Static analysis of new lightweight racing wheel for Formula Society of Automotive Engineers (FSAE) race car for product innovation

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ABSTRACT

A lightweight wheel has the potential to be widely used to enhance the safety of racing cars and improve car performance by providing an estimation of wheel width spokes quantity, and other constant variables. This study is, therefore, aimed at designing a new lightweight racing wheel. In this study, a Finite Element Model (FEA) was implemented to investigate the static analysis of the newly designed lightweight racing wheel. Since the lightweight wheel characteristics play an important role in the stability and control of the racing car under severe manoeuvres, the wheel mass, von Mises stress, deformation, and safety factor were determined. It was observed that the circumferential component is vital for estimating the lightweight design of racing car wheel design. Therefore, this parameter could be better assessed for future studies.

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INTRODUCTION

Design brings new innovations to market by utilizing knowledge of manufacturing techniques, product development, technical design, and rapid prototyping. From the context of engineering design, creativity is one of the important engineering skills required in the competitive industrial situation. Engineering designers must deal with a variety of design issues, from concept ideation to detail and manufacturing. Most engineering design problems can be easily solved by improving the creativity strategies (Ma'arof et al. 2022). Static analysis is an important

KEYWORDS

Static analysis, Formula Society of Automotive Engineers (FSAE), wheel design, product innovation, ISO3006:2015 standards.

tool for engineering design creativity (Toh and Miller 2013; Samuel 2006; Obieke et al. 2021). Numerous studies, methods and programs are available to boost engineering design and creativity.

For example, the Formula Society of Automotive Engineers (FSAE) is a class of formulas organized and overseen by the Society of Automotive Engineers (SAE) (Nor et al. 2019; Nor et al. 2020; Nor et al. 2022). It challenges teams of university students to conceive, design, fabricate, develop, and compete with formula-style vehicles. Studies are paying more attention to the lightweight design of automobiles since the automotive industry demands higher energy efficiency and environmental protection (Tisza and Czinege 2018; Han 2020). One of the key components of a FSAE vehicle is the racing wheel. It is responsible for a variety of criteria, such as security, stability, performance, and fuel efficiency.

Static analysis has grown from a simple compiler optimization technique to a main player in software correctness and verification. A static analysis of the new models was conducted using the finite element method, and the results were compared to the initial model design. Statics analysis can be an advantage in detecting flaws in code at specific locations or parts, it can be carried out by trained software assurance developers who have a thorough understanding of the code. It allows for faster turnaround on fixes. When automated tools are used, it is relatively quick. Besides, the entire code base can be scanned by automated tools, which can provide mitigation recommendations, reducing the time spent on research. Furthermore, this analysis enables flaws to be discovered earlier in the development life cycle, lowering the cost of remediation. Based on these advantages, most studies have discovered the potential of static analysis in the design all parts of automobiles. This can be seen as most of the studied have applied and conducted finite analysis for all automobile parts. For example, Nguyen et al. 2019 stimulated the complex dynamics of bus and truck's chassis used to verify the structural integrity of the chassis and support design optimization, respectively (Ghazaly 2014).

In the context of tire or wheel design, there are two types of wheel constructions in wheel manufacturing, namely one piece, and multi-pieces wheel. One-piece wheels are made out of one continuous piece of material, while the multi-piece wheel is made out of multiple pieces of the same or different materials and can be in a combination of two-piece rims or the less common three-piece rims (Li et al. 2014). One-piece wheels do not require an additional joining process while the multi-pieces require a joining process in order to form a complete wheel through welding, bolting, or riveting. One-piece wheels are also generally lighter compared to multi-piece wheels because the wheels are made out of a single component and require no further joining components. While multi-piece wheels consist of multiple components and require an additional joining process in order to form a proper wheel. The extra weight of the weldments, bolts, or rivets will increase the weight of the wheels (Genthner and Mikkelsen 2022; Blawert et al. 2004). The wheels must be as light as possible to ensure energy efficiency. Therefore, this study aims to design a new lightweight racing wheel. This is because the wheels play an important role in motorsports racing such as FSAE. The wheel was selected as the component of interest since the wheel is one of the core members of the vehicle's drivetrain system that drives the vehicle forward. The wheels were designed via the use of CAD and analyzed with the use of FEA software. The designed wheels were then validated via the ISO3006:2015 standards. The result of this study shall provide a clear understanding of wheel designs and its effects towards the overall performance of the wheel.

METHODOLOGY

Static analysis study was carried out for the benchmark and 36-wheel specimens via the FEA through Solidworks. The purpose of the analysis was to study how the wheels behaved when the FSAE vehicle was under static conditions with the consideration of the driver's weight. Assuming the weight distribution of the FSAE vehicle was 50/50, the vehicle is bearing the same weight on both the front and rear axles. Thus, every wheel was loaded with similar loads. Table 1 shows the design parameters used in this study.

Table 1: Design Parameters

Constant variable (CV)	Manipulated variable (MV)	Responding variable (RV)
		Static analysis
Wheel material	Wheel width	Wheel mass
Wheel construction	Spokes quantity	Von Mises stress
Wheel diameter		Deformation
Wheel offset		Safety factor

According to the Brown Formula Racing Team, the common average mass of FSAE vehicles is 475 Ib (~215kg, 2109N), divided by four tires, which is 530N, was applied to the wheel's centre bore. According to Kasprzak and Gentz, 2006 the suggested tire pressure for FSAE that uses Goodyear tires is 83kPa. Therefore, assuming the Goodyear tire will be used for the vehicle. Hence, 0.083MPa of pressure was applied to the wheel barrel during the study. Besides, according to the publication of Body Mass Index (BMI) of adults, the mean body weight of Malaysian adults aged between 18 and 59 years was 66.56kg (~653N) will be taken as the weight of the driver, divided by four tires, which was around 163N. The force of 693N (distributed weight of the vehicle and driver) was applied to the wheel bore, and the tire pressure of 0.083MPa was applied to the wheel barrel.

Based on Fig. 1, the wheel bore was constrained. This was the area where the wheel would be in contact and secured to the wheel shaft in a real-life situation.

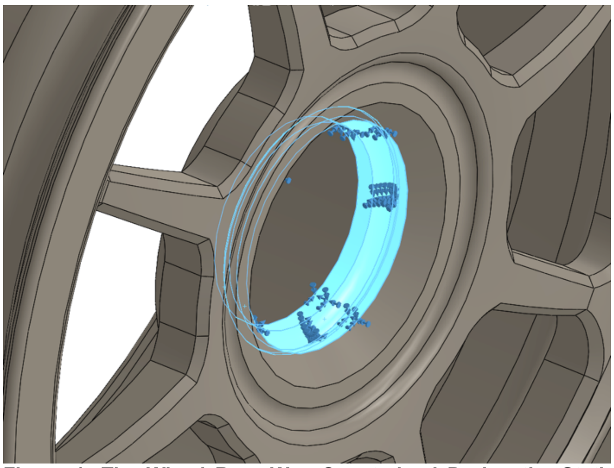


Figure 1: The Wheel Bore Was Constrained During the Static Analysis.

The green arrows shown in Fig. 2 indicate the tire pressure of 0.083MPa. The red arrows indicated the distributed load of the vehicle and driver at 690N. Lastly, the yellow arrows in the wheel bore indicate the constrained region.

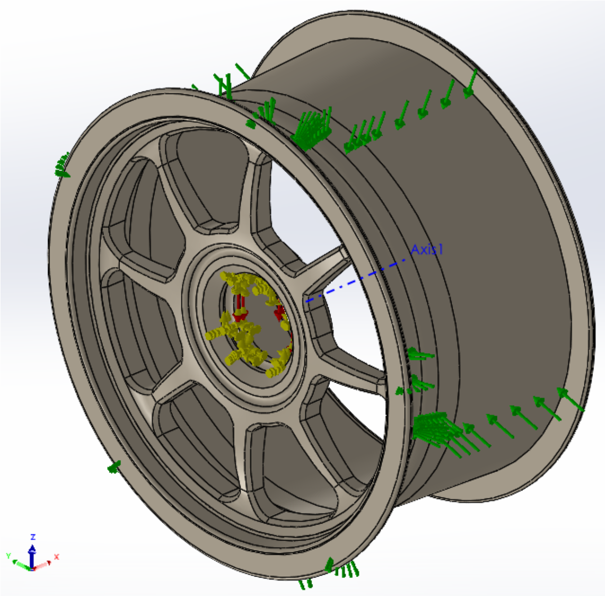


Figure 2: The simulation setup for the static analysis

RESULTS

The results of the analysis, such as wheel mass, von Mises stress, displacement, and safety factor, were collected. The wheel mass was extremely important because the study aimed to design a lightweight racing wheel. Therefore, it allows us to compare each of the wheel masses of the benchmark wheel and the 36-wheel specimens. Besides, the von Mises stress was also important as it allowed us to determine the magnitude of the stresses in the wheels that resulted from the external loads.

Then, the deformation, also known as displacement, assesses the extent to which the wheels' nodes had shifted due to the loads. Finally, the safety factor was extremely important as it allows us to determine whether the wheel specimens were safe by comparing the maximum strength of the material to the maximum stress in the wheels. A safety factor of less than 1 means that the wheels could not withstand the static loads. Likewise, a safety factor of more than 1 indicates that the wheels were able to withstand the applied load. The static analysis results were tabulated systematically according to the codes of the wheel specimens. Table 2 shows the comparison results of the static analysis on the benchmark wheel (7W8S) in different materials, magnesium alloy and PEEK 90HMF20.

Table 2: Comparison results of benchmark wheel in different materials

Benchmark material	Mass (kg)	von Mises (MPa)		Displacement (mm)		Min safety factor (≥1)
(7W8S)		Max	Min	Max	Min	
Magnesium	2.75	3.88	0.006	0.017	0	50.31
PEEK 90HMF20	2.21	3.79	0.003	0.036	0	73.93

While Table 3 shows the full results of the 36 specimens in PEEK 90HMF20. Besides, the PEEK 90HMF20 7W8S specimen was able to attain a safety factor of 73.93, which was 32% higher than the safety factor of the magnesium alloy benchmark wheel at 50.31 during the analysis. Moreover, the magnesium alloy benchmark 7W8S wheel was having a mass of 2.745kg while the mass of the PEEK 90HMF20 7W8S was 24% lighter at 2.213kg. Hence, the analysis shows that the PEEK 90HMF20 is a suitable alternative material to replace the magnesium alloy for wheel manufacturing.

Table 3: Improvements of benchmark wheel in different materials

Mass (kg)		Mg	PEEK 90HMF20	Percentage difference
		2.745	2.213	-24%
von Mises (MPa)	Max	3.876	3.79	-2.20%
	Min	0.005586	0.0029	-92.60%
Displacement (mm)	Max	0.017	0.0359	52.60%
	Min	0	0	0
Min safety factor (≥1)		50.31	73.93	31.90%

DISCUSSION

The static analysis results were taken, and four plots were created to compare the results of the benchmark wheel to each of the 36-wheel specimens. By doing this, it allows us to study the relationship between the results of the static analysis and the wheel specimens. Besides, it allows us to visualize the results well and determine which specimens were performing better. In the plots, different colors were used to distinguish the wheel specimens. In these plots, the red bar indicates the magnesium alloy benchmark wheel while the yellow and blue bars separate each of the 36 PEEK 90HMF20 wheel specimens according to the various wheel widths (5.5", 6", 6.5", 7", 7.5" and 8") to prevent confusion to the reader.

Wheel masses against wheel specimens

Fig. 3 shows the plot of wheel masses against wheel specimens. As mentioned previously, this study aimed to design a lightweight racing wheel. Therefore, the masses of each wheel specimens were extremely important. It allows us to determine the suitability of the PEEK 90HMF20 in replacing the traditional magnesium alloy. With the plot, it allows us to determine which wheel specimen had the lightest wheel mass.

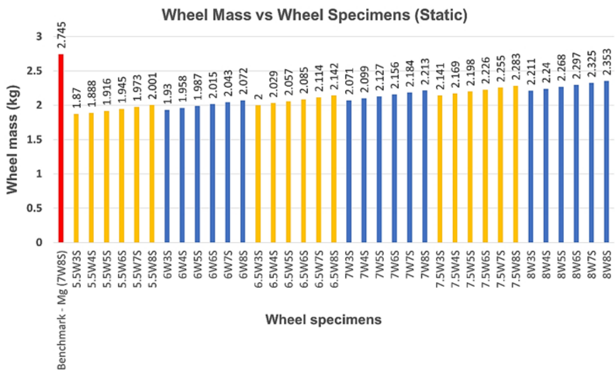


Figure 3: Plot of wheel masses against wheel specimens

Based on the plot of the wheel mass against wheel specimens as shown in the figure above, the red bar indicates the benchmark magnesium 7W8S wheel. It can be easily seen that the mass of the magnesium alloy benchmark wheel was heavier than the wheels made from PEEK 90HMF20. The heaviest configuration of the PEEK 90HMF20 wheel, 8W8S at 2.353kg was 0.392kg (-17%) lighter than the magnesium benchmark wheel, 7W8S at 2.745kg. The result will be more noticeable when comparing the PEEK 90HMF20 7W8S configuration wheel (2.213kg, -19%) to the magnesium benchmark wheel which was also a 7W8S configuration (2.745kg). The lightest wheel configuration was found to be the 5.5W3S at 1.87kg which was reasonable due to its shortest width at 5.5” and least spokes quantity. Hence, it can be concluded that the PEEK 90HMF20 was an ideal material to replace the traditional magnesium alloy during wheel manufacturing.

Von Mises stresses against wheel specimens

Figure 4 shows the plot of von Mises stresses against the wheel specimens. As mentioned previously, the von Mises stress allows us to study the magnitude of the stresses in the wheels due to the applied loads. According to Simscale, the higher the von Mises stress, the higher the chance for the material to yield. Therefore, it is important for the wheel to have lower von Mises stress to avoid yielding from happening within the wheels. Hence, the plot allows us to determine which wheel specimen had the lowest von Mises stress during the test.

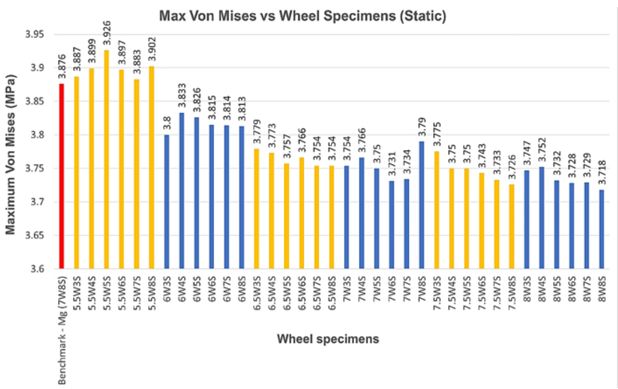


Figure 4: Plot of maximum von Mises stresses against wheel specimens.

Based on the plot of the maximum von Mises stresses against wheel specimens as shown in the figure above, the magnesium benchmark wheel indicated by the red bar had von Mises stress of 3.876MPa which was lower than all of the 5.5” wheels. However, the rest of the specimens in other wheel widths performed better than the benchmark by having lower von Mises stresses. Based on the plot, it can be observed that the 8W8S wheel had the lowest von Mises stress at 3.718MPa while the 5W5.5S wheel had the highest stress at 3.926MPa.

Besides, it is apparent that the von Mises stress decreased as the wheel width and spoke quantity increased. Consequently, it can be concluded that both the wheel width and spoke quantity played vital roles in affecting the von Mises stress. According to the simple formula of pressure calculation, P=F/A, the lower the area of an object, the lower the pressure being experienced by the object. In this case, a wider wheel that consists of a large quantity of spokes has a larger overall surface area. Therefore, a wheel with a larger surface area experiences a lower magnitude of von Mises stress.

***Maximum* displacements against wheel specimens**

Fig. 5 shows the plot of maximum displacement against wheel specimens. As mentioned previously, the displacement, also known as deformation, allows us to study how much the wheels deformed due to the external loads. This was important as it allows us to study the behavior of the wheels during the static condition.

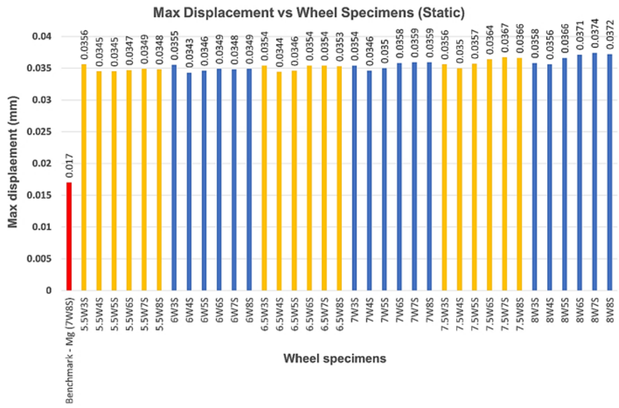


Figure 5: Plot of maximum displacements against wheel specimens

Based on the plot of the maximum displacement against wheel specimens as shown in the figure above, the benchmark wheel, indicated by the red bar had the lowest displacement at 0.017mm compared to the rest of the wheel specimens. Among the specimens, the 8W7S wheel had the maximum deformation of 0.0374mm, while the 6W4S wheel had the minimum deformation of 0.0343mm. Based on the plot, it can also be noted that the 36-wheel specimens had a similar displacement range despite having different widths and spoke quantities. Unlike the brittle material, ductile material has a larger plastic deformation region in the stress-strain curve. This allows the material to be able to absorb more stresses without having any cracks in the material (Venugopal et al. 2022). Therefore, allowing the ductile material to withstand more stresses than brittle material before failure occurs. Table 4 shows the composition of the AZ31 magnesium allow.

Besides the strength-ductility balance of AZ31 magnesium alloy via accumulated extrusion bonding combined with two-stage artificial cooling, the traditional magnesium alloys such as AZ31 did not perform well in deformation compared to modern magnesium alloys (Han et al. 2021). In order to improve the mechanical properties of the alloys, rare earth elements such as Gd (gadolinium), Yn (yttrium nitride), Y (yttrium), Ce (cerium), Sm (samarium) were added to the alloys’ compositions in order to improve the ductility and strength of the alloys. Based on Xu et al. 2015, the composition of the magnesium alloy AZ31, as shown below, did not consist of any rare earth elements. Therefore, this was the reason why the AZ31 alloys did not perform well in deformation.

Table 4: The composition of the AZ31 magnesium alloy

Al	2.6
Zn	0.86
Fe	0.0015
Cu	0.0012
Mn	0.2859
Ni	0.001
Si	0.0092
Mg	Balance

Minimum safety factors against wheel specimens

Figure 6 shows the plot of minimum safety factors against wheel specimens. The safety factor is extremely important as it allows us to determine whether the wheels will fail due to the external loads. Based on the figure below, a dotted blue line was added to the plot which indicates the safety factor of 1. This is the minimum safety factor which the wheels must achieve in order to be deemed safe.

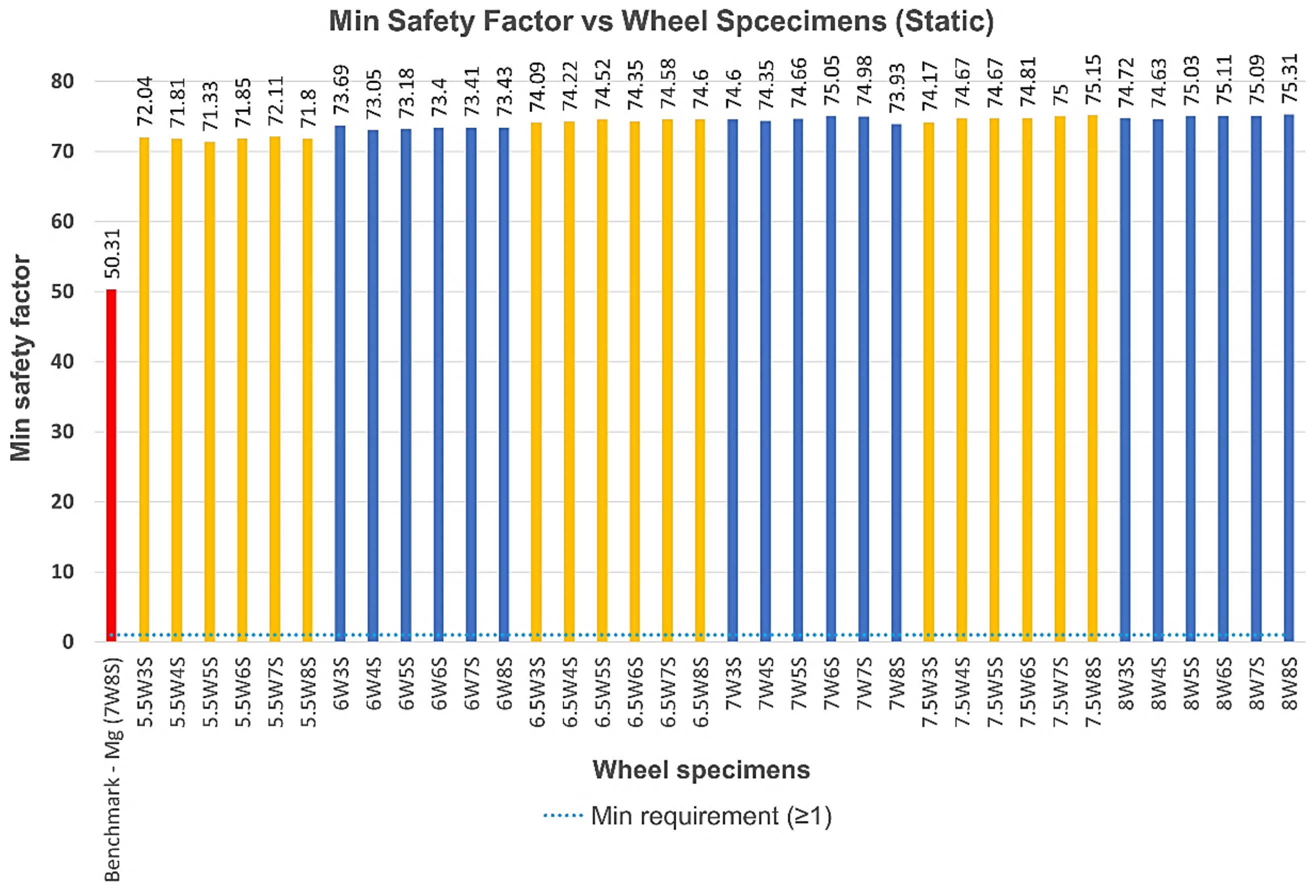
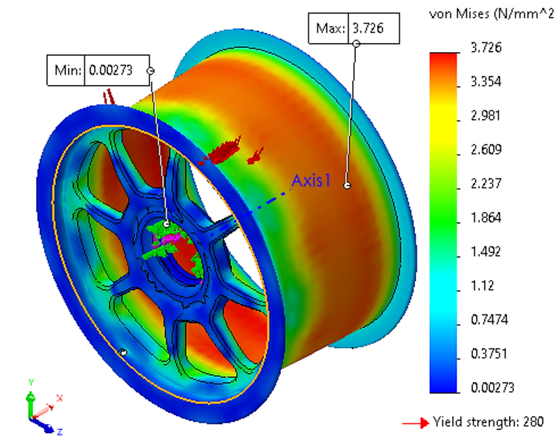


Figure 6: Plot of minimum safety factors against wheel specimens

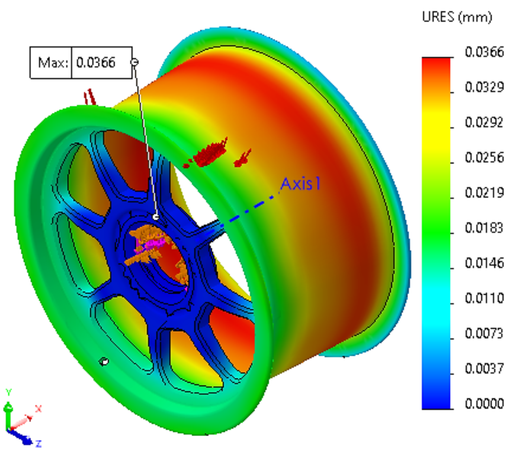
According to the plot of the minimum safety factor against wheel specimens as shown in the figure above, all of the wheels had exceeded far beyond the minimum safety factor of 1. This is valid because the purpose of the static analysis was to study the behavior of the wheels under static conditions. This is because the main purpose of a wheel is to drive the vehicle forward and backward, not just to provide stationary support to the vehicle. The wheels must be able to withstand the external loads without failing during extreme events such as high-speed cornering. Therefore, a wheel should achieve a very high value of static safety factor, as shown in the plot above.

Based on the plot above, the benchmark wheel indicated by the red bar has the lowest maximum safety factor of 50.31 compared to the rest of the wheel specimens. Among the PEEK 90HMF20 specimens, the 8W8S wheel had a maximum safety factor of 75.31, while the 5.5W5S wheel had a minimum deformation of 71.33. Based on the plot, it also can be noted that the 36-wheel specimens had a similar range of displacement despite having different width and spoke quantity lengths. Therefore, it can be concluded that the material of the wheel plays a vital role in affecting the safety factor of the wheel. Hence, the PEEK 90HMF20 can be an alternative material to replace the magnesium alloy for wheel manufacturing.

During the static analysis, the only purpose of the wheel was to provide stationary support to the vehicle without failing. Therefore, the weight of the vehicle and driver was assumed to be distributed evenly to each of the 4 wheels. Besides, the tyre pressure was also added to the wheel barrel to simulate the wheel with the tyre mounted. Fig. 7 shows the weak points in the wheel during the analysis.

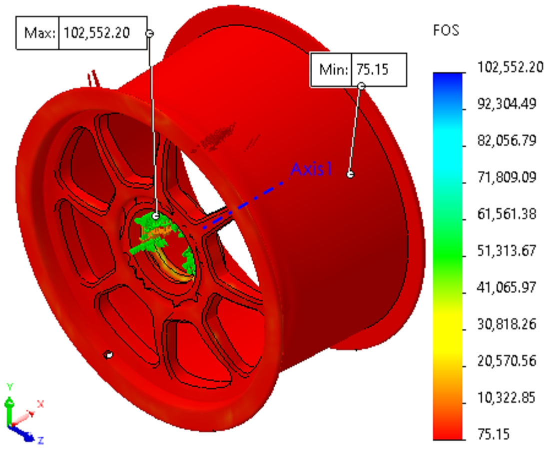


(a)



(MPa)

(b)



(c)

Figure 7: The weak points in the wheel during static analysis: a) von Mises Stress, b) Displacement (mm), and c) Safety factor

Based on Fig. 7, it can be noticed that the wheel barrel exhibited the maximum amount of von Mises stress at 3.726MPa, and it also suffered the most displacement (deformation) at 0.0366mm. Besides, the wheel barrel was also having the minimum amount of static safety factor at 75.15. This was due to the tire pressure of 0.083MPa. Therefore, the thickness of the wheel barrel can be increased to improve the results. However, by doing this, it increases the wheel mass. Since the static safety factor of 75.15 attained by this specimen was far beyond the safety factor of 50.31 attained by the benchmark wheel. Hence, the improvement to the wheel by increasing the thickness of the wheel barrel can be omitted.

CONCLUSION

This study designed a new lightweight racing wheel. A Finite Element Model (FEA) was implemented to investigate the static analysis of the newly designed lightweight racing wheel. Since the lightweight wheel characteristics play an important role in the stability and control of the racing car under severe manoeuvres, the wheel mass, von Mises stress, deformation, and safety factor were determined. Conclusively, the static analysis allows us to study the behavior of the wheels during the static condition. This was an important analysis as the main purpose of the wheels was to drive the vehicle. Therefore, the wheel specimens were expected to pass the static analysis without any failures. Even so, this study was limited to simulation-based assessment only. Hence, for real-world application, it is highly advised that experimental studies are also carried out.

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