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Dynamic Cornering Fatigue Test of New Lightweight Racing Wheel for Formula Society of Automotive Engineers (FSAE) Race Car

Muhammad Izzat Nor Ma'arof[1,*], Anies Faziehen Zakaria[2], Riang Liang[1], Girma Tadesse Chala[3], Nurzaki Ikhsan[4], Mohamad Fariz Mohamed Nasir[5]

1 Department of Mechanical Engineering, INTI International University, 71800 Nilai, Negeri Sembilan, Malaysia
2 Department of Engineering Education, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia
3 International College of Engineering and Management, Muscat, Oman
4 School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA, 40450, Shah Alam, Selangor, Malaysia
5 STARE Resources Sdn. Bhd., Wisma Rampai, 2-4-29, Fourth Floor, Jalan 34/26, Taman Sri Rampai, 53300 Kuala Lumpur, Malaysia

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ABSTRACT

This paper presents the design of a new lightweight racing wheel. A lightweight wheel has the potential of providing better manoeuvrability and overall control during high performance operation. In this study, a Finite Element Model (FEA) was implemented to investigate the dynamic cornering fatigue of the newly designed lightweight racing wheel. Due to the reason that the test was performed in a worst-case scenario and the specimens were required to achieve the minimum life cycles, out of the 36 specimens, the result has shown that only 12 specimens were able to pass the test. Based on the analysis, the specimens highlighted in green were those that could pass the test. It can be noted that those passed specimens were having 7 and 8 spokes. Conclusively, the cornering fatigue test shows that the spoke is vital in affecting the wheels' performance. For future studies, it is recommended that experimental studies are conducted.

1. Introduction

Car racing competition such as Formula Society of Automotive Engineers (FSAE) is a platform to train new engineers and designers toward producing the well-developed automotive parts. Racing wheel is one of the essential parts in the race car that need to be highlighted in design safest and fastest card racing [1]. To determine the optimal design, the computational analysis can be helpful. There is a series of testing needed to produce a better racing wheel. This study has proposed the new light weight design of racing wheel as the new part. A dynamic fatigue test was conducted by using a benchmarking approach. A total of 36 spacemen was tested, however, only 12 specimens were achieved the race car standard. The finding is helpful as the reference and benchmarking design for the new light racing wheel and improvement for the safest car racing.

* *Corresponding author.*
E-mail address: muhammadizzat.maarof@newinti.edu.my

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The car racing is a big part in car industry and automotive age. The car racing culture is originated from the beginning of the car production. The car racing culture help to improve most the technology, and testing various of automotive part, system and also components [2]. Today's, race car has evolved to become safer, faster and efficient. Besides, this car racing is an exciting sport and significant sport in various academic and industrial perspectives such as industrial design [3], manufacturing [4] and engineering education. With well-developed race car, one of the critical components that getting more attention is wheel design and performance [5]. Traditionally, the new wheel design and performance testing (i.e. accelerated fatigue test) was conducted in the laboratory before the production stage. However, the testing will consume more time, approximately six months for the design based on the requirement, and the prototype will take at least a week to complete. The time-consuming process is due to the complex shape and style of steel wheel and it is influencing the assessment of fatigue life using analytical approach. An improvement process is needed to meet the race car standard with high-quality product, reliability, safety, and comfort. Therefore, the computer simulation is widely used to design and develop the critical part of the racing wheel.

Looking toward the important of car racing industry toward engineering design and education, INTI International University takes a proactive action to train their students for participating involve in Formula Society of Automotive Engineers (FSAE) Race car. FSAE is Formula SAE is a student design competition organized by SAE International that aimed to challenges students to conceive, design, fabricate, and compete with small formula-style racing cars. (Kolossvary, Dory, & Feszty) [6] Teams spend approximately a year designing, building, and preparing their vehicles for a competition. These cars are judged in a series of static and dynamic events, including technical inspection, cost, presentation, engineering design, solo performance trials and high-performance endurance. Focusing on the FSAE challenge, this study presented the new lightweight racing wheel design. INTI International University's FSAE vehicle. Without proper engineering designs and analyses, a high wheel will be damaged and fail during the cornering test if it could not withstand the extreme loads. This will cause disastrous accident to both the FSAE driver and other road users. Therefore, the test was extremely important as it evaluates the wheels' structural performance, allowing us to study how well the wheels could cope with the stresses during the cornering event. This paper focuses on the dynamic cornering fatigue test to determine the wheel design and performance.

2. Literature Review

The car racing performance research is a study that focuses on improvement for all the parts, components, design and performance for both racing sports and product design. Besides, a car racing competition allows the car racing improvement. In FSAE, most studies were conducted to improve various parts of the race car using different tools and analysis [7-9]. For example, racing wheel both core and rear wheel is a complicated racing system that influence most of the car performance and stability [10]. Besides, Shinde *et al.,* [11] investigated the causes of the failure of an FSAE car front wheel hub which broke down during testing using SEM analysis. This study found that the combined effect of bending, torsional shear and axial stresses led to the initiation of a crack which propagated during testing of the car ultimately resulting in the catastrophic failure of the hub. Thus, the wheel design can be improved by determining the design's failure factors. Other than wheel, the fuel efficiency of the FSAE also contribute to the success of race car [12]. This study suggested the woven carbon fibre composite to improve the car efficiency. The woven carbon fibre composite helps reduce overall weight of the vehicle. The project incorporated the design of wheel rims using CREO and SolidWorks, analysis of rims for safety via ANSYS composite pre-post and simulation software.

Another analysis using ANYSS was conducted to analyse and optimize the rear wheel core of FSC racing car conducted an analysis and optimization of rear wheel core of FSC racing car based on ANSYS [10]. The pure aluminium alloy material conforms to the requirements of the car to the deformation to improve its wheel resistance. The steering wheel is particularly significant as the driver's direct control device for controlling the car. It has stringent standards in terms of stability, strength, and ergonomics. A paddle shift mechanism is commonly found in FSAE racing cars. A well-designed steering wheel can provide the driver with long-distance driving comfort. Simultaneously, a more tactile and reliable shift mechanism facilitates the driver's more convenient control of the transmission gear when driving on the track, allowing the car's performance to shine (Wang and Wang) [13].

3. Research Methodology

The dynamic cornering fatigue test is a standard SAE test (SAE) which simulates cornering induced loads to the wheel. Dynamic cornering fatigue test (DCFT), also known as bending fatigue test was carried out for the benchmark wheel and 36-wheel specimens. Ref (Cai, Wang, Huang, Liu, & Liu) [2] was conducted a test to simulate the load condition of the wheels when the vehicle was cornering. According to the PDCTEAM [14], the cornering is a measurement of the force exerted on the vehicle's centre of gravity during the cornering event. The force is measured in g-force but expressed as lateral acceleration (PDCTEAM).

3.1 Analysis Setup

The DCFT were carried out according to the International Organization for Standardization's 2015 Road vehicles – Passenger car wheels for road use – Test methods, ISO 3006: 2015. It is an international standardized uniform test method developed and established by the Society of Automotive Engineers (SAE). The standard consists of two laboratory methods such as DCFT and DRFT. (ISO3006, 2015) With this ISO standard, it allows us to carry out the wheel testing in a more standardized approach, therefore, generating a more reliable result.

According to the ISO 3006: 2015 for DCFT, the wheel was loaded on a specific cornering test machine as shown in the simple Figure 1 below. The bottom wheel flange of the wheel will be clamped, and a shaft will be attached to the mounting surface of the wheel. A force will be generated to the bottom part of the shaft. This was to create a constant cyclical rotation bending moment to the upper end of the shaft that was mounted to the wheel. Therefore, this test setup was able to simulate the wheel during the cornering event. The wheel will be considered safe if the wheel was able to meet at least 1x105 cycles without having a crack during the test [2].

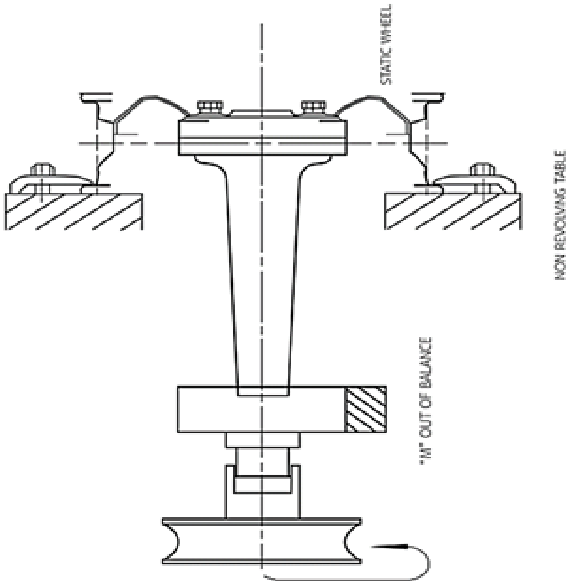

Fig. 1. Contour Setup of Dynamic Cornering Fatigue Testing Machine (Cai, Wang, Huang, Liu, & Liu)

The cornering test was carried out by using the SolidWorks. The fixture was set to the bottom wheel flange of the wheel based on the ISO 3006: 2015. As similar to the static analysis in the subsection 4.3.1 above, a force of 693N was applied to the wheel bore to act as the distributed weight of the FSAE vehicle and the driver. The tire pressure of 0.083MPa was applied to the wheel barrel. However, in the DCFT, an angular velocity was added to simulate the wheel in rotating situation. Besides, lateral force was added to the inner wheel mounting surface during the cornering test. Lastly, a moment was also added to the wheel mounting surface to simulate the bending force generated by the shaft of the test machine.

According to the Formula SAE Rules 2021 handbook, every FSAE vehicle will go through the Autocross Event, which evaluates the vehicle's manoeuvrability and handling on a tight course. The most extreme turn was a hairpin turn with a 9m outside diameter. The handbook also mentioned that the average speeds of the vehicle should be 40km/h to 48 km/h [15]. Therefore, the maximum speed of the FSAE vehicle during the Autocross Event will be assumed to be 48 km/h, roughly 13.333 m/s. Hence, the calculation of angular velocity of the wheel was done as follow:

$$W_c = \frac{V}{r} \tag{1}$$

Where ω_c stands for the angular velocity of the FSAE vehicle in rad/s during the cornering, v is the speed of the vehicle in m/s, and r is the radius of the wheel in m. The diameter of the wheel is 13”, which is roughly 0.3302m, thus, the radius of the wheel is 0.1651m.

Besides, the calculation of the lateral force was carried out as follows:

$$a_c = \frac{V^2}{r_c} \tag{2}$$

Where a_c stands for the angular acceleration of the FSAE vehicle in rad2/s during the cornering, v is the vehicle speed, and r_c is the radius of the 9m hairpin turn at 4.5m.

The calculated value of angular acceleration of the vehicle at 39.504 rad2/s was then applied to the calculation of the lateral force as shown below:

$$F_L = ma_c \quad (3)$$

Where F_L is the lateral force, in newton, N, in which was exerted to the wheel when the FSAE vehicle was cornering. The m is the mass of the vehicle at 215kg, and the a_C stands for angular acceleration of 39.504 rad^2/s.

According (Bagherzadeh, Murugesan, & Deka, 2020) , the length of the bending shaft of the test machine was 500mm (0.5m). Therefore, the length of the shaft was assumed to be 0.5m. Besides, the total weight of the FSAE vehicle at 2109N (215kg) was taken and assumed to be the bending force during the worst-case scenario. In SolidWorks, the "Remote Load" was used to create the bending moment. Based on the Figure 2 below, the distance between the inner wheel mounting and the location of the applied force of 2109N was 0.5m on the x direction. The force was set to face the direction of -z direction, so that the bending moment was created.

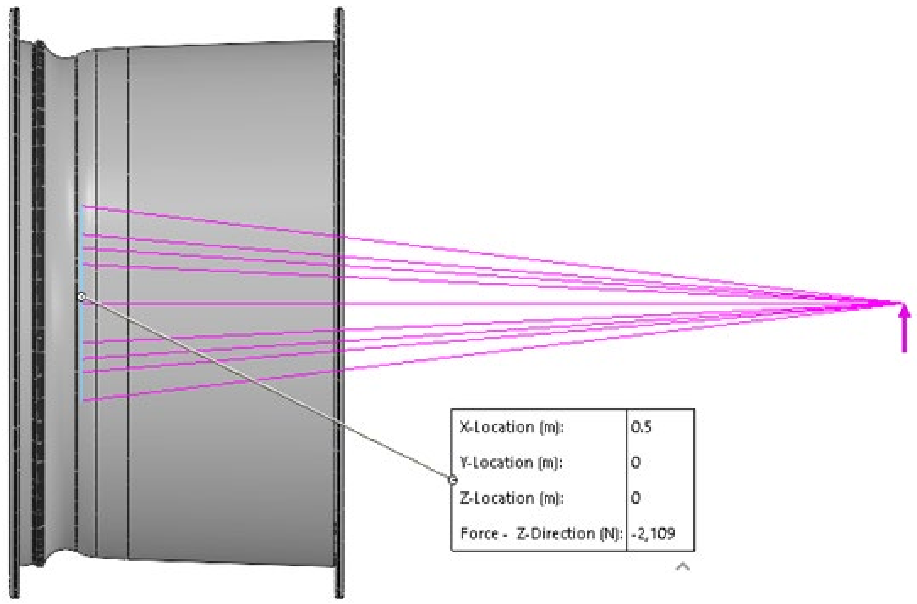

Fig. 2. The bending moment was created by using the "Remote Load" function in SolidWorks (Bagherzadeh, Murugesan, & Deka)

Figure 3 shows the wheel model with its lower wheel flange that indicated by the blue highlighted area was constrained in order to simulate the ISO 3006:2015 test.

Figure 4 shows the complete setup of the analysis. The distributed load of the vehicle was indicated by the pink arrows, purple arrows indicate the tire pressure, red arrow indicates the angular velocity, and the yellow arrows indicate the lateral force. Finally, the blue arrow indicates the bending moment to simulate the wheel in cornering action.

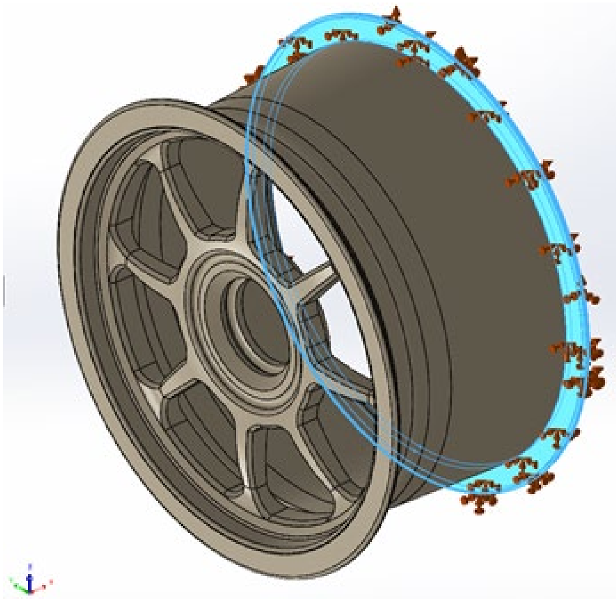

Fig. 3. The lower wheel flange was constrained during the analysis

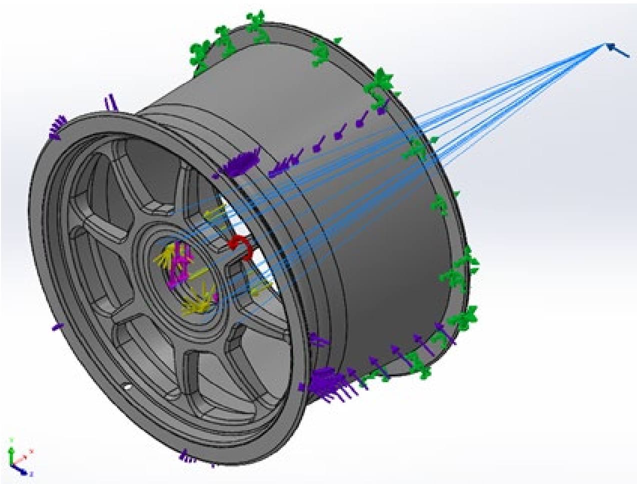

Fig. 4. The isometric view of the test setup for the DCFT

4. Results

After carrying out the DCFT, the results such as damage percentage, minimum total life (life cycle), and minimum load factor were collected and tabulated accordingly to the specimen codes. According to the SolidWorks' official help website, the damage percentage indicates the percentage of cumulative damage in which the value of 1 indicates that the fatigue event consumes 100% of the model life. The life indicates the total number of cycles that causes the model to fatigue. The SN curves of the materials will be used to calculate the total life. Lastly, the load factor indicates the load factor of safety at each location of the model. A load factor of safety of three indicates that the model will experiences fatigue failure if multiplying all the defined loads for static study by 3.

The results of the DCFT were tabulated systematically according to the codes of the wheel specimens as shown in the Table 1. Table 2 shows the comparison results of the fatigue cornering analysis on the benchmark wheel (7W8S) in different materials, magnesium, and PEEK 90HMF20.

Table 1
Analysis setup

Constant variable (CV)	Manipulated variable (MV)	Responding variable (RV) DCFT
Wheel material	Wheel width	Damage percentage
Wheel construction	Spokes quantity	Life cycle
Wheel diameter		Load factor
Wheel offset		

Table 2
Comparison results of benchmark wheel in different material

Benchmark material (7W8S)	Damage percentage (%)		Min total life (cycle, $\geq 1 \times 10^5$)	Min load factor (≥ 1)
	Max	Min		
Magnesium	2917	2	34277	0.86
PEEK 90HMF20	17	9	5746723	1.24

While the Table 3 shows the full results of the 36 specimens in PEEK 90HMF20.

Table 3
Improvements of benchmark wheel in different material

		Mg	PEEK 90HMF20	Percentage difference
Damage (%)	Max	2917	17	-17058.8 %
	Min	2	9	+77.8 %
Min total life (cycle, $\geq 1 \times 10^5$)		34277	5746723	+99.4 %
Min safety factor (≥ 1)		0.86	1.24	+30.6 %

5. Discussion

The results of the DCFT were taken and three plots were created to compare the results of the benchmark wheel to each of the 36-wheel specimens. The plots are the maximum damage percentages, minimum life cycles, and minimum load factors against wheel specimens. This allows us to visualize the results well and also allowing us to determine which specimens were performing better during the DCFT. Similarly, different colours were used to distinguish the magnesium alloy benchmark wheel and the PEEK 90HMF20 wheel specimens.

5.1 Maximum Damage Percentages against Wheel Specimens

The Figure 5 the plot of maximum damage percentages against wheel specimens. As mentioned previously, the damage percentages allow us to determine how much the wheel models suffer damages that measured in percentage due to the external loads during the cornering event. A model that suffers high value of damage percentage shows that the large portion of model life was eliminated by the fatigue event. Therefore, it is important to have lower damage percentage so that the wheel will be able to last longer. With this plot, we can study the outcome of the cornering test and determine which wheel specimens exhibit the lowest damage percentage.

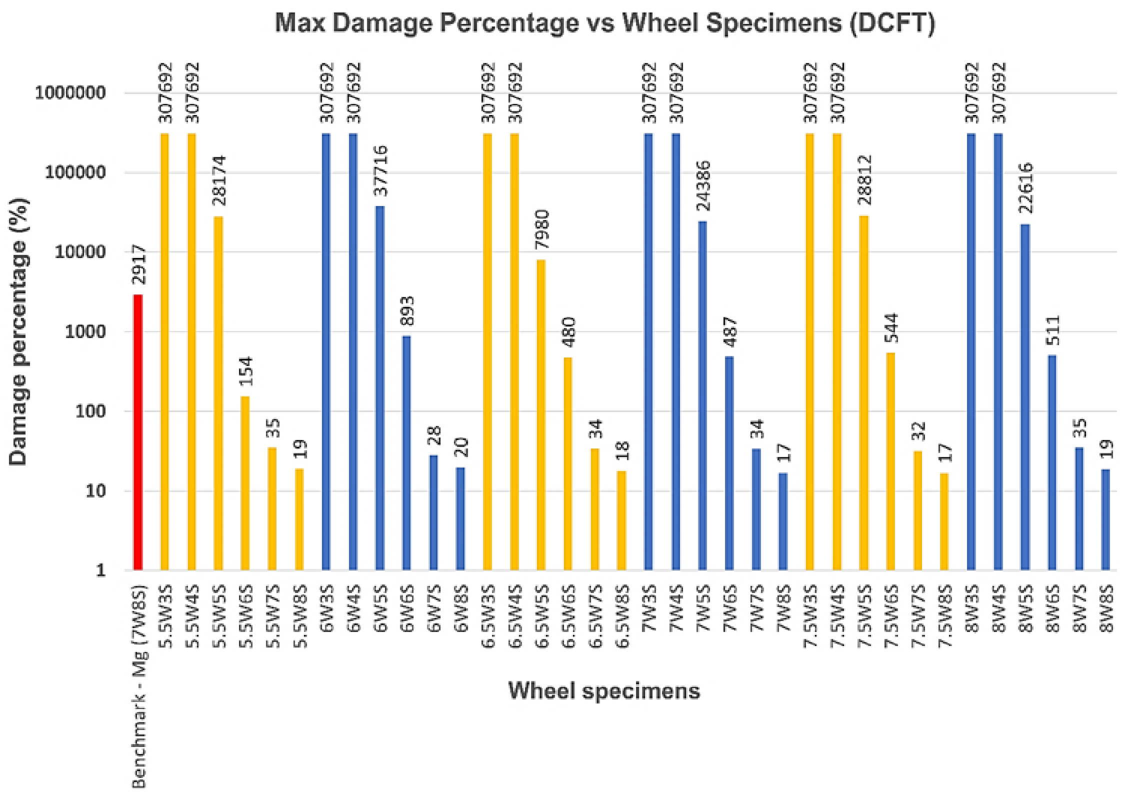

Fig. 5. Plot of maximum damage percentages against wheel specimens

Based on the plot above, the magnesium benchmark wheel that indicated by the red bar was having a percentage damage of 2917%. Among the PEEK 90HMF20 wheel specimens, every 3S and 4S wheels experienced the similar amount of maximum damage percentage at 307692% despite having different wheel width. This was because the stresses that presented in the wheel model had exceeded the maximum stress value in the SN curve of the PEEK 90HMF20 as shown in the Figure 6 below. However, SolidWorks allows us to continue the study by using the smallest number of cycles in the SN curve to determine the damage percentages in the wheels. Therefore, all of the 3S and 4S wheels were experiencing the similar value of damage percentages.

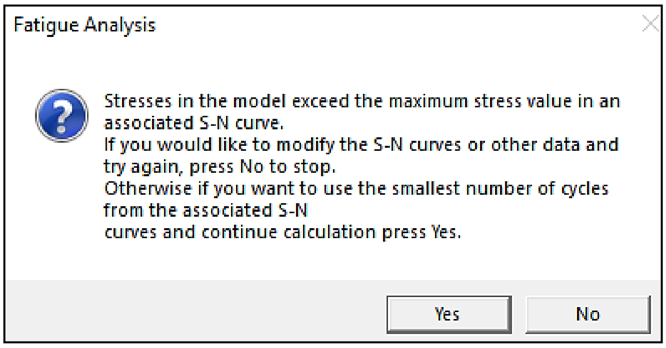

Fig. 6. Fatigue analysis problem during the 3S and 4S wheels' simulations

Based on the Figure 6, it is noticeable that the magnesium alloy benchmark wheel performed better than all of the 3S, 4S and 5S wheels. However, the rest of the 6S, 7S, and 8S wheels were having a lower damage percentage compared to the benchmark wheel with the lowest percentage of 17% that exhibited by both 7W8S and 7.5W8S wheels. Besides, a similar trend can also be observed in each of the wheel widths, the damage percentage decreased as the wheel width and spoke quantity increased. Therefore, it can be concluded that a wheel with wider width and having a greater number of spokes exhibits lower damage percentage.

5.2 Minimum Life Cycles against Wheel Specimens

The Figure 7 below shows the plot of maximum life cycles against wheel specimens. As mentioned before, the life cycle indicates that total number of cycles that a model was able to run before fatigue failure occurs. According to Cai *et al.,* the wheel must be able to demonstrate at least 1x505 cycles DCFT in order to be deemed safe. Similar to the plot of static safety factor, a blue dotted line was added to the plot to indicate the minimum cycles of 1x505. Thus, it allows us to determine easily on which wheels were safe and which were not.

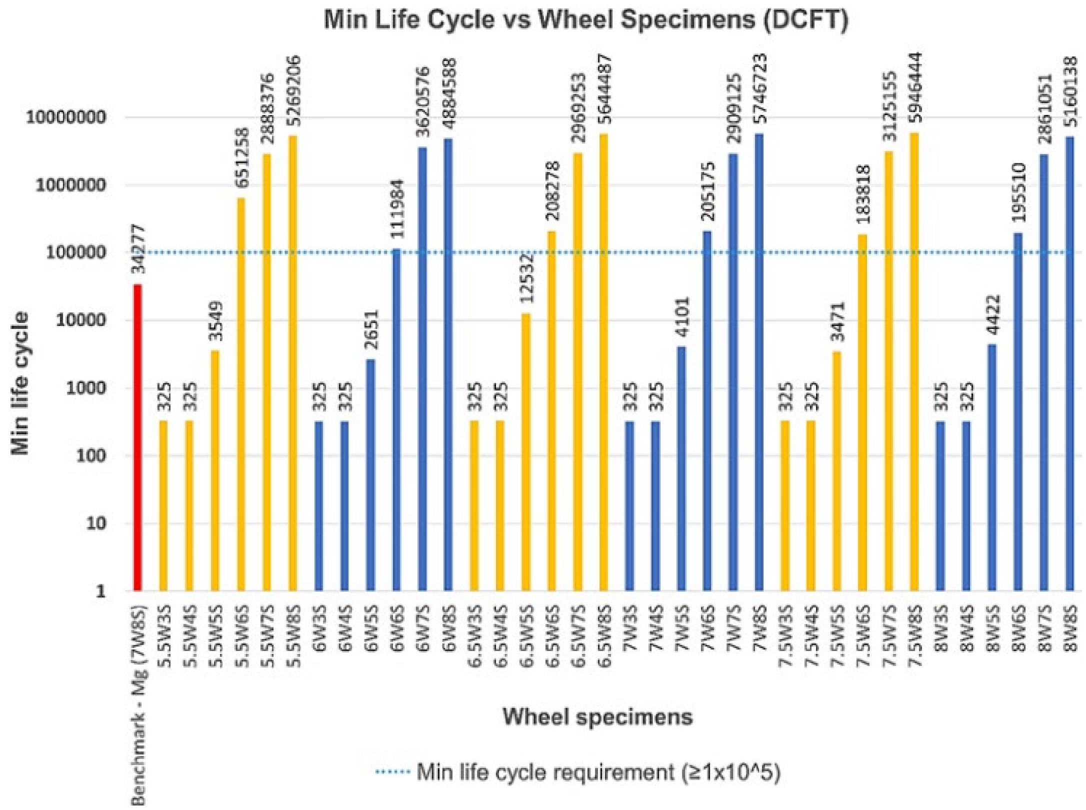

Fig. 7. Plot of minimum life cycles against wheel specimens

According to the plot of the minimum life cycles against wheel specimens as shown in the figure above, some of the wheel specimens were able to achieve millions of cycles during the cornering test while some of the wheels were exhibiting only hundreds of cycles. Due to the huge difference between the highest and lowest cycles, therefore, the plot is a semi-log graph where the minimum life cycles on the y-axis is in the exponential scale of base 10. By doing this, it allows us to read the life cycles of each of the wheels at ease.

Based on the plot above, the magnesium alloy benchmark wheel was having a life of 34277 cycles in which had failed to meet the minimum requirement of 1x505 cycles. Among the PEEK 90HMF20 wheel specimens, the 3S, 4S, and 5S wheels in every wheel width also failed to meet the minimum 1x505 cycle requirement while the 6S, 7S, and 8S wheels were able to meet requirement. The specimens that exhibited the highest cycle was 5946444 cycles by the 7.5W8S wheel while all of the 3S and 4S wheels exhibited the lowest life cycle at only 325 cycles. As mentioned earlier, this is due to the reason that the stresses that presented in the wheel model had exceeded the maximum stress value in the SN curve of the PEEK 90HMF20. Therefore, SolidWorks assumed the lowest life cycles that presented in the SN curve for these wheels during the calculations. As a results, among the wheels, only the 6S, 7S, and 8S wheels can be deemed safe during the cornering fatigue test.

5.3 Minimum Load Factors against Wheel Specimens

The Figure 8 shows the plot of minimum load factors against wheel specimens. As mentioned earlier, the load factor refers the load factor of safety at each node of the model. Similar to the static safety factor, the wheels must be able to meet the minimum requirement of 1 load safety factor during the DCFT in order to be deemed safe. Therefore, a blue dotted line was also added to the plot to indicate the minimum load factor of 1.

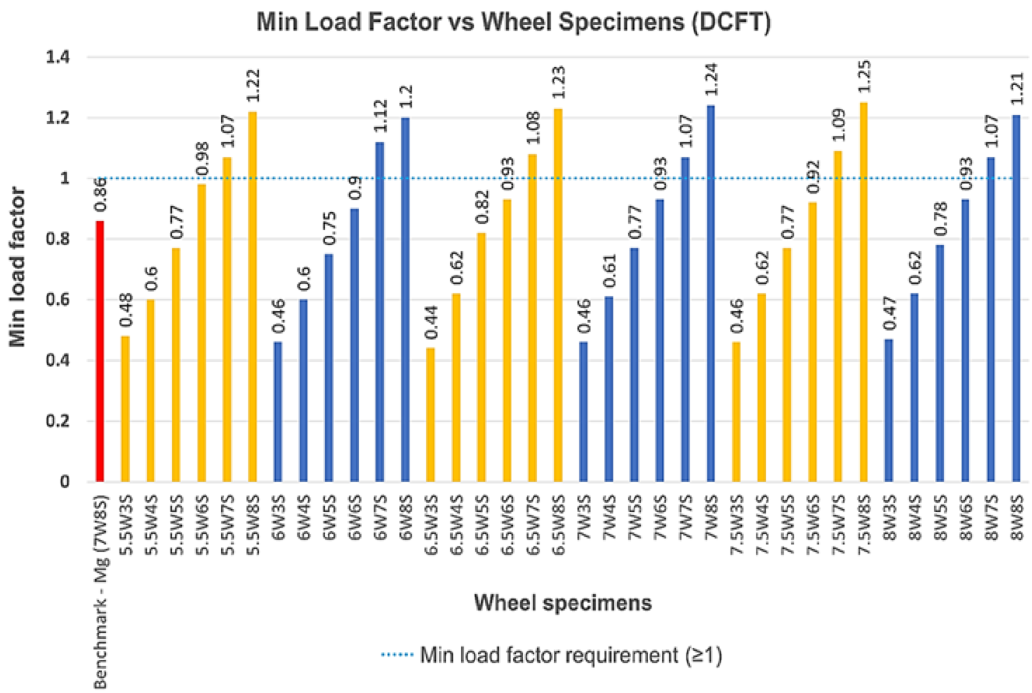

Fig. 8. Plot of minimum load factors against wheel specimens

According to the plot of the minimum load factors against wheel specimens as shown in the figure above, some of the wheel specimens were able to exceed the minimum load factor of 1 while some of the wheels could not. The magnesium alloy benchmark wheel was one of the wheels that had failed to meet the minimum requirement at only 0.86. Among the PEEK 90HMF20 specimens, all of the 3S, 4S, 5S, and 6S wheels had also failed to meet the requirement despite having different wheel widths. The only specimens that were able to meet the requirement were the 7S and 8S wheels in which the highest load factor was exhibited by the 7.5W8S wheel at 1.25. Therefore, it can be concluded that having a larger quantity of spokes allows the wheels to achieve a higher value of load factor. In conclusion, with larger spokes, the loads can then be distributed more to each spoke, thereby, reducing the stresses in the weak points of each spoke and increasing the load factor.

6. Conclusion

In conclusion, the dynamic cornering fatigue test allows us to study the behaviour of the wheels when performing extreme cornering events. The wheels were set to perform cornering at 9m of hairpin turn with the maximum speed of 48km/h. This was to simulate the wheels to perform cornering during the worst-case scenario. During the test, the wheels were loaded with multiple loads such as the lateral force and bending moment when the vehicle performed cornering. Besides, the wheels were also required to meet a minimum life cycle of 1x105 cornering cycles. Due to the reason that the test was performed in a worst-case scenario and the specimens were required to achieve the minimum life cycles, out of the 36 specimens, only 12 specimens were able to pass the test. Based on the table above, the specimens highlighted in green were those that could pass the test. It can be notified that those passed specimens were having 7 and 8 spokes. Conclusively, the cornering fatigue test shows that the spoke is vital in affecting the wheels' performance. For future studies, it is recommended that experimental studies are conducted.

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