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ORIGINAL CONTRIBUTION

Design and Analysis of Carbon Reinforced Composite Plate for Robotic Omni-Wheel: Replacement of Costly Metals

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Abstract The plates of the Omni wheel on which rollers are mounted are made of different materials like Polymers as nylon or metals like Aluminum these materials the ratio of providing strength according to its weight is significantly less. The plate material should be selected to withstand the respective robot's total weight. So in this regard, the Carbon fiber reinforced polymer plate is designed for Omni wheel plates are used. The hand lay-up method is used to manufacture composite plates with matrix material as epoxy resin and sandwich material is used Lantor coremat. The bending tests were performed, and the maximum bending strength achieved was approximately 2.2 KN. The theoretical calculations reveal that the induced bending stress is 209.18 N/mm^2, while the experimental results indicate that the permissible bending stress is 234.37 N/mm^2. Analysis was performed using ANSYS on the assembled carbon fiber robotic omni wheel. The analysis showed that the neck region and the upper face of the teeth of the wheel experienced the most significant deformation. Based on the bending test and simulation results, the carbon fiber plate is the best alternative material for the robotic omni wheel.

Keywords Carbon fiber · Robotic Omni wheel · Bending test · Simulation results

Abbreviations

Rn	Reaction on the wheel
U	Coefficient of friction
r	Radius of a wheel
σb	Induced and permissible bending stress
z	Section modulus
Iyy	Moment of inertia about bending axis

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Introduction

Robotic Omni wheel drive is a holonomic drive that can easily rotate in any direction. Omni wheels consist of small discs and rollers mounted around the circumference perpendicular to the turning direction [1]. For many industrial applications, Carbon fiber-reinforced thermoplastic polymers are an optimistic composite [2, 3]. Among the fascinating carbonaceous materials, carbon fiber has superior mechanical qualities and the highest level of chemical stability. Carbon fibers are typically defined as materials with a carbon content of greater than 92% by weight that form a fibrous shape. Additionally, carbon fibers offer self-lubricating qualities and high thermal resilience, which enhance the robustness and tribological characteristics of polymer-reinforced composites [4]. Combining cellulose and carbon materials can further adjust the microstructure of the composite [5]. Carbon fiber-reinforced polymer has excellent specific strength, stiffness, and fatigue properties compared to commonly used metals [6]. The fields where the integration of lightweight, high strength and excellent conductivity are required are military, aerospace, and defense; thus, Carbon nanotube-reinforced (CNF) polymer matrix composites can possibly be used [7]. Conducting filler-containing polymer composites are limited because they may become brittle under specific loading conditions. Researchers studying polymer composites are interested in carbon nanotubes (CNTs) because of their mechanical and tribological characteristics. The van der Waals forces between carbon nanotubes and the polymer matrix interface may

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significantly improve the interaction [8, 9]. The specimen's bending, tensile, and compressive strengths are increased by 14, 36, and 30%, respectively, filled with 3 wt% used CaCO3 composite [10, 11]. The strength and flexural modulus were enhanced by adding very low cellulose nanofiber. Tested the intervention is a very low CNF (~ 1 wt%) strengthened epoxy resin matrix (epoxy CNF) composite. Carbon fiber composites' kinking, buckling, and delamination behaviors Tested the intervention is carbon/glass mixed thermoplastic epoxy composite rods [12]. Polymer-based composite materials will be used for actuators and various mechatronic components. The conventional materials of stepper motors and rotary joints of robots are replaced with polymer-based composite materials [13]. Green, ultra-high-performance, fiber-reinforced cementitious composites (GUSMRC) are most suitable for robotics structural applications due to their excellent mechanical properties [14].

Polymer composites derived from two-dimensional graphene are an eco-friendly manufacturing technology. The numerous applications of this material include aerospace and robotics [15]. The superelastic effect and shape memory effect are popular characteristics in robotic actuator design principles. Shape memory technology is most significant in designing soft robotics [16]. To control vibration in structures, viscoelastic damping treatment is the most effective solution regarding the material characterization, modeling, and optimization of robotics [17]. A linear equation solver is used in finite element modeling applicable to manufacturing operations. The parallel solution is integrated into previously developed three-dimensional finite element computer software for issues such as large deformations, contact expansion, or electrical and thermal fields [18].

The developed omni-wheeled mobile robot efficiently provides locomotion to the required position and follows a controlled trajectory relative to the referenced trajectory by maintaining a minimum error [19]. The motion analysis of the robot is compared with other literature on the same workspace conditions. Due to the unexpected uncertainties, the policy studied earlier under simulation environments is converted to real robots [20]. Holonomic and omnidirectional locomotion systems can operate in any random direction without affecting their belonging position and alignment with 3 Degree of freedom mobility [21]. Omnidirectional wheeled mobile robots are popular because they can move in any direction [22]. Introduces the concept of compact omnidirectional mobile robots, discusses the specific wheel arrangement proposed by the authors, presents experimental results comparing the proposed arrangement with a conventional one, and highlights the potential advantages of the proposed arrangement for industrial transport robots [23, 24].

Based on the literature studies, there is scope for developing carbon fiber for use in robotic omnidirectional wheels. The objective of this work is to manufacture a carbon fiber composite plate for a robotic omnidirectional wheel drive using the hand layup process. Theoretical and experimental comparisons will be performed to validate the bending stress and assess the feasibility of using a carbon fiber plate for the robotic wheel. An ANSYS simulation of the manufactured plate will be conducted to identify the regions where maximum deformation occurs.

Materials and Methods

Carbon fibers have a modulus of elasticity ranging between 200 to 800 GPa. The ultimate elongation is 0.3–2.5 %, where the lower elongation relates to the higher stiffness and is inverse. Carbon fibers are not affected by water and are more durable against many chemical liquids. They provide good resistance to fatigue loads, neither show any creep nor relaxation and do not rust easily [25]. The hand lay-up process for carbon fiber composites involves manually placing carbon fiber fabric or pre-preg sheets in a mold, then applying resin and consolidation, as shown in Fig. 1. Cleaned the mold surface and applied a release agent to prevent the composite from sticking to the mold. The first carbon fiber fabric or pre-preg sheet layer was placed onto the prepared mold surface. Smooth out any wrinkles or air bubbles using a brush or roller. Ensured that fabric was thoroughly wetted with resin but not overly saturated. Continued layering the carbon fiber fabric or pre-preg sheets one by one, applying resin between each layer for fabric [26]. For pre-preg sheets, no additional resin is required between layers. Kept the mold at a specific temperature for a specified time or allow it to cure at room temperature. After curing the composite, carefully remove the mold. Trimmed any excess material or surfaces

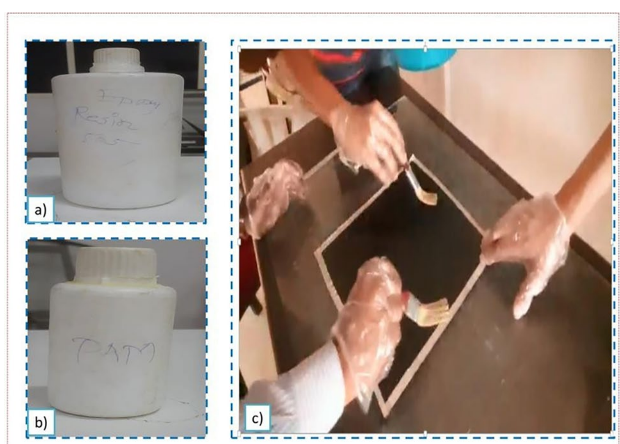


Fig. 1 Hand-layup Process: **a** Matrix material, **b** hardner, **c** Lay-up process

Fig. 2 **a** Carbon fiber sheet, **b** Carbon fiber material, **c** Coremat material, **d** Matrix material

to achieve the desired final shape and finish. The manufactured carbon fiber composite is shown in Figure 2a.

Reinforcement Material

The reinforcement material used 400 GSM -12 K Bi-directional Plain Woven Carbon Fabric, continuous type fiber reinforcement, as shown in Figure 2b. We selected this type of reinforcement due to its unique properties. When cured after impregnation with resin, it becomes stiff or of good strength. The detailed specification of the carbon fiber is shown in Table 1.

Table 1 Specification of carbon fiber

Specification of reinforcement	
Areal weight	400 (g/m^2)
Standard width	1000 (mm)
Dry fabric thickness	0.42 (mm)
Density	1.8 (g/cc)
Filament diameter	7 (μm)
Tensile strength	4000 (MPa)
Tensile modulus	240 (GPa)

Sandwich Material

The sandwich material is used Lantor Coremat Xi is a sandwich material, as shown in Fig. 2c. It is a polyester nonwoven and suitable for all similar types of resins, consisting of Polyester, Vinylester, Phenolic, and Epoxy. It is compatible with hand lay-up and spray-up processes. The detailed specification of the matrix material is shown in Table 2.

Table 2 Specification of Coremat material

Specification of sandwich material	
Thickness (mm)	3
Dry weight (g/m^2)	80
Resin uptake (kg/m^2)	1.8
Flexural modulus (MPa)	1100
Shear modulus (MPa)	35

Matrix Material

The matrix material used as thermosetting polymer Matrix is an epoxy Resin 505 for making these Carbon Fiber Plates, as shown in Fig. 2d. We use a Hardener name as PAM, which is mixed with resin. Epoxy Resin 505 is also known as a moderate viscosity liquid Epoxy Resin consists of reactive diluents [27]. The resin can withstand mechanical and chemical characteristics in the cured state with good pigment and fiberglass cloth wetting. The detailed specification of the matrix material is shown is Table 3.

Carbon Fiber Composite Robotic Omini Wheel

The Omni wheel is a robotic wheel that offers unique capabilities and enhanced maneuverability compared to conventional wheels. It is designed to move in any direction, including forward, backward, sideways, and even rotate in place. Figure 3a, b CAD model of Carbon fiber and Robotic Omini wheel with carbon fiber plate. The Omni wheel is a regular wheel with additional small rollers attached around its circumference. When the rollers move in the same direction, the wheel moves forward or backward like a regular wheel [28]. However, the Omni wheel can move sideways or around its axis by varying the roller speeds and directions. This unique movement capability makes the Omni wheel well-suited for applications requiring precise maneuverability, such as robotic platforms, autonomous vehicles, and material handling systems. Figure 3e shows the Assemble Carbon fiber Omini wheels to the vehicle. It allows for smooth and efficient navigation in tight spaces and the ability to change direction quickly [29]. The Omni wheel has applications in various fields, including manufacturing, logistics, robotics research, and even entertainment, where it is used in robotic toys and exhibits. Its versatility and ability to move in any direction make it a valuable tool for engineers and designers seeking innovative solutions for mobility challenges. Figure 3c, d shows the actual Carbon fiber plate assembled to Omini Wheel.

Table 3 Specification of Matrix material

Specification of matrix material	
Density at 27 °C of resin (g/cc)	1.0–1.150
Density at 27 °C of hardener	0.900–0.950
Mixing ratio	100:10
Pot life of 500 gm mix	10–15(min)
Volumetric shrinkage (%)	%1.%2 ax

Result and Discussions

Theoretical Calculations

$$\text{Bending moment on wheel assembly} = (\text{Rn} \times \text{u}) \times \text{r}$$

$$\text{Reaction on wheel(Rn)} = \text{Overall weight of } robot/4$$
$$340/4 = 85\ \text{N}$$

$$\text{Coefficient of friction between dry rubber\&plywood} = 0.7$$

$$\text{Radius of Wheel(r)} = 60\ \text{mm.}$$

$$\text{Bending moment on wheel assembly} = (85 \times 0.7) \times 60$$
$$= 3570\ \text{N.mm}$$

$$\text{Bending moment acts on 1 plate} = 3570/4$$
$$= 892.5\ \text{N.mm}$$

$$\text{Induced bending stress}(\sigma \text{b})$$
$$= \text{Bending moment acts on one plate}/section\ \text{modulus}$$

$$\text{Section modulus(Z)}$$
$$= \text{Moment of inertia about bending axis}/\text{radius of wheel}$$

$$\text{Moment ofinertiaabout bending axis(IYY)}$$
$$= \text{Diameter of plate} \times (\text{thickness of plate})^3/12$$
$$= 120 \times (4)^3/12$$
$$= 640\ \text{mm}^4$$

(By considering 60%of material removal from solid rectangular plate)

$$\text{Actual moment of inertia about bending axis(IYYact)} = 0.4 \times \text{I}_{\text{YY}}$$
$$= 256\ \text{mm}^4$$

$$\text{Section modulus(Z)} = \text{I}_{\text{YYact}}/\text{y}$$
$$= 256/60$$
$$= 4.267\ \text{mm}^3$$

$$\text{Induced bending stress}(\sigma \text{b}) = 892.5/4.267$$
$$= 209.18\ \text{N/mm}^2$$

Experimental Result

By Performing 3-Point Bending Test, Breaking Load = 2000 N Breaking load = 2000 N

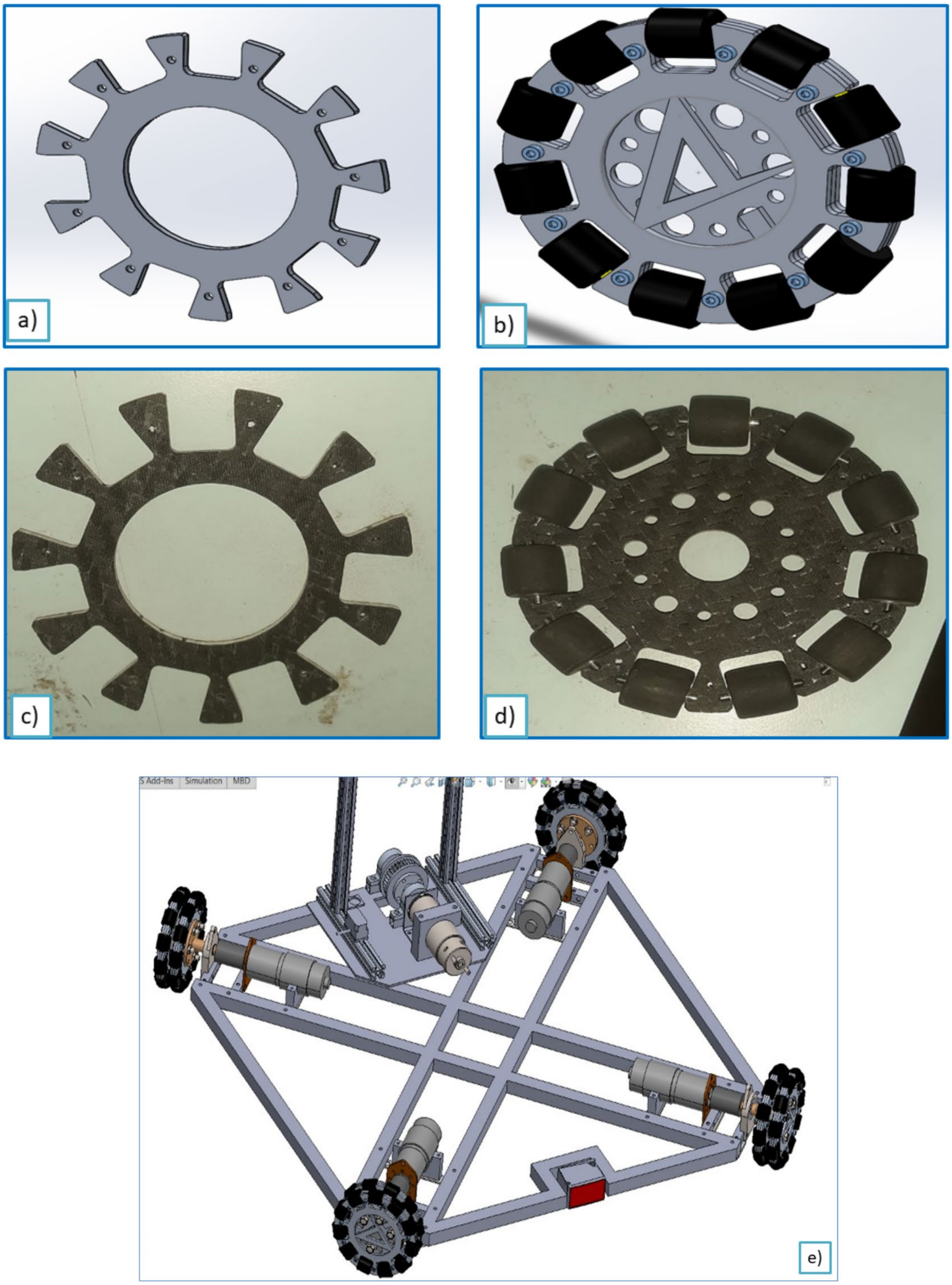


Fig. 3 **a** Carbon fiber, **b** Robotic Omini wheel with carbon fiber plate, **c** Carbon fiber plate, **d** Carbon fiber plate assembled to Omini Wheel, **e** Assemble Carbon fiber Omini wheels to the vehicle

Table 4 Theoretical results bending stress

Sr. No	Factors	Theoretical results	Experimental results
1	Bending moment on wheel assembly	3570 N.mm	
2	Bending moment acts on 1 plate	892.5 N.mm	
3	Induced bending stress (σb)	209.18 N/mm^2	234.375 N/mm^2

Table 5 Experimental results of bending stress

Displacement (mm)	Load (KN)
2	0.3
4	0.9
6	1.4
8	1.9
9	**2.0 (Ultimate bending stress)**
10	1.
12	1.4
14	1.3
16	1.3

$$\text{Permissible bending stress}(\sigma b) = 3PS/2\ bh^2$$
$$= 3 \times 2000 \times 150/2 \times 120 \times 16$$
$$= 234.375\ \text{N/mm}^2$$

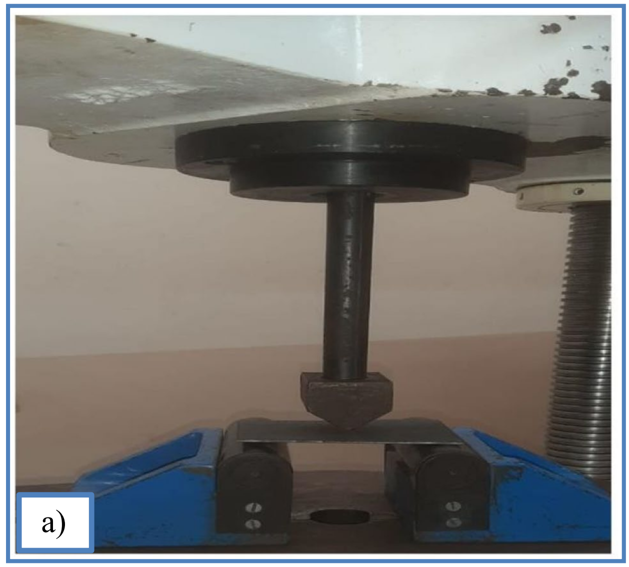
Table 4 shows the theoretical calculation results the induced bending stress is 209.18 N/mm^2. By performing 3-Point bending test breaking load of 2 KN as shown in Table 5 and so that we got the permissible bending stress of 234.375 N/mm^2. As our induced bending stress according to our application is 209.18 N/mm^2 which is less than Permissible bending stress, so we can concluded that our manufactured wheel plate is sufficient to sustain the load of our application.

Bending Test Results

To conduct a 3-point bending test on the bending sample, we followed the ASTM standard ASTM D790 guidelines. The sample had specific dimensions of 3.2 mm × 12.7 mm × 127 mm, which were carefully measured and prepared [30]. To set up the test, we positioned the specimen horizontally on the supports of a three-point bending fixture, as depicted in Fig. 4a. The distance between the supports was determined based on the dimensions of the sample and the requirements outlined in the test method. This ensured that the bending force would be uniformly applied to the specimen. Before initiating the actual test, it was crucial to condition the specimens to specific environmental conditions. We maintained a controlled room temperature environment to ensure consistent testing conditions across all samples. Once the specimens were appropriately conditioned, we applied a load to the center of the specimen using a universal testing machine consisting of suitable load cells [31]. The load was applied constantly, as specified in the test method [32]. We continuously monitored the sample's load and corresponding deflection throughout the test. During the test, we carefully observed and recorded the specimen's behavior [33]. One of the critical measurements we obtained was the maximum load or force sustained by the sample before failure. The specimen endured a maximum load of approximately 2.2 KN in this test [34]. This value provided insights into the material's strength and resistance to bending forces. Additionally, we measured the deflection or strain of the sample at specific points or intervals during the test. These measurements allowed us to assess the specimen's deformation characteristics and structural integrity. In this test, the deflection or strain recorded at specific points was approximately 14.9 mm, as illustrated in Fig. 4b. Following the ASTM standard and meticulously conducting the 3-point bending test, we gathered valuable data about the sample's mechanical properties and behavior under bending forces. These findings contribute to understanding the material's performance and can aid in various engineering and design applications.

Simulation Results

Applying fine Mesh to our part was a crucial step in obtaining precise and reliable results regarding deformation. Using a fine Mesh, we captured intricate details and accurately simulated the part's behavior under various loading conditions [35]. This meticulous approach allowed us to gain valuable insights into the structural response and identify critical areas that experienced significant deformation [36]. Upon analyzing the results obtained from the simulation, we focused on evaluating the total deformation of the part [37]. This parameter gave us a comprehensive understanding of how the part responded to external forces and exhibited deformation throughout its structure [38]. By examining Fig. 5a, we observed that the maximum deformation occurred at the neck region and the upper face of the teeth of the wheel. Being a relatively slender and vulnerable section, the neck region experienced substantial deformation [39]. This finding suggests that additional reinforcement or design modifications might be necessary to enhance the part's structural integrity in that



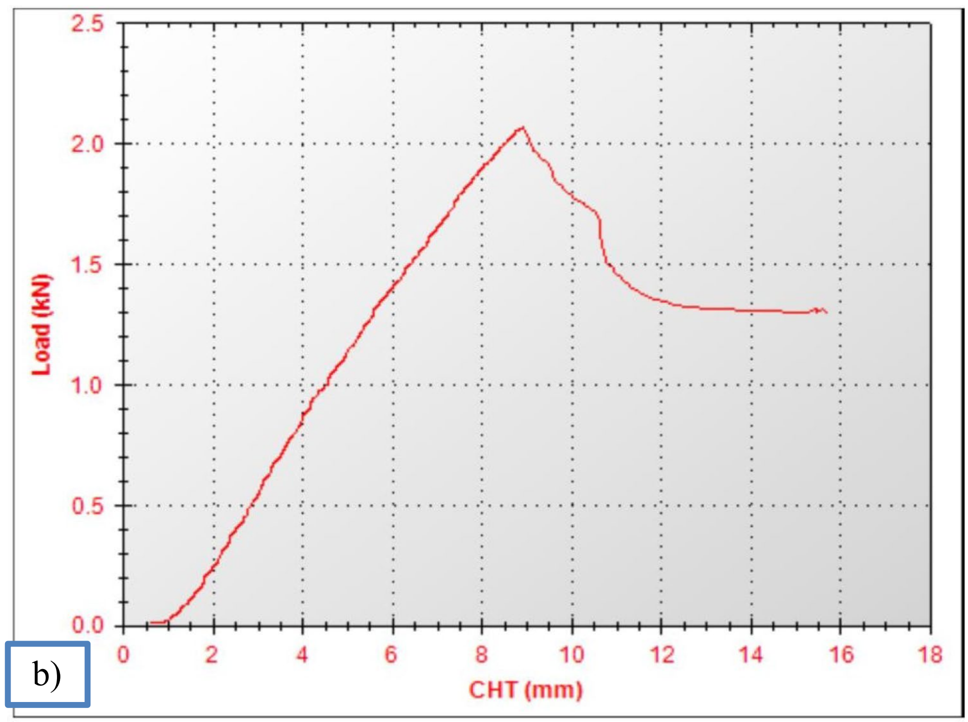


Fig. 4 **a** Specimen position in bending test. **b** Bending test results

area. Similarly, the upper face of the teeth of the wheel exhibited significant deformation, which could potentially impact the overall performance and functionality of the part [40]. To quantify the extent of deformation, we determined the maximum total deformation value to be 0.012309 mm. It is worth noting that this value fell below the design specification for deformation, as indicated in Fig. 5b. This outcome implies that the part's structural response remained within the acceptable limits during the design phase. However, it also highlights the importance of validating the design against potential failure criteria and evaluating the overall performance of the part to ensure it meets the desired specifications. In summary, the application of fine Mesh allowed us to capture the deformation behavior of the part accurately [41]. Our analysis revealed that the neck region and the upper face of the teeth of the wheel experienced the most significant deformation. Despite the maximum total deformation being below the design value, further examination and consideration of potential design improvements may be warranted to optimize the part's performance and reliability.

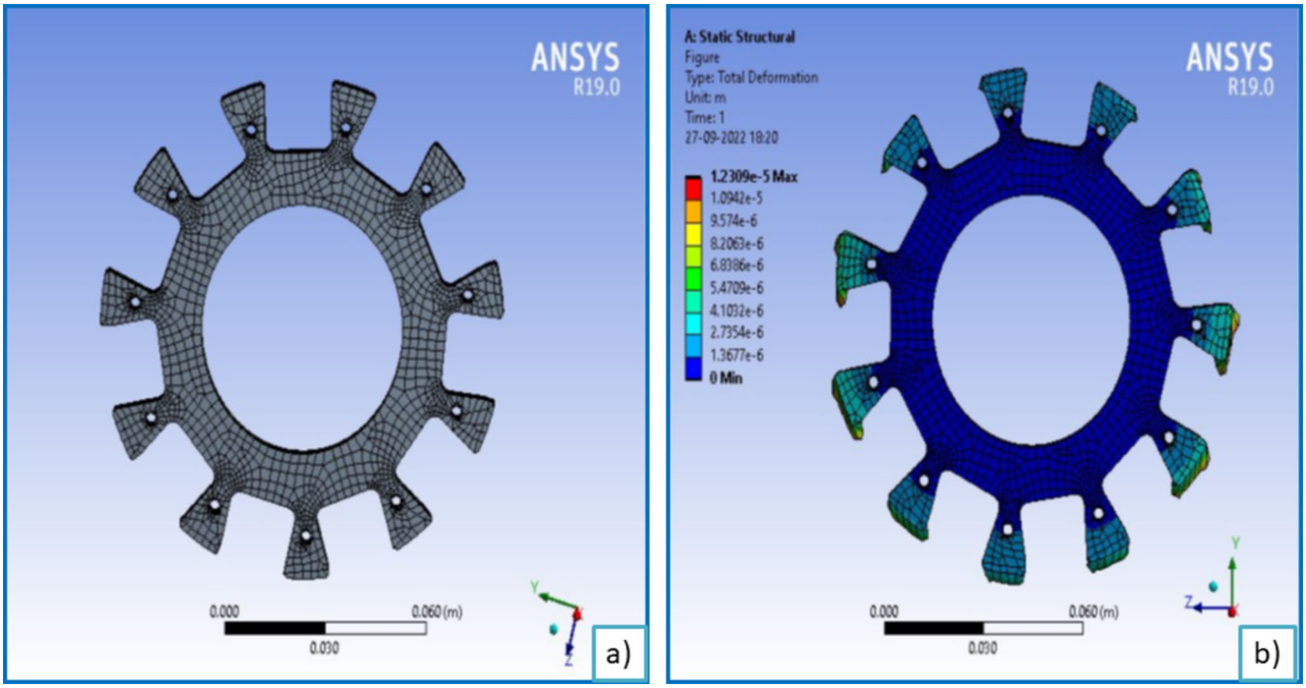


Fig. 5 **a** Meshing of Carbon fiber plate model, **b** Simulation results of carbon fiber plate

Conclusions

The carbon fiber composite plate for the robotic omni wheel was successfully designed and fabricated using the hand lay-up procedure. The bending strength of the plate was measured to be approximately 2 KN. The theoretical calculation of induced bending stress is 209.18 N/mm2, while the experimental results reveal that the permissible bending stress is 234.37 N/mm2. Since the induced stress is less than the permissible bending stress, it can be concluded that the manufactured carbon fiber plate is sufficient to sustain the load. ANSYS simulation results identified the upper part of the neck region of the teeth as the area experiencing maximum stress. Based on these findings, it can be concluded that the carbon fiber plate is a superior alternative material, offering a favorable strength-to-weight ratio compared to other materials for the robotic omni wheel and it will replace to the costly materials.

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Data availability Data will be made available on request.

Declarations

Conflict of interest Authors declare that no any competing interest.

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