Structural and fatigue analysis of car wheel rims with carbon fibre composites

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Abstract

Purpose – The purpose of this study is to follow up on the structural and fatigue analysis of car wheel rims with carbon fibre composites in order to ensure the vehicular safety. The wheel is an essential element of the vehicle suspension system that supports the static and dynamic loads encountered during its motion. The rim provides a firm base to hold the tire and supports the wheel, and it is also one of the load-bearing elements in the entire automobile as the car's weight and occupants' weight act upon it. The wheel rim should be strong enough to withstand the load with such a background, ensuring vehicle safety, comfort and performance. The dimensions, shape, structure and material of the rim are crucial factors for studying vehicle handling characteristics that demand automobile designers' concern.

Design/methodology/approach – In the present study, solid models of three different wheel rims, namely, R-1, R-2 and R-3, designed for three different cars, are modelled in SOLIDWORKS. Different carbon composite materials of polyetheretherketone (PEEK), namely, PEEK 90 HMF 40, PEEK 450 CA 30, PEEK 450 GL 40 and carbon fibre reinforced polymer-unidirectional (CFRP-UD) are used as rim materials for conducting the structural and fatigue analysis using ANSYS Workbench.

Findings – The results thus obtained in the analyses are used to identify the better carbon fibre composite material for the wheel rim such that it gives better structural properties and less fatigue. The R-3 model rim has shown better structural properties and less fatigue with PEEK 90 HMF 40 material.

Originality/value – The carbon composite materials used in this study have shown promissory results that can be used as an alternative for aluminium, steel and other regular materials.

Keywords Wheel rim, PEEK material, Composite material, Carbon fibre reinforced polymer

Paper type Research paper

1. Introduction

The wheel is a part that allows efficient movement of an object across a surface when a force presses the object to the surface (Karuppusamy *et al.*, 2016; Mishra and Singh, 2019). A wheel rim is the outer circular design on which the inside edge of the tire is mounted on the vehicle (Venkateswararao and Dharmaraju, 2014). The rim is a highly stressed component in an automobile that is subjected to bending and torsional loads (Sivaprasad *et al.*, 2014; Mangire *et al.*, 2015). The spoke–wheel rim assembly contributes to the significant weight addition in the vehicle after the engine and the development of lighter rims is essential to reduce the overall vehicle's weight (Shekhar *et al.*, 2020; Parmar *et al.*, 2015; Karthik *et al.*, 2016). The automotive industry has continuously developed new materials, to sustain all loads, to lower manufacturing costs and improve fuel economy (Kale *et al.*, 2015). The traditional materials, steel and aluminium, have long since crossed the verge of innovation; their advantages in strength, stability, life, formability, toughness, impact resistance and resilience are challenged by the high-strength carbon fibre–polymer composites. Composite materials are new materials created by combining two or more metals or non-metals. Typically, composite materials are lighter and stronger than conventional metals. Carbon fibres are light in weight, have high strength, can resist high temperatures and are corrosion resistant. Dispersed in an epoxy matrix, the carbon-fibre-reinforced composite (CFRP) can replace conventional materials (Esfandiari and Khezeli, 2019; Esfandiari and Esfandiari, 2017), showing great promise as materials for current and future automotive, aerospace and industrial applications.

Carbon fibre composites are expensive, as their fabrication is difficult in the case of manufacturing complex and intricate components, but compared to traditional materials, the advantages offered, justify their cost. Thus, their everyday use is limited to the niche segment of automobiles like luxury and sports cars (Korkut *et al.*, 2020; Sai Yashwanth *et al.*, 2022). The common application areas comprise the body panels, structures of the performance elements, passenger cell components, diffusers and roofing. Recent research has paved the path for the extension of CFRP's in dynamic components like wheel rims and axle shafts, offering excellent fatigue resistance of carbon fibre (Czypionka and Kienhöfer, 2019; Panda *et al.*, 2016).

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Wheel rims provide a platform for mounting the tires, transmitting the torque from the axle to the tires (Doria and Taraborrelli, 2016; Tsinias and Mavros, 2019). The wheel along with the tyre has to take the vehicle load, provide a cushioning effect and cope with the steering control (Ganesh and Periyasamy, 2014). Wheel rim experiences radial, torsional and bending loads. The rim is considered as an unsprung mass as it is directly in contact with the road. Therefore, the weight of the rims plays a vital role in the car's dynamics (Vilar *et al.*, 2019; Strigel *et al.*, 2019; Saurabh and Sameer, 2013; Rohan, 2015). Weight reduction of the wheel rim results in better control of wheel movement and allows the springs or dampers to enable proper contact between the road and the tire. The reduced weight provides the wheel's improved grip and cornering ability at high speeds.

Furthermore, for a rotating body, reducing weight indicates that a wheel requires smaller torque to rotate and needs less force for acceleration and braking, resulting in better handling of an automobile. Recent research has enabled the usage of various alternate materials used for wheel rim construction. Finite element analysis was performed by considering four materials – PEEK 90 HMF 40, PEEK 450 CA 40, PEEK 450 GL 30 and CFRP-UD. The different metrics considered in this present study were total deformation, von Mises stress and strain, damage, safety factor and life (Lidoriya *et al.*, 2013).

2. Materials

Three different carbon composite materials, namely, PEEK 90 HMF 40, PEEK 450 CA 30, PEEK 450 GL 40 and CFRP-UD are used as materials for rims R1, R2 and R3. The properties of the materials are listed in the below Table 1.

3. Methodology

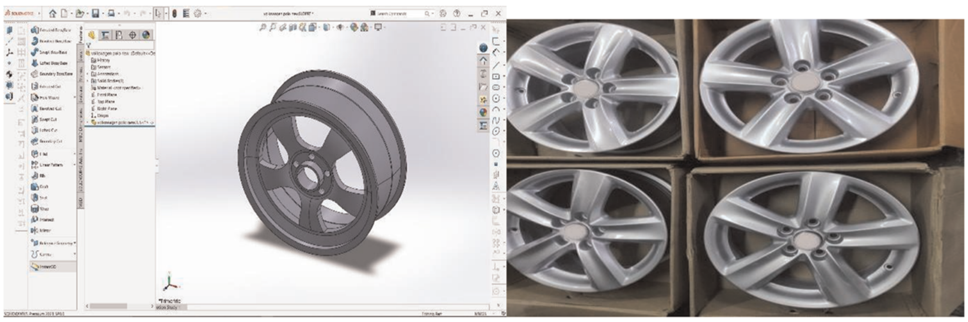
Initially, wheel rims, R1–R3, are designed using SOLIDWORKS software. Furthermore, the wheel rim models are imported into the ANSYS software to estimate total deformation, von Mises stress, von Mises strain, damage and safety factor. Figures 1–3 show the wheel rims R1, R2 and R3,

Table 1 Properties of materials assigned for wheel rims

Material	Density (kg/m^3)	Young's modulus (GPa)			Poisson's ratio			Tensile yield strength (MPa)	Tensile ultimate strength (MPa)
PEEK 90 HMF 40	1,450	4.50			0.48			330	100
PEEK 450 CA 30	1,400	28			0.44			220	100
PEEK 450 GL 40	1,510	11.50			0.40			210	185
CFRP-UD	1,490	X	Y	Z	X	Y	Z	310	280
		121	8.60	8.60	0.27	0.40	0.27		

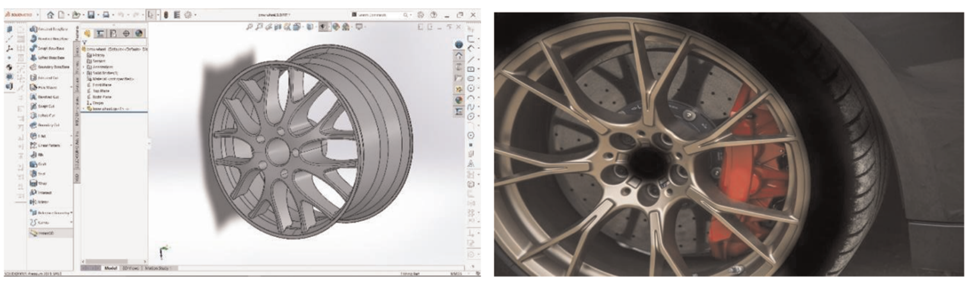
Source: www.victrex.com/

Figure 1 Model of wheel rim R-1 along with its original design



Source: IndiaMART

Figure 2 Model of wheel rim R-2 along with its original design



Source: indianautosblog.com

Figure 3 Model of wheel rim R-3 along with its original design

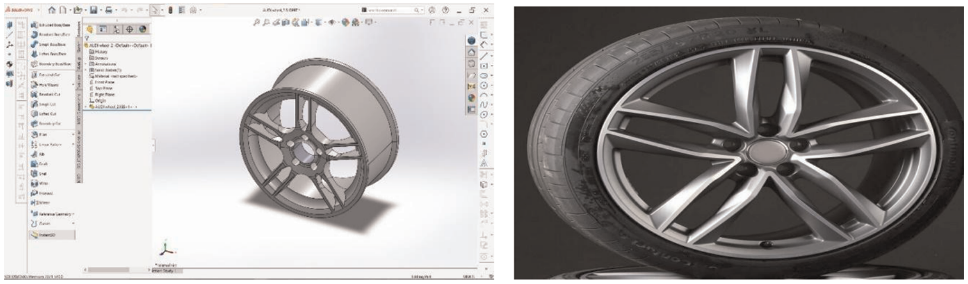


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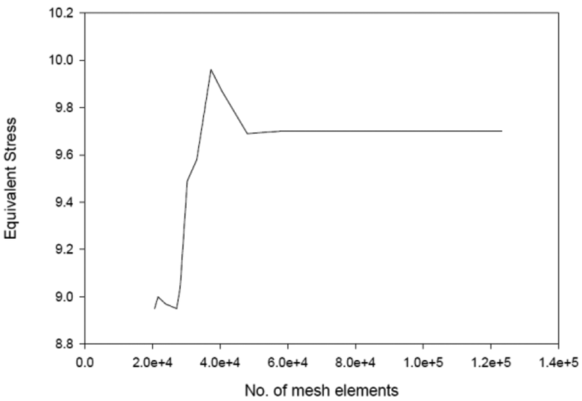
Figure 4 Grid independence test



Source: Figures by authors

respectively, which are modelled in SOLIDWORKS along with their original design.

The wheel rim models (R1–R3) are designed in SOLIDWORKS and are imported into the ANSYS software for further analysis by considering different materials for the rims. Furthermore, meshing is done in ANSYS for the imported rim models, and the boundary conditions are applied to the rim.

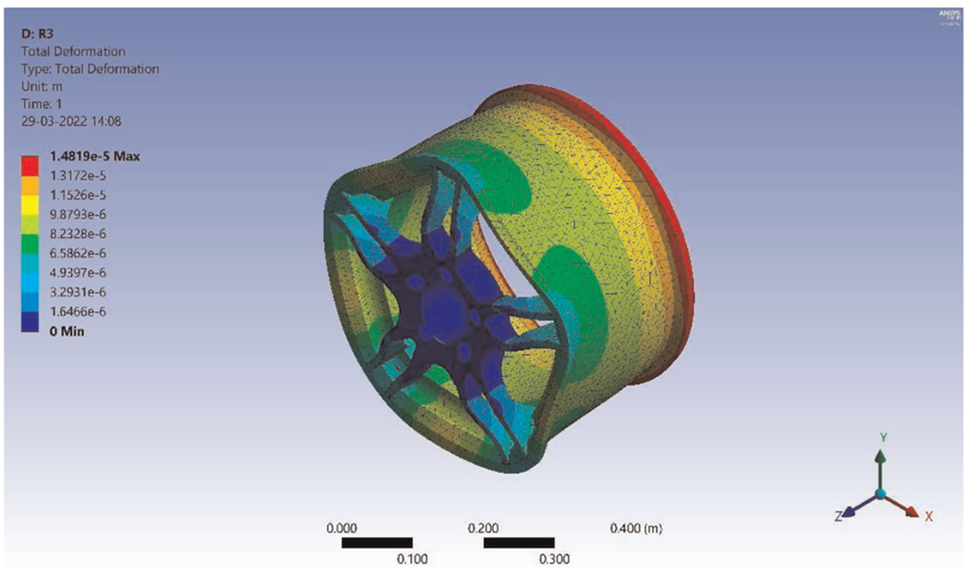
The wheel rim is considered in static conditions, and the conditions like fixed supports, pressure and force (curb weight) are applied on the wheel rim for the static analysis, and the entire load is assumed to be acting at the centre of gravity of the wheel (Natrayan *et al.*, 2016).

To compare the three models of the wheel rims, namely, R1, R2 and R3, their average weight is considered to be 1450.67 kg, the load acting on each wheel is 362.6 kg, the total force acting on each wheel is 3,557.76 N and the maximum pressure allowed in the wheel rim is 0.241 MPa. The grid independence test is done for obtaining optimum mesh size, and the same is shown in Figure 4.

4. Results and discussion

The present study analyses three different wheel rims, R1, R2 and R3, using four different materials, namely, PEEK 90 HMF 40, PEEK 450 CA 30, PEEK 450 GL 40 and

Figure 5 Total deformation of rim R3 with PEEK 90 HMF 40

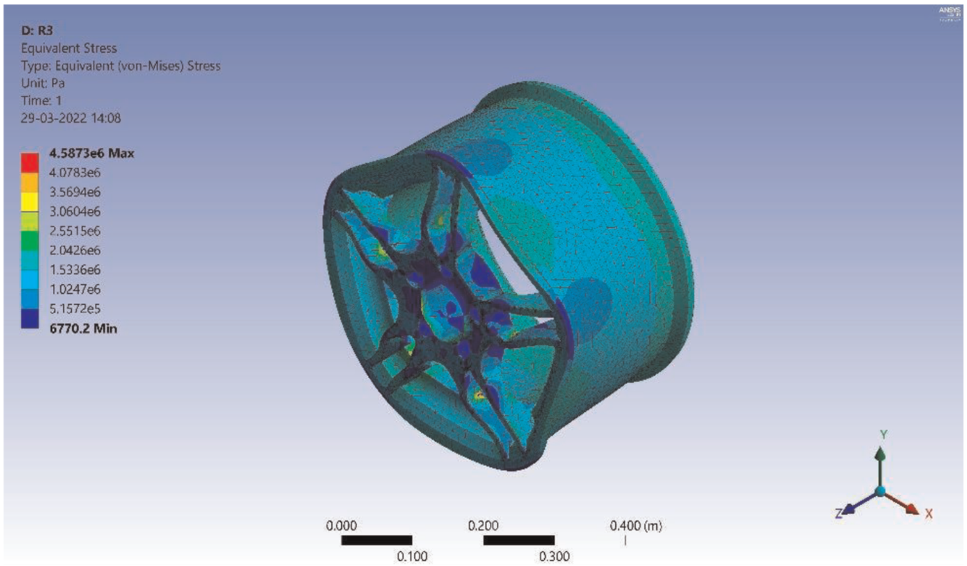


Source: Authors' own, in concurrence with the data in Table 4

CFRP-UD. During simulation, the lug holes are fixed, pressure is applied on the wheel rim's entire outer surface and force due to curb weight is applied on the inner surface of the centre bore. On changing the materials, at constant maximum allowable pressure of 0.241 MPa for a curb weight of 3557.76 N, structural factors such as total deformation, von Mises stress and von Mises strain are along with damage, life and factor of safety are calculated using the Fatigue tool.

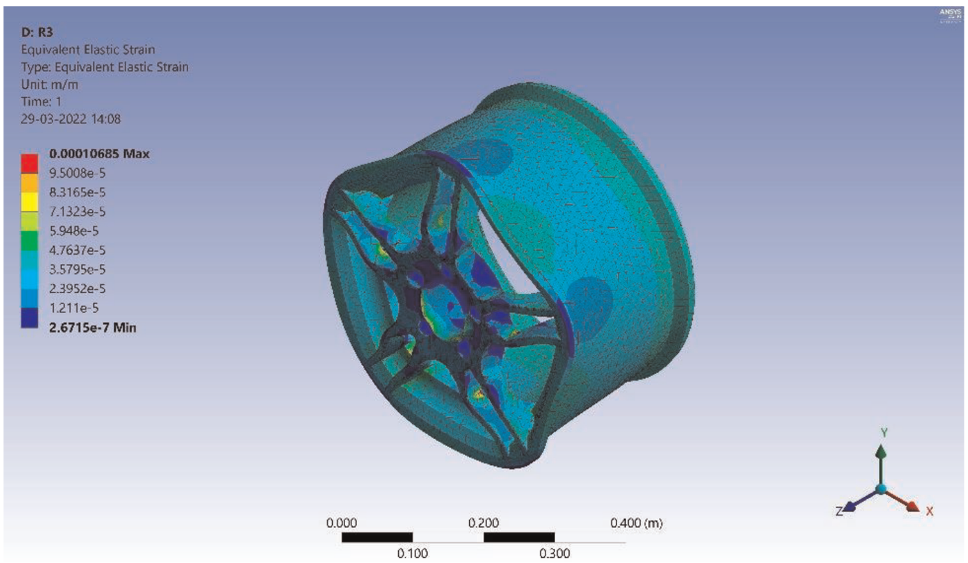
PEEK 90 HMF 40 exhibited a minimum total deformation, von Mises stress and strain of the considered materials as shown in Figures 5–10. The decrease in total deformation can be justified by the lower ratio of equivalent stress to equivalent strain, i.e. Young's modulus. The rim R3 is the most optimal design as it resulted in minimum von Mises stress and deformation because of the larger surface area. Therefore, the rim R3 and PEEK 90 HMF 40 are the most suitable of all the designs and materials considered for analysis. The stress for the material PEEK 90 HMF 40 in rim R3 is nearly 12% lower than rim R1 and 25% less than rim R2. However, the material CFRP shows the highest stress values of 23.387, 29.107 and 9.5802 MPa for the rims

Figure 6 Von Mises stress of rim R3 with PEEK 90 HMF 40



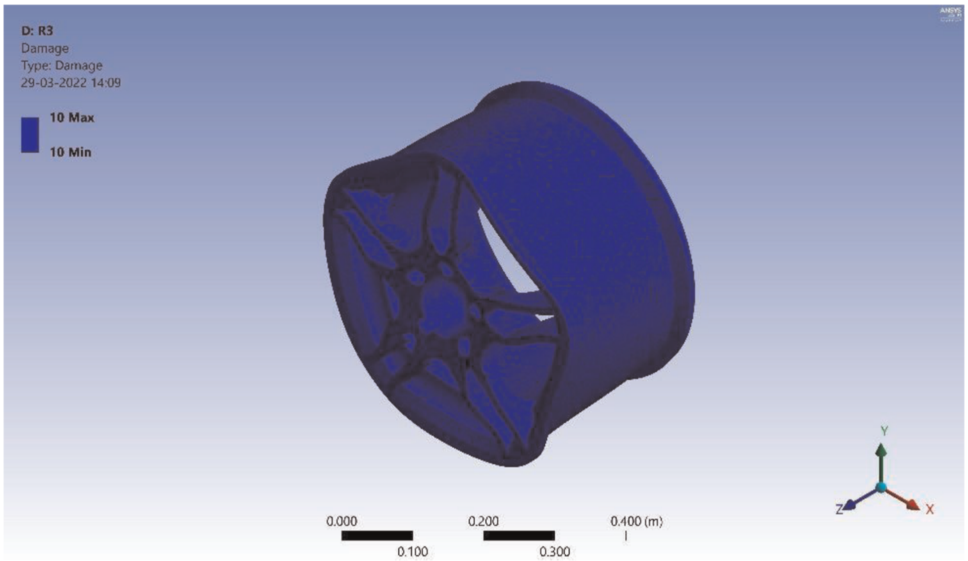
Source: Authors' own, in concurrence with the data in Table 4

Figure 7 Von Mises strain of rim R3 with PEEK 90 HMF 40



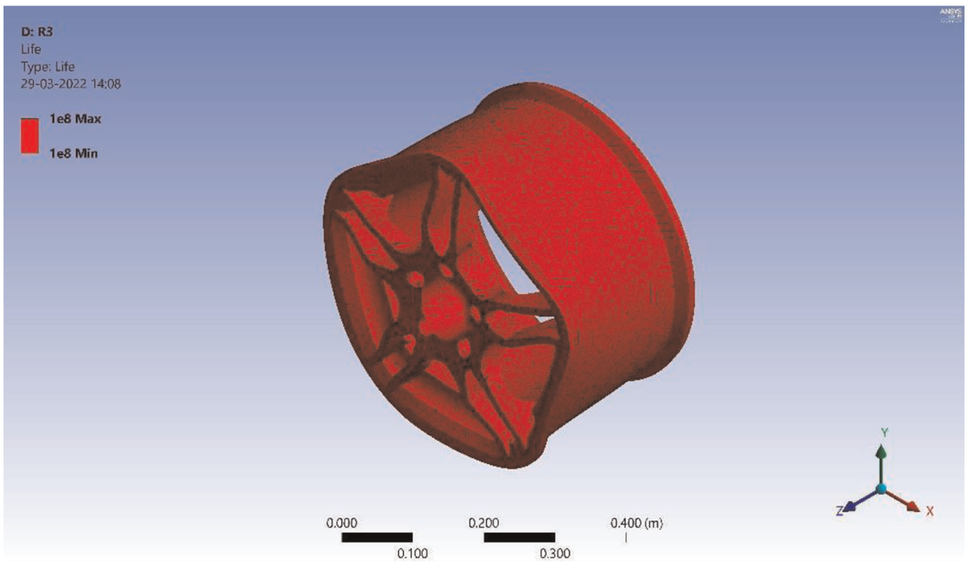
Source: Authors' own, in concurrence with the data in Table 4

Figure 8 Damage of rim R3 with PEEK 90 HMF 40



Source: Authors' own, in concurrence with the data in Table 4

Figure 9 Life of rim R3 with PEEK 90 HMF 40



Source: Authors' own, in concurrence with the data in Table 4

R1, R2 and R3, respectively, resulting in higher total deformation.

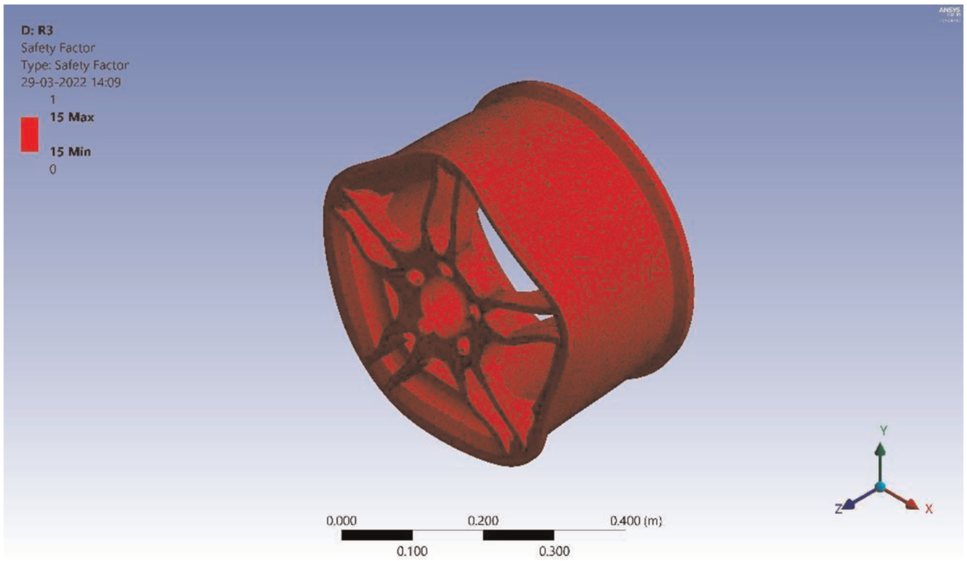
The results show that the safety factor obtained remained constant for all the materials and wheel designs considered, as factor safety depends on maximum permissible stress and maximum allowable stress, which remain nearly constant for a particular wheel rim design, while damage and life for the three materials: PEEK 90HMF 40, PEEK 450 CA 30 and PEEK 450 GL 40, are identical. CFRP-UD shows maximum damage with minimum life for the rims R1–R3 due to design aspects (see Tables 2–4).

5. Conclusions

The methodology to analyse and suggest the best carbon composite for the manufacture of wheels is presented in this study. The factors like structural integrity, the load-carrying capacity of the rim and the lightweight of the material are considered to ensure comfort to the occupants. The following conclusions are made from the results obtained from the analysis of rims:

- The use of carbon composite rim is found to last until it is damaged in a way that compromises the bond between resin and carbon fibres.

Figure 10 Safety factor of rim R3 with PEEK 90 HMF 40



Source: Authors' own, in concurrence with the data in Table 4

Table 2 Results of rim R1

Material	Total deformation (mm)	Von Mises stress (MPa)	Von Mises strain (mm/mm)	Damage	Safety factor	Life (cycles)
PEEK 90 HMF 40	0.018562	10.394	0.00024464	10	15	1×10^8
PEEK 450 CA 30	0.02804	10.455	0.00037597	10	15	1×10^8
PEEK 450 GL 40	0.067367	10.519	0.00093446	10	15	1×10^8
CFRP UD	0.076432	23.387	0.0014032	1,000	15	1×10^6

Source: Tables by authors

Table 3 Results of rim R2

Material	Total deformation (mm)	Von Mises stress (MPa)	Von Mises strain (mm/mm)	Damage	Safety factor	Life (cycles)
PEEK 90 HMF 40	0.02899	5.7376	0.00013345	10	15	1×10^8
PEEK 450 CA 30	0.044711	5.864	0.00020945	10	15	1×10^8
PEEK 450 GL 40	0.10923	5.9896	0.00052089	10	15	1×10^8
CFRP UD	0.067564	29.107	0.0013276	1,000	15	1×10^6

Source: Tables by authors

Table 4 Results of rim R3

Material	Total deformation (mm)	Von Mises stress (MPa)	Von Mises strain (mm/mm)	Damage	Safety factor	Life (cycles)
PEEK 90 HMF 40	0.014819	4.5873	0.00016085	10	15	1×10^8
PEEK 450 CA 30	0.022518	4.592	0.00016422	10	15	1×10^8
PEEK 450 GL 40	0.054247	4.6031	0.00040073	10	15	1×10^8
CFRP UD	0.067476	9.5802	0.00068427	1000	15	1×10^6

Source: Tables by authors

- The design of rim R3 with PEEK-90 HMF 40 material is the most optimal and reliable due to its long life as minor deformation, stress and strain are induced in the material.
- It is attributed to the reduction in the vehicle's overall weight and lower fuel consumption rate than the traditional vehicle having a usual alloy wheel due to less inertia and a better life cycle.
- Also, carbon composite rims result in less stress generation, better braking time and improved overall handling and control on the road.
- Hence, owing to reliability and safety aspects, it proves to be a better counterpart to the pervading traditional materials used for manufacturing wheel rims of the vehicles.

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Further reading

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