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Experimental Investigation of Mechanical Behavior of CFRP-AA7075-T6 Composite and Finite Element Analysis for Automotive Wheel Rim Application

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A B S T R A C T

Lightweight with high strength material is the new requirement of the modern world and composite materials are the best option as the solution. Owing to high strength to weight ratio and corrosion resistant of Carbon Fiber Reinforced Polymer (CFRP) compared to aluminum (AA7075-T6), they are well suited to fulfill the demand of modern needs. The present work investigates the mechanical behavior of CFRP-AA7075-T6 composite material experimentally. Finite element analysis (FEA) has also been conducted for the evaluation of stress, strain, and deformation for the application as automobile wheel rims. CFRP-AA7075-T6 shows superior to AA7075-T6 in terms of flexural strength. Impact test reveal that the prepared composite absorbed 11% more energy than AA7075-T6. The strength-to-weight ratio of the prepared composite is 73% higher than that of AA7075-T6. FEA of automobile wheel rim models of prepared composite gives better results than the AA7075-T6 sample. CFRP-AA7075-T6 composite exhibits the lower deformation and equivalent elastic strain of 18.11% and 17.26% respectively than AA7075-T6 at same load level.

1. INTRODUCTION

Lightweight design is one of the concepts that have undergone the most research across a variety of industries. Due to their lightweight and favorable mechanical properties, composite materials are being used more frequently in the transportation industry [1]. Its primary goal is to reduce the impact of climate change by utilizing less material and energy. A lightweight design could also increase driving performance, such as greater acceleration, higher structural strength and rigidity, and better safety performance, in addition to reducing carbon footprint [2]. A composite material contains two or more different materials with superior mechanical properties [3]. The basic goal of composites is to combine the qualities of two elements into one new substance, typically covering the flaws of the original material [4]. There is a distinction made between the static wheel loads that apply in the absence of acceleration. Vehicle weight and energy use are tightly correlated and a 10% weight reduction leads to an annual boost in fuel efficiency of roughly 7%. The effects of changes in vehicle weight on its performance traits and found that the weight of electric vehicles is one of the factors that might influence their dynamic and range characteristics [5]. In order to reduce the weight of vehicles using polymers, the two most common techniques are to replace ferrous and non-ferrous metals with polymers and to increase the rigidities and specific strengths of polymers [6].

In this case, aluminum is ideal for the metal component because of its anti-corrosiveness and lightweight. Various components like as engine radiators, wheels, bumpers, suspension parts, engine cylinder blocks, transmission bodies and body parts, the hoods, the doors, and even the frame are made of aluminum alloy [7]. Lightweight is constructed using aluminum alloy 6061 since it is robust and flexible. Although the most used materials of automobiles are steel, the automotive industry has started to pay more attention to fuel efficiency, reducing CO_2 emissions, hence aluminum alloy is playing an important role in modern vehicles [8].

Carbon Fiber Reinforced Polymer (CFRP) is ideal because of its lightweight and high fatigue strength. Carbon fiber-reinforced polymers are five times lighter as well as five times stronger than steel and seven times stronger, two times stiffer, and 1.5 times lighter than aluminum. Using CFRPs instead of aluminum can reduce 40% of mass while having almost the same mechanical properties [9]. For this reason, the advantages of CFRP in the automotive industry include weight reduction, part integration, crashworthiness, durability and toughness, as well as aesthetic appeal. Due to the significant decrease in vehicle weight, this improves fuel economy and efficiency while lowering CO2 emissions. CFRP is used in different automobile parts such as bumpers, body panels, suspension, steering, and brakes [10, 11]. Other automotive applications of composites outside of body panels include instrument panels, drive shafts, fuel tanks, cross-wheel beams, and intake manifolds [12]. One of the major threats of using CFRP is its high cost.

In order to achieve cost effectiveness of material, one of the popular methods is to prepare composite using the core is made of low density and low stiffness, whereas the skins are thin faces of laminates with high stiffness and strength [13-15]. This combination, when joined together, offers the sandwich structure a high flexural strength. For joining the sandwich structure, epoxy resin used as an adhesive, which is the most common thermoset resin that helps a composite be stronger, more durable, and chemically resistant. The chemical reaction starts when epoxy resin and hardener are combined. The temperature and humidity of the surroundings and the epoxy mixture will have an impact on the rate or speed of the chemical reaction involving the epoxy as well as the degree of cure [16,17]. The recommended temperature range for curing epoxy is between 70 and 80F, and humidity levels should be below 85%, ideally between 50 and 60%, for the duration of the cure cycle and to establish effective bonding, a pressure of 0.28 ± 0.03 MPa is used [18,19].

For the fabrication process of composite different literature described different factors. Hegde [20] found that by taking into account elements like the fiber-to-resin ratio, the usage of U anchors, the kind, form, fiber orientation, and the region of application, CFRP's strength was increased. Tamilarasan [21] studied the mechanical properties did SEM of the carbon fiber aluminum sandwich composites. Bellini [22] did performance analysis on various structural qualities of CFRP/Al fiber metal laminates, with and without adhesive. Sun [23] found that in the carbon fiber/aluminum foam sandwich structures with the 200 g/m^2 aramid-fiber composite adhesive joints, the average critical compression load was enhanced by 47%. Bao [24] used carbon fiber-epoxy composite to make automotive wheel hubs. According to the aforementioned research investigations, CFRP-Al composite material is desired as one of the materials and being used in several applications.

The aim of this study is to investigation the mechanical behavior of CFRP-AA7075-T6 composite material experimentally. Additionally numerical analysis was done for the application of automobile wheel rims.

2. MATERIALS AND METHODS

2.1 Materials

Carbon Fiber Reinforced Polymer (CFRP) and aluminum alloy (AA7075-T6) were used to fabricate the composite samples. Chemical composition was determined using Q2 ION spark emission spectrometer (Bruker, Germany). The carbon fiber was used as a face material and AA6061 as the core material. The face sheets have been joined to a core using resin and hardener. Two-component epoxy was used for bonding. The mixing ratio of the epoxy is half portion of resin (bisphenol A based) and half is hardener (polyethylene polyamine) by volume. Table 1 and Table 2 show the specification of CFRP and the chemical composition of AA7075-T6 respectively.

Table 1. Specification of CFRP.

Properties	Specification
Thickness (mm)	2
Pattern	2*2 Twill Weave
Density (g/cc)	1.5
Finish	Matt finish
Application	Aerospace, Automobile
Color	Black
Country of origin	India

Table 2. Chemical composition of AA7075-T6.

Material	Chemical composition [%]				
AA7075-T6	Al	Mg	Si	Fe	Cu
	90.13	2.76	0.108	0.163	0.954
	Cr	Zn	Ti	Mn	Others
	0.23	5.41	0.034	0.154	0.057

2.2 Methods

a. Composite preparation

At first, the samples were cut using a precision grinding machine from the parent sheet according to the ASTM standard size. To smoothen out the sharp edge square file and emery paper were used. Then the CFRP sample was rinsed with fresh water and kept for drying in an open atmosphere. To ensure strong bonding, crisscross inverted roots were made on both surfaces of the aluminum plate. Adhesive for the composite, thermoset resin of two-component epoxy was used with the mixing ratio of 1:1 by volume. One part is bisphenol a based resin and the other one is polyethylene polyamine, hardener. For the preparation of the adhesive, 2ml of resin was taken in a beaker- 1 for one sample. The resin was stirred with a stirring rod about 2 to 3 minutes and then it was kept for resting. 2ml hardener was taken in another beaker namely beaker-2. After that, the hardener was poured slowly into the resin in beaker-1 with stirring. The whole process was performed at room temperature (25° C) and 45% atmospheric humidity. The hand lay-up technique was used to form the (CFRP-Epoxy-AA7075-T6-Epoxy-CFRP) sandwich structure. The sandwich structure was kept under the force of a C-clamp for 2 hours to squeeze out extra epoxy and to bleed out the air pockets between the layers. Extra epoxy was scraped off and the surface was cleaned. The sample was kept for 24 hours to cure the epoxy. The force was removed by releasing the clamps and the sample was kept for air-drying for another 24 hours. Figure 1 and Figure 2 shows the schematic diagram of the sandwich composite structure and the prepared composite structure respectively.

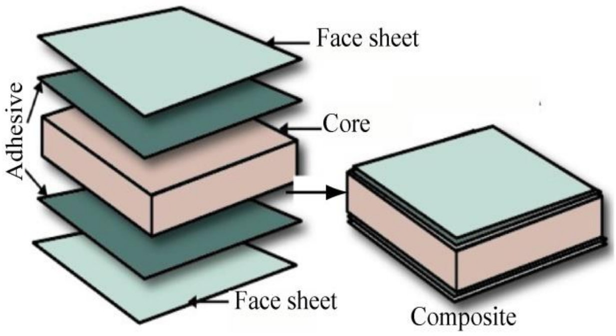

Fig. 1. Schematic diagram of sandwich structure.

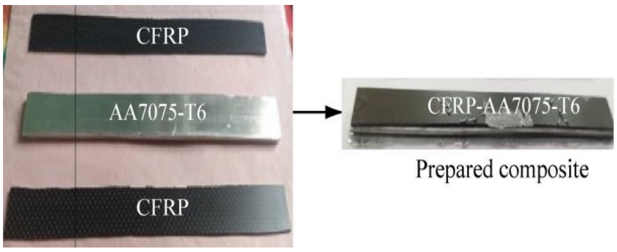

Fig. 2. Prepared composite structure.

b. Mechanical testing

Bending test

Three-point bending test was carried out on a rectangular specimen according to ASTM standards to calculate flexural strength using a Universal Testing Machine (HUT106A, China). The specimen with a rectangular cross-section was placed on two parallel supporting pins. The load was applied in the middle using a loading pin. Then the bending load was carried out until the load started decreasing. Then bending stress was calculated using this load. The values were taken by taking measurements several times for each. Figure 3 shows the 3-point bending test set-up under a universal testing machine.

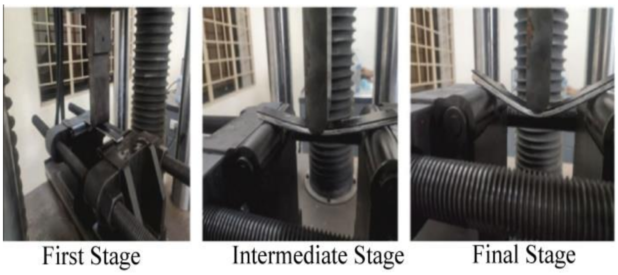

Fig. 3. Three-point bending test set-up under universal testing.

Impact test

Charpy impact testing has been used to evaluate the toughness of the materials. It was done according to the ASTM A370 standard. The specimen used for charpy impact testing is rectangular with or without notch cut in one side. Here, specimen includes the rectangular bar without notch. For CFRP, AA7075-T6 and prepared CFRP-AA7075-T6 composite samples for charpy test are 10 mm × 1.0 mm × 55 mm, 10 mm × 2.0 mm × 55 mm and 10 mm × 4.25 mm × 55 mm respectively.

c. Physical characterization

Density

Mass per unit volume is the definition of a material's density. In essence, density is a measurement of how closely stuff is packed. Density was calculated by the following formula $\rho = M/V$, where ρ is density, M is mass, and V is volume.

d. Strength to weight ratio or specific strength

The specific strength is a material is the strength divided by its density. It is also known as the strength-to-weight ratio or strength/weight ratio. In this study, bending stress was used to calculate the strength to weight ratio.

e. FE Modeling

The numerical analysis of the rim was done in the ANSYS 2020 Workbench to determine and compare the mechanical properties of the prepared CFRP-AA7075-T6 composite and AA7075-T6. After completing the material properties, the geometry was attached to the ANSYS workbench, and meshes were created. The actual model of the rim was created in the SOLIDWORKS program, and the file was saved in the "IGES" format. Choosing the appropriate mesh method and mesh size for the components required to make the mesh element and node. Implementing boundary conditions, which entails putting loads and fixed supports on the rim, was the next stage. To ensure the accuracy of the analysis, the full weight of the vehicle and the maximum permissible load was applied together with a fixed support that was mounted on the bolt. Figure 4 shows the simulation steps. The load calculation procedure is shown in Table 3.

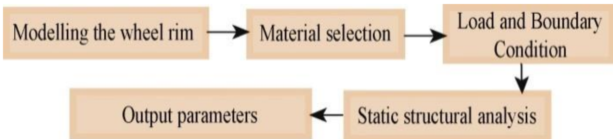

Fig. 4. Simulation steps.

Table 3. Load calculation.

	Car Weight (Kg)	Driver's weight (kg)	Passenger weight (kg)	Total weight (kg)	Total weight (N)
1	1544	50	66×0	1594	15637
2	1544	50	66×1	1660	16285
3	1544	50	66×2	1726	16932
4	1544	50	66×3	1792	17580
5	1544	50	66×4	1858	18227

3. RESULTS AND DISCUSSION

Figure 5 shows the bending stress of AA7075-T6, CFRP and CFRP-AA7075-T6 composite. The aluminum alloy (AA7075-T6) shows low bending stress of 294 MPa whereas CFRP shows very high bending stress of 1552 MPa. The prepared composite (CFRP-AA7075-T6) shows intermediate flexural stress of 446 MPa which is higher than that found by S. Genna et al. [25] for CFRP laminates with recycled carbon fiber (200 MPa) obtained by resin infusion under flexible tooling (RIFT) technology and Katagiri et al. [26] for three-point bending tests of the CFRP specimen (318 MPa).

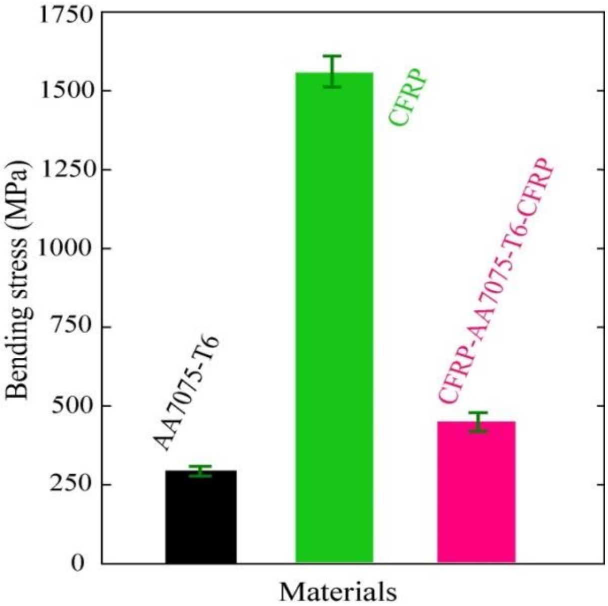

Fig. 5. Bending stress of AA7075-T6, CFRP and CFRP-AA7075-T6 composite.

Figure 6 shows the impact strength results from charpy test and found that the impact strength was increased 11% for the composite (253.7 kJ/m^2) from aluminium sample (229 kJ/m^2). Y. Wan et. al [27] found that the impact energy for hybrid metal wire net/woven carbon-fiber reinforced composite laminates significantly improved. Figure 7 (a) and Figure 7(b) shows the composite sample before and after the impact test and found the separation of CFRP fiber after the test sample. Figure 8 shows the density of AA7075-T6, CFRP and CFRP-AA7075-T6 composite. It was found that aluminum alloy has a higher density of 2500 kg/m^3 compared to CFRP and the prepared composite, which is similar to other research work [28]. Figure 9 shows the strength-to-weight ratio of same materials. Prepared composite (CFRP-AA7075-T6) shows a 73% higher strength-to-weight ratio than aluminum alloy (AA7075-T6) which can be shown clearly in enlarge view inside Fig. 9. Amanollahi et al. [29] found the increase of strength-to-weight ratio of laminated carbon steel/6061 aluminum composite is only a 22%. Figure 10 shows the FEA results of the load-versus-deformation behavior of AA7075-T6, CFRP and CFRP-AA7075-T6 composite and found that at the same amount of load prepared composite experiences lower deformation than aluminum alloy. The actual model of a rim made of CFRP-AA7075-T6 composite material and aluminum alloy separately and compared in the numerical analysis. Here, the properties of the rim were analyzed according to applying different loads to the rim. At different load conditions (this load was calculated according to the number of passengers), the total deformation of aluminum alloy is 0.936 mm to 1.09 mm with increasing the load from 15637 N to 18227 N, whereas the deformation of the prepared composite was 0.77 mm to 0.902 mm at the same load change.

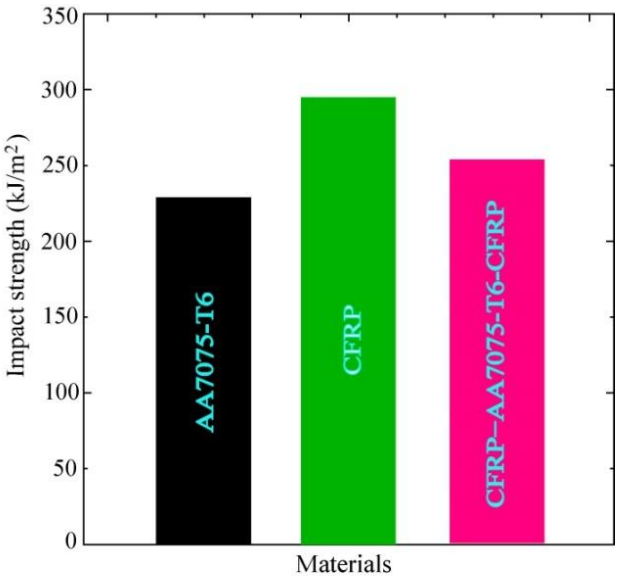

Fig. 6. Impact strength of AA7075-T6, CFRP and CFRP-AA7075-T6 composite.

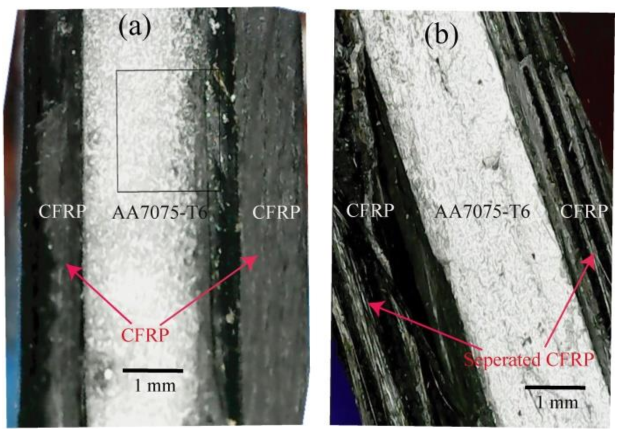

Fig. 7. Optical microscope image of composite (a) before impact test and (b) after impact test.

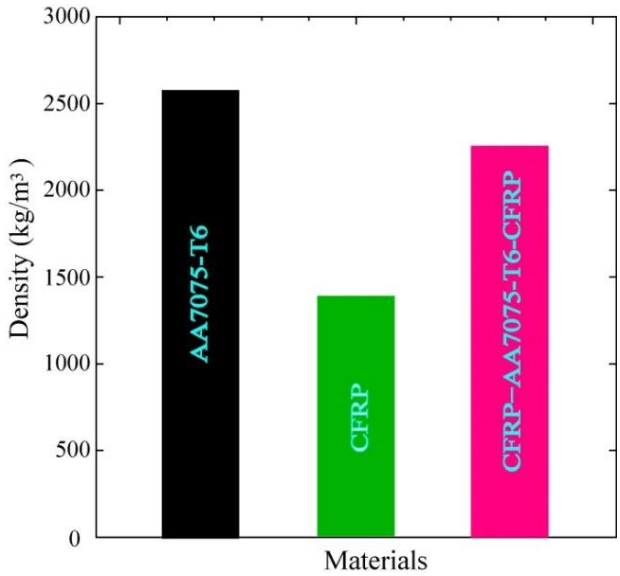

Fig. 8. Density of AA7075-T6, CFRP and CFRP-AA7075-T6 composite.

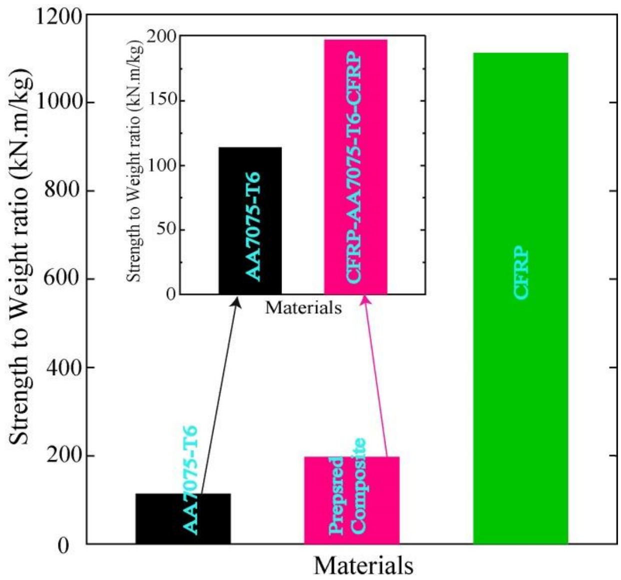

Fig. 9. Strength to weight ratio of AA7075-T6, CFRP and CFRP-AA7075-T6 composite.

Figure 11(a), 11(b), Figure 12(a), 12(b), and Figure 13(a), 13(b), show the total deformation, equivalent stress, and equivalent elastic strain of prepared composite and aluminum alloy at a load of 16932 N respectively. The results are tabulated in Table 3 and found that the deformation as well as the equivalent elastic strain of prepared composite is lower than that of aluminum alloy at the same loading condition.

From the numerical and experimental investigations, it is proven that the prepared composite showed the least amount of strain and deformation. From Table 3, it is shown that for the same applied load, prepared composite material deformation is 18.11% lower than aluminum alloy.

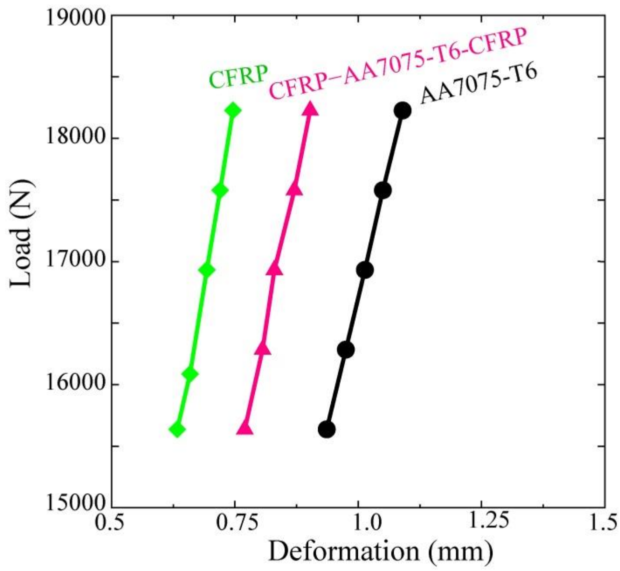

Fig. 10. FEA results of the load-versus-deformation behavior of AA7075-T6, CFRP and CFRP-AA7075-T6 composite.

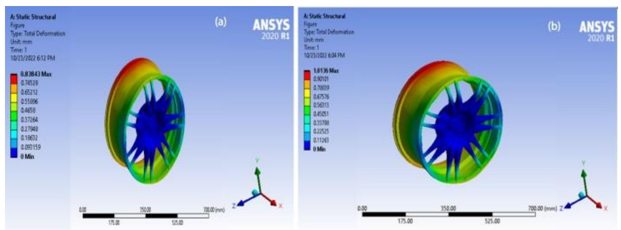

Fig. 11. Total deformation at 16932 N load (a) CFRP-AA7075-T6 composite (b) AA7075-T6.

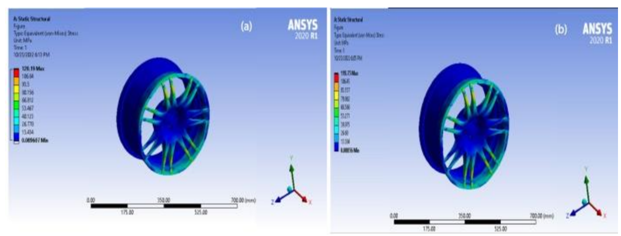

Fig. 12. Equivalent stress at 16932 N load (a) CFRP-AA7075-T6 composite (b) AA7075-T6.

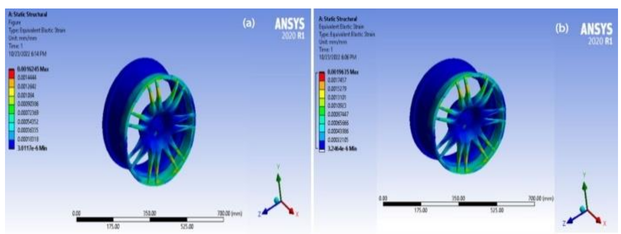

Fig. 13. Equivalent Elastic Strain at 16932 N load (a) CFRP-AA7075-T6 composite (b) AA7075-T6.

Table 4. Simulation results of AA7075-T6 & prepared composite at 16932 N load

Properties	AA7075-T6	CFRP-AA7075-T6
Total deformation (mm)	1.0136	0.83
Equivalent Stress (MPa)	119.75	120.19
Equivalent Elastic Strain	0.0019635	0.0016245

4. CONCLUSION

In this study, a sandwich composite structure of carbon fiber-reinforced aluminum was successfully prepared, and its mechanical property and numerical analysis were assessed. Using the results of the experimental research and the numerical analysis, the following conclusions were made:

- The CFRP-AA7075-T6 composite showed greater bending strength of 51% higher than AA7075-T6 sample.
- The CFRP-AA7075-T6 composite absorbed 11% higher impact energy than AA7075-T6 sample.
- The CFRP-AA7075-T6 composite showed 73% higher strength to weight ratio than AA7075-T6 sample.
- The CFRP-AA7075-T6 composite wheel rim deformation was 18.11% lower than AA7075-T6 sample at a load of 16932 N.
- The prepared composite wheel rim, the equivalent elastic strain was 17.26% lower than the AA7075-T6 sample at a load of 16932 N.

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