent stress distribution (FRP=40×200 mm<sup>2</sup> and F=1.5 kN).

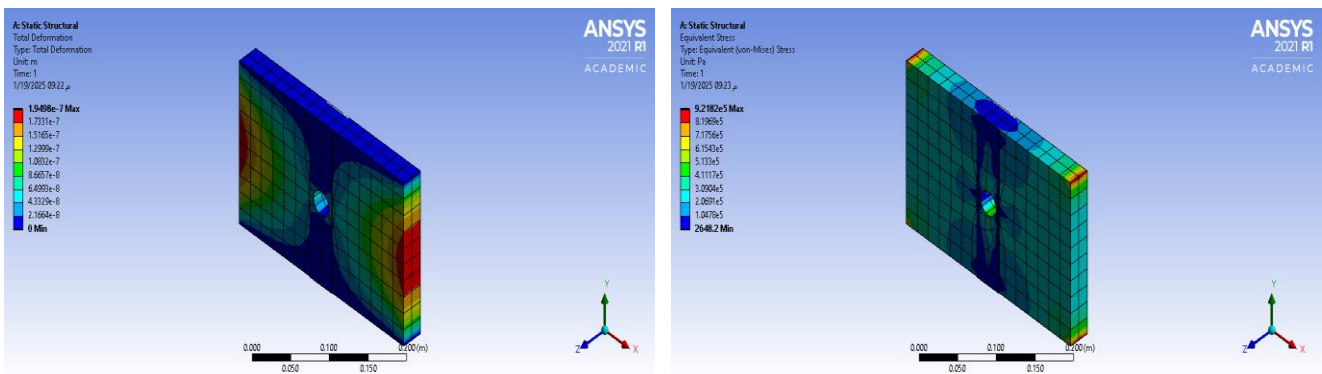


Fig. 9. Total deformation and equivalent stress distribution (FRP=40×200 mm<sup>2</sup> and F=2.0 kN).

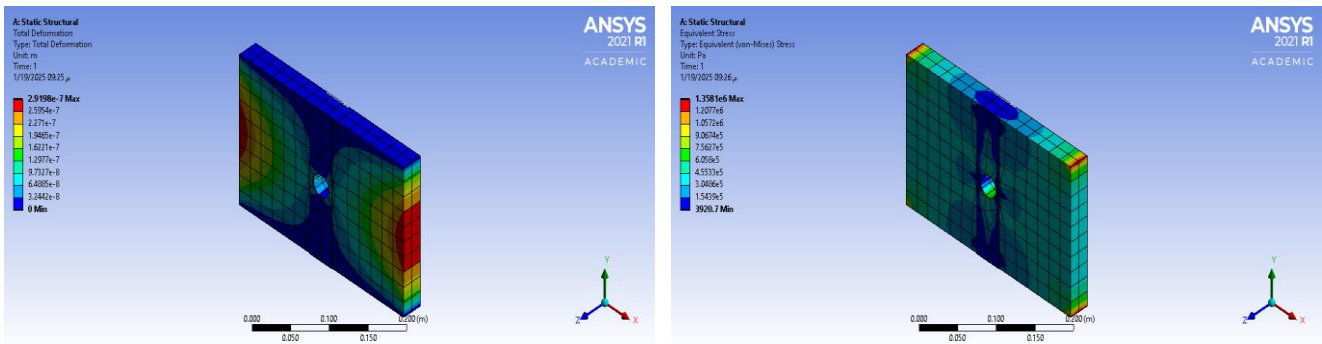


Fig. 10. Total deformation and equivalent stress distribution (FRP=40×200 mm<sup>2</sup> and F=3.0 kN).

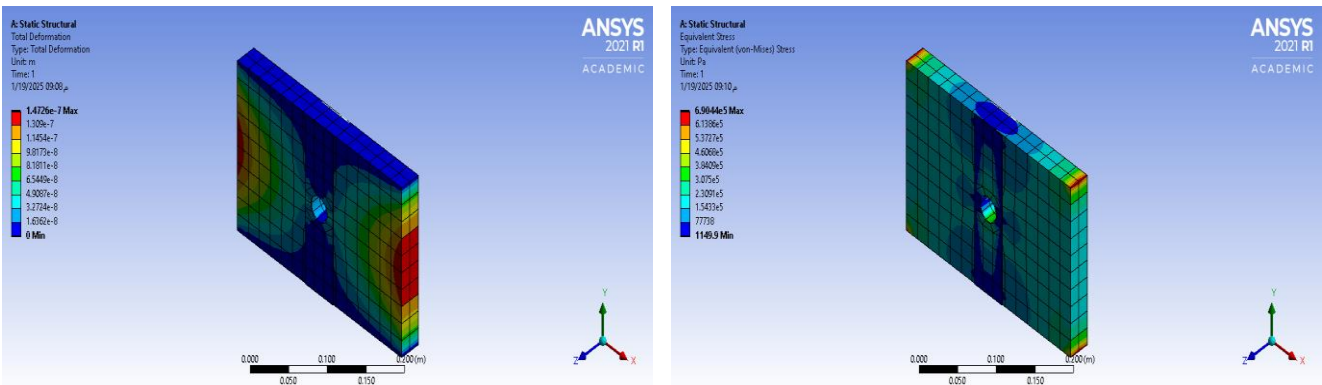


Fig. 11. Total deformation and equivalent stress distribution (FRP=50×200 mm<sup>2</sup> and F=1.5 kN).

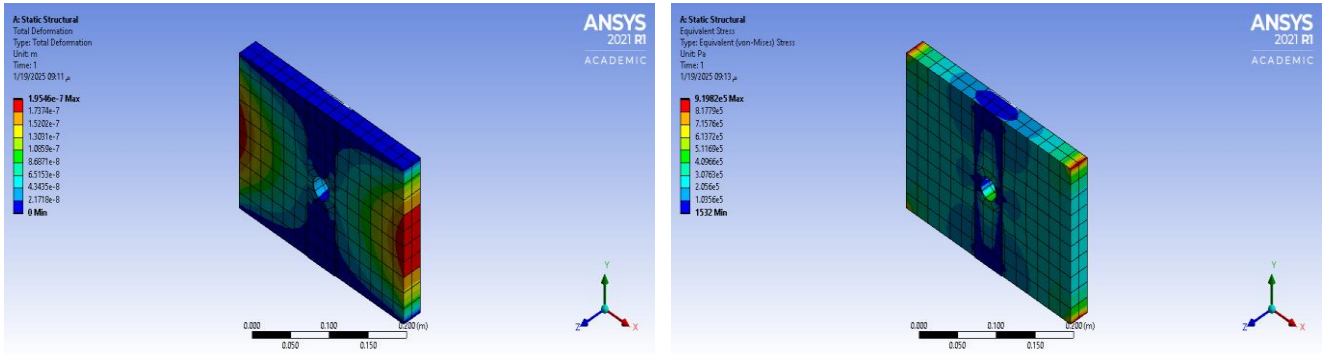


Fig. 12. Total deformation and equivalent stress distribution (FRP=50×200 mm<sup>2</sup> and F=2.0 kN).

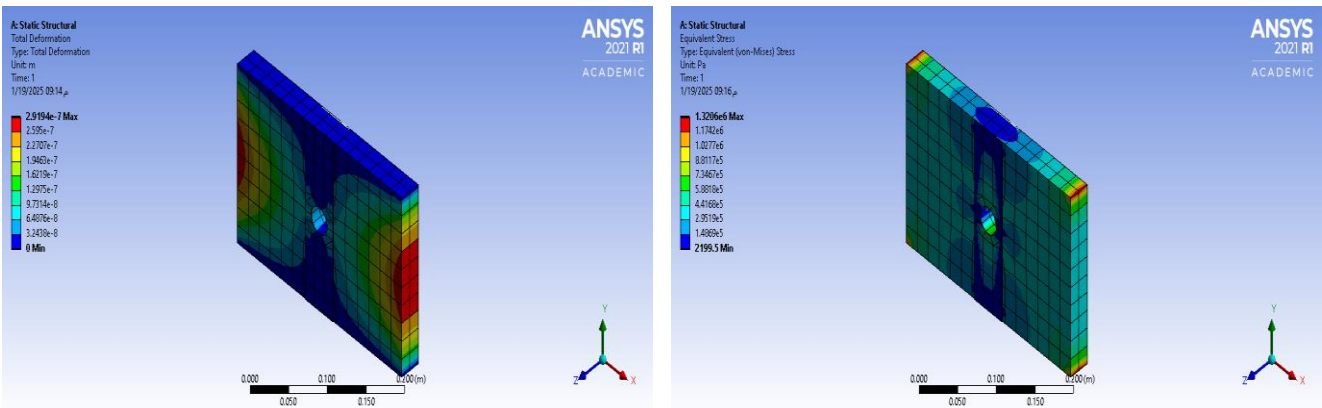


Fig. 13. Total deformation and equivalent stress distribution (FRP=50×200 mm<sup>2</sup> and F=3.0 kN).

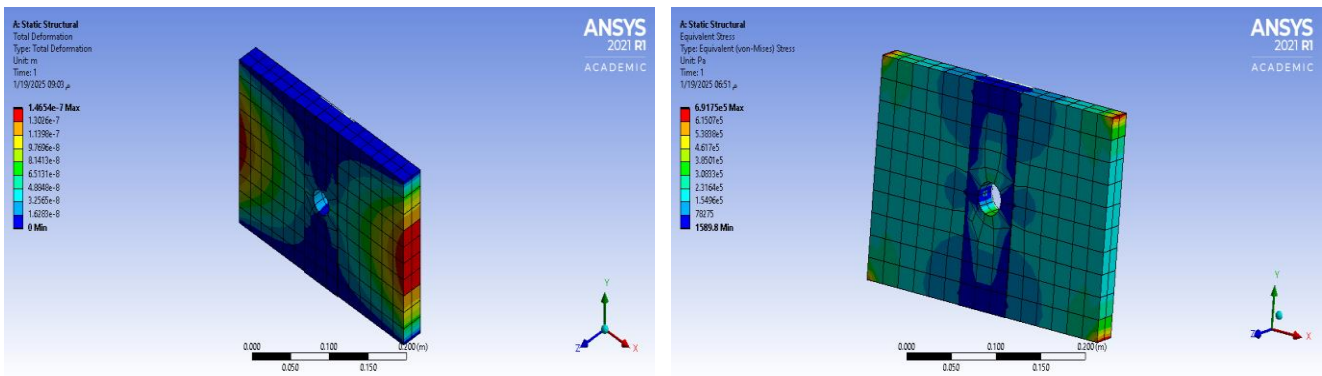


Fig. 14. Total deformation and equivalent stress distribution (FRP=60×200 mm<sup>2</sup> and F=1.5 kN).

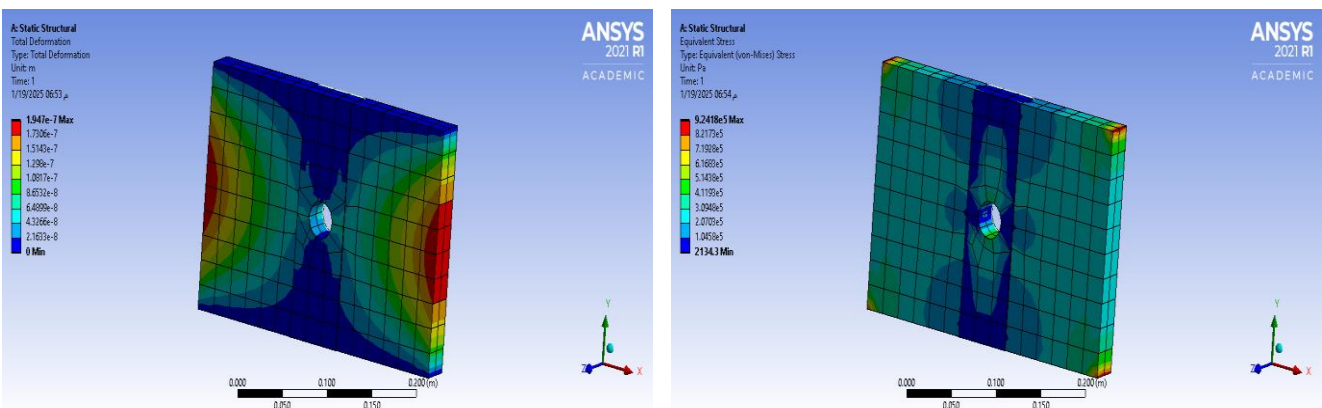
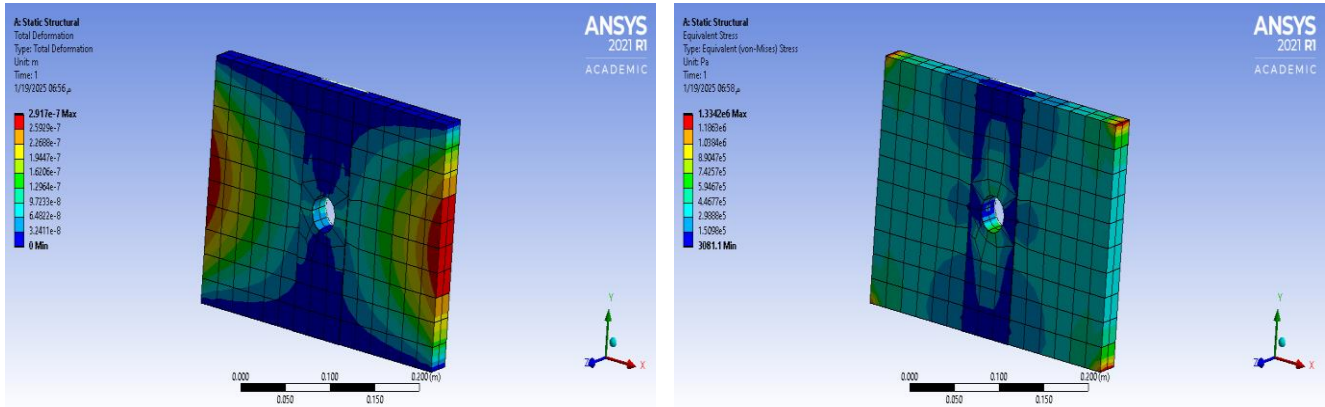


Fig. 15. Total deformation and equivalent stress distribution (FRP=60×200 mm<sup>2</sup> and F=2.0 kN).



**Fig. 16.** Total deformation and equivalent stress distribution (FRP=60×200 mm<sup>2</sup> and F=3.0 kN).

Figs. 3–5 illustrate the stress concentration and deformation in the unreinforced plate under different load conditions. The results confirm that stress accumulation is highest around the hole, leading to significant structural weakening.

Figs. 8–16 present the deformation and stress distribution in the reinforced plates for different reinforcement widths. The results demonstrate a clear improvement in load-bearing capacity, with stress concentration

significantly reduced as the reinforcement width increases.

Table 2 shows the change in total deformation and equivalent stress values before and after reinforcement by the composite material.

Figs. 17–19 show the linear relationship between the stress and total deformation values induced by the applied force for the cases before and after the addition of the composite material.

**Table 2.** Evaluation of the reinforcement effect.

Parameters		Before fiber reinforcement	After fiber reinforcement	Change (%)	
FRP=40×200 mm <sup>2</sup>	F=1.5 kN	Total deformation (m)	1.45e-07	1.46e-07	+0.69
		Equivalent stress (Pa)	6.95 e05	6.90 e05	-0.72
	F=2.0 kN	Total deformation (m)	1.93e-07	1.95e-07	+1.04
		Equivalent stress (Pa)	9.27 e05	9.22 e05	-0.54
	F=3.0 kN	Total deformation (m)	2.90e-07	2.92e-07	+0.69
		Equivalent stress (Pa)	1.39 e06	1.35 e06	-2.88
FRP=50×200 mm <sup>2</sup>	F=1.5 kN	Total deformation (m)	1.45e-07	1.47e-07	+1.38
		Equivalent stress (Pa)	6.95 e05	6.90 e05	-0.72
	F=2.0 kN	Total deformation (m)	1.93e-07	1.95e-07	+1.04
		Equivalent stress (Pa)	9.27 e05	9.20 e05	-0.76
	F=3.0 kN	Total deformation (m)	2.90e-07	2.92e-07	+0.69
		Equivalent stress (Pa)	1.39 e06	1.32 e06	-5.04
FRP=60×200 mm <sup>2</sup>	F=1.5 kN	Total deformation (m)	1.45e-07	1.46e-07	+0.69
		Equivalent stress (Pa)	6.95 e05	6.91 e05	-0.58
	F=2.0 kN	Total deformation (m)	1.93e-07	1.95e-07	+1.04
		Equivalent stress (Pa)	9.27 e05	9.24 e05	-0.32
	F=3.0 kN	Total deformation (m)	2.90e-07	2.92e-07	+0.69
		Equivalent stress (Pa)	1.39 e06	1.33 e06	-4.32

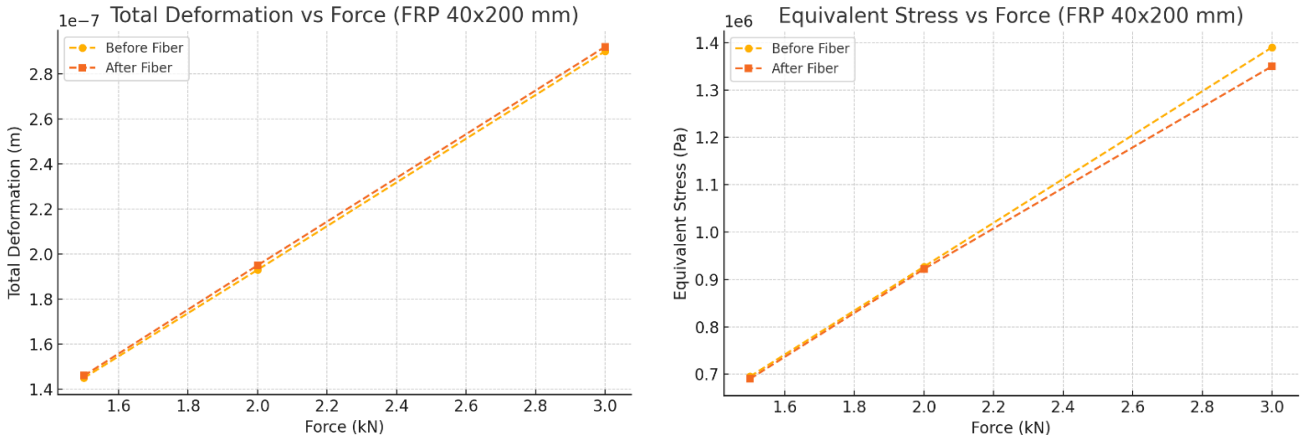


Fig. 17. Total deformation and equivalent stress graph (FRP=40×200 mm<sup>2</sup>).

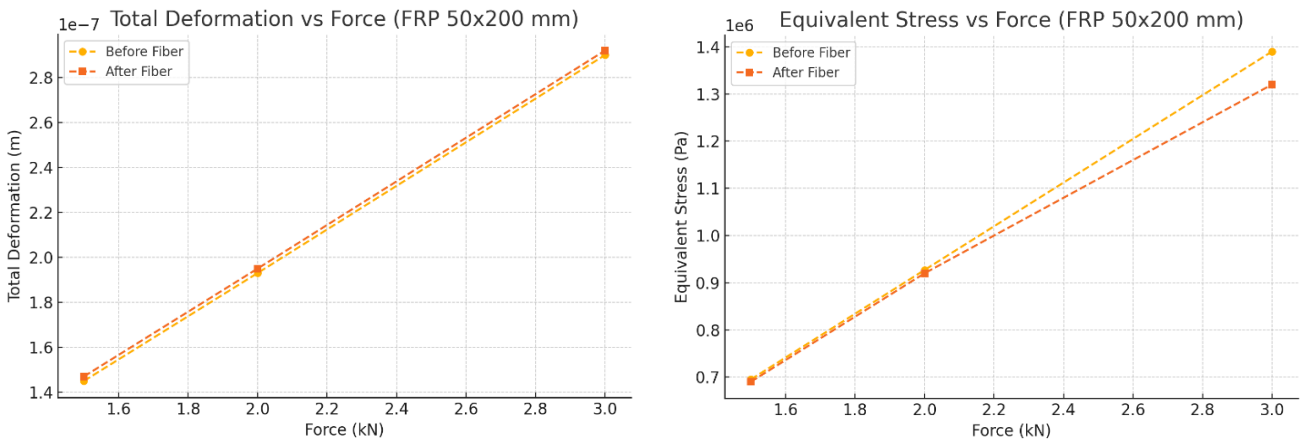


Fig. 18. Total deformation and equivalent stress graph (FRP=50×200 mm<sup>2</sup>).

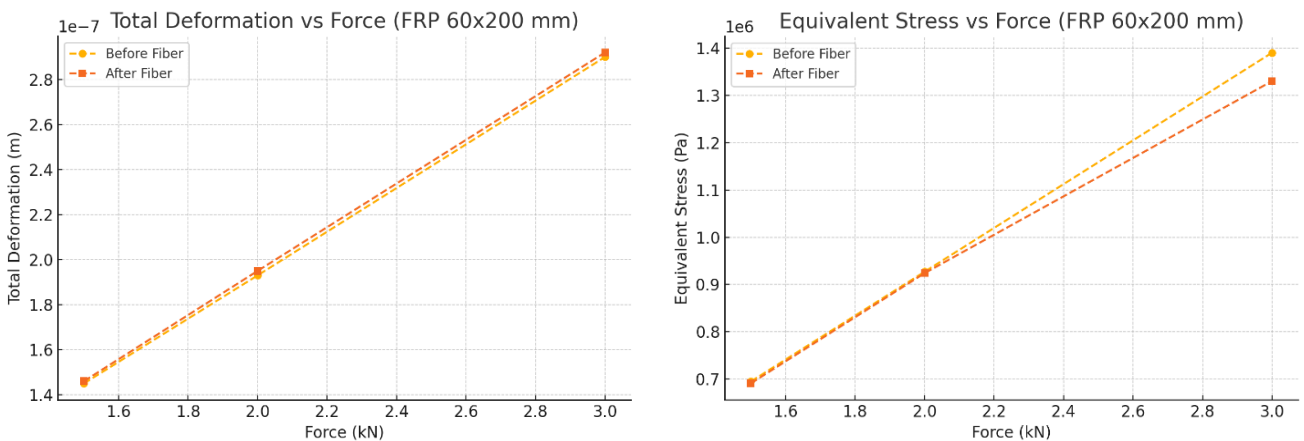


Fig. 19. Total deformation and equivalent stress graph (FRP=60×200 mm<sup>2</sup>).

Under forces of 1.5, 2.0, and 3.0 kN applied laterally, the unreinforced plate exhibited significant deformation and stress concentrations around the perforation. The stress distribution highlighted areas of high von Mises stress around the circular hole, reducing the load-bearing capacity of the plate. The addition of FRP material symmetrically around the hole significantly enhanced the mechanical performance of the plate. Compared to the unreinforced scenario, the reinforced plate showed reduced stress concentrations. This improvement was consistent across all loading conditions. The effective-ness of the re-

inforcement was evident from the comparison of deformation and stress distributions between the reinforced and unreinforced plates.

According to obtained results the FRP reinforcement mitigated stress concentrations and improved the plate's ability to distribute loads more evenly, enhancing structural integrity. The comparative analysis demonstrated that the FRP material contributed to a substantial reduction in von Mises stress, particularly under higher loads (3.0 kN). This indicates the potential of FRP reinforcements in extending the lifespan and reliability of perforated plates.

## 4. Conclusions

This study examined the effects of reinforcing a perforated steel plate with fiber-reinforced polymer (FRP) composites around the perforation to improve its structural performance. Critical mechanical parameters such as total deformation and equivalent stress (von Mises stress) under varying loading conditions were evaluated by finite element analysis (FEA) performed with ANSYS software.

This study demonstrates that reinforcing perforated steel plates with FRP significantly reduces stress concentration, thereby improving structural integrity. The findings provide valuable insights for engineers and designers in optimizing reinforcement strategies for practical applications in construction and industrial settings.

The results emphasize the importance of reinforcement in extending the service life of structural elements subjected to mechanical stress. By distributing loads more effectively, FRP materials reduce the risk of localized failure, ensuring more durable and reliable performance over time. This is particularly relevant for industries such as aerospace, automotive, and civil engineering, where lightweight yet strong materials are essential for efficient structural performance.

Future research could further explore experimental validation of the findings by conducting physical load tests on reinforced perforated plates. Moreover, studying the long-term durability of FRP reinforcements under dynamic and cyclic loading conditions will provide deeper insights into their practical applications. Investigations into alternative reinforcement configurations and fiber orientations could also enhance the effectiveness of strengthening techniques.

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### Conflict of Interest

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

### Author Contributions

All of the authors made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; were involved in drafting the manuscript or revising it critically for important intellectual content; and gave final approval of the version to be published.

### Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

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