PROGRESS IN ENGINEERING APPLICATION AND TECHNOLOGY
e-ISSN: 2773-5303

PEAT

Vol. 5 No. 1 (2024) 320-329
https://publisher.uthm.edu.my/periodicals/index.php/peat

Design and Analysis Quarter Car Test Rig Model by Using Simulation Software

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DOI: https://doi.org/10.30880/peat.2024.05.01.034

Article Info

Received: 28 December 2023
Accepted: 18 January 2024
Available online: 15 June 2024

Keywords

Quarter Car, Test rig, FEA Simulation, Static Condition, Cornering Condition

Abstract

This thesis presents the design and analysis of a quarter-car test rig model to study fundamental vehicle dynamics. The objective of this research is to develop a new quarter car test rig model and the structure's safety has been analyzed using Solidwork software. To achieve this purpose, the previous quarter's car test rig models are studied through a literature review to find a base model. After that, new variants of designs were formed through the design tree, and all designs were based on the base model. From all variants of design, the best design of the variants was selected through a screening process, and lastly, a scoring concept method was used to find the final design. The parameters considered for comparison include the structure, materials, cost, and dimension, and the most essential characteristic is the Finite Element Analysis (FEA) simulation result of the test rigs. Graphs were recorded and analyzed for maximum stress, maximum displacement, and Factor of Safety (FOS). The materials used and the shape of the test rig frame have influenced the simulation result. The highest marks model based on the scoring table has been chosen as the final design in this study. The result has determined the suitability of the test rig for real-world applications. The results obtained from this study will provide valuable insights into the mechanical performance of the quarter-car test rig model, helping to ensure its safety and effectiveness. This research contributes to vehicle dynamics by comprehensively understanding the design and analysis process for quarter-car test rig models.

1. Introduction

Most engineers have struggled with quality, development time and performance of products under development. It also happened in the automotive industries because it was necessary to improve the efficiency of research and development due to changing market demand. Nowadays, the primary industry trend is building more indoor lab test equipment. Testing in a laboratory environment allows engineers to have greater control of the experiment and less time required compared to a road test. Generally, laboratory testing is required one-fourth of the time as a road test [1].

The vehicle suspension system is intended to provide a good road holding characteristic to ensure maximum traction at all road conditions and good ride comfort to the passengers by absorbing a part of the vibrations induced by the road profile. Therefore, several simulations and testing need to be carried out during the design phase. Therefore, a test rig is the most suitable equipment that can be used to examine the quality of the suspension system. Test rigs offer higher flexibility to incorporate different suspension systems at a lower cost. Test rigs can also induce the road profile and measure the system responses, such as sprung and unsprung mass vibrations.

However, safety is the most crucial issue in manufacturing test rigs because many tests with high forces will be applied. Forces such as aerodynamic forces and vehicle roll-induced moment forces will be applied to the test rig structure when doing the testing activity [2]. In addition, the available quarter car test rig in the market is quite expensive nowadays and still does not offer the flexibility needed. In order to overcome the problem, a new quarter car test rig model has been designed after the scoring and screening process. After that, a finite element analysis (FEA) was made using technical software. The result has been compared based on mechanical performance and design parameters.

2. Materials and Methods

A scoring and screening process has been used to improve an existing quarter-car test rig. Some variants of test rigs will be compared in the process. The variable design of the test rig was produced from the base model using the design tree method. The first step in this study is to find a base model from a literature review and previous research. So, Figure 1 below shows three base models from previous research used in this project. Each model will be divided into four criteria, which are frame structure, materials, linear guide motion, and dimension of the rig. Table 1 below shows the characteristics of each base model.

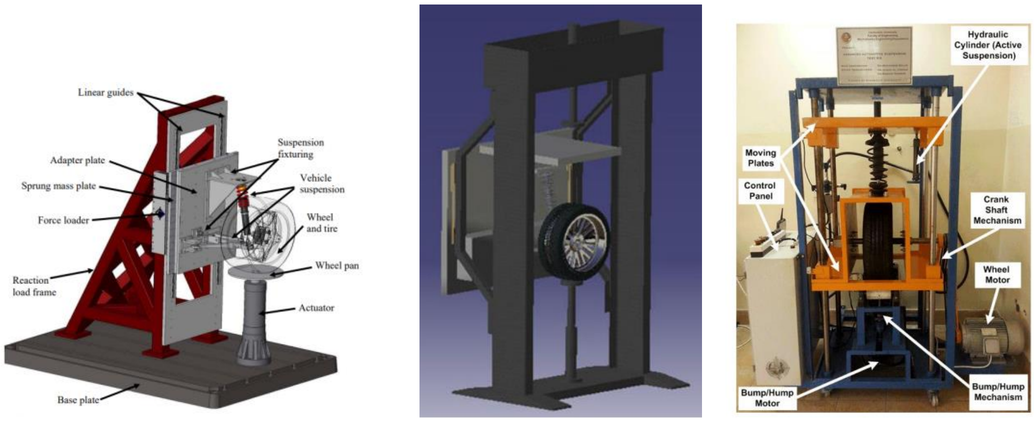


Fig. 1 *Base Model in this project.*

Table 1 *Characteristics of Base Model [1][2][3]*

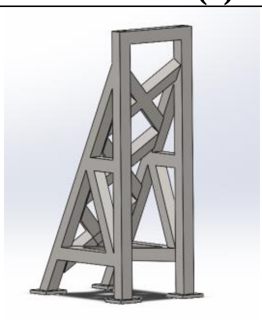
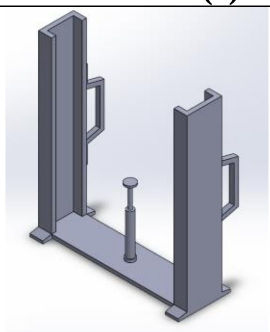
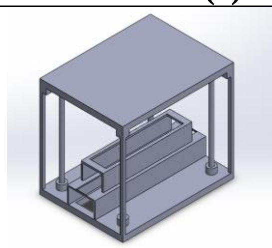
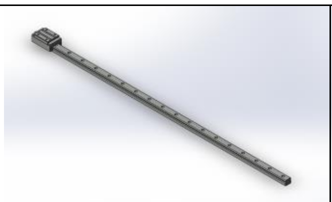
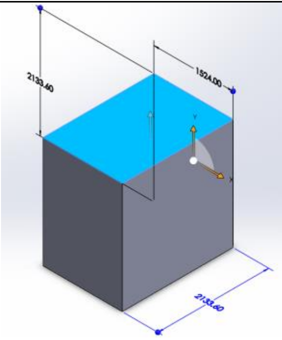
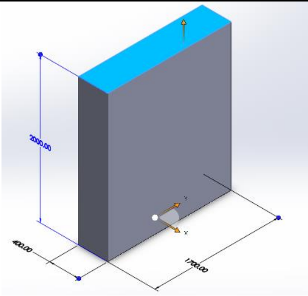
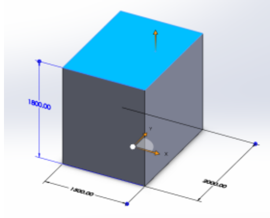
Characteristics	Base Model (1)	Base Model (2)	Base Model (3)
Frame Structures (F)			
Materials (M)	low-carbon steel		Stainless-Steel

Table 1 *Continue*

Linear Guides Motion (L)	 Design by NSK Corporation engineers (2260 N)	 Design by Rollon (10000 N)	
Dimension (D)	 (2.1 x 1.5 x 2.1) m	 (0.4 x 1.7 × 2.0) m	 (2.0 x 1.5 × 1.8) m

In the design tree process, the variants produced will be labelled as F, M, L, and D, representing the base model's attributes, which are frame structure, materials, linear motion guide, and dimension, respectively. Numbers 1, 2, and 3 represent the models from the base model (1), Base model (2), and base model (3), respectively. So, 36 variants of the test rig have been produced from the design tree process, and all the variants will go through the following process which is the screening process.

2.1 Design Tree

Three base models have been used in this study, and each model has been divided into several attributes, which are frame structure, materials, linear motion guides, and dimensions. Each attribute from each base model has been matched to an attribute from the other model, forming a new design of the quarter car test rig model. However, each base model sometimes did not have each attribute. For example, the base model from Prasanna Mishra does not have materials, and the model from Mohammad Salah does not have a linear motion guide. Figure 2 shows the design tree process for this project.

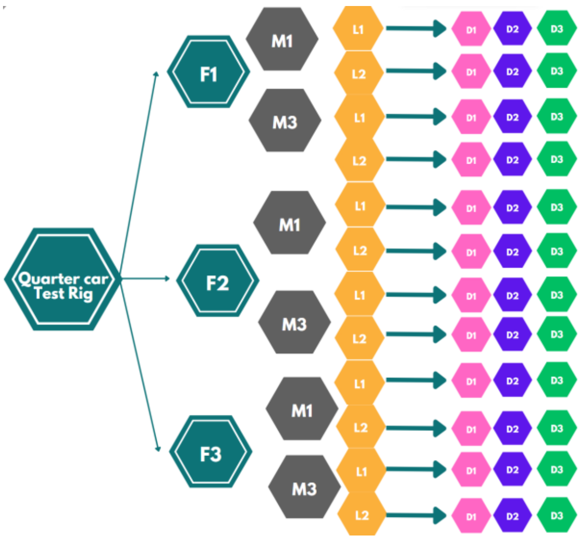


Fig. 2 *Design Tree for This Study*

2.2 Screening Process

In the screening process, all characteristics of 36 variants will be compared with the base model (1). The reason base model (1) has been chosen as a comparison because of from all three base model taken from previous research, only base model (1) has complete characteristic information while for base model (2) and base model (3) did not have complete information. The article does not specify the information of the material used for base model (2). The same goes for the base model's linear guide motion (3).

Four criteria of each design variant have been compared with the base model (1). The first criteria is parts of frame structures. If the test rig's frame structure has many components or parts, assembling or building the test rig will be more difficult. So, test rigs with a few parts and components will be preferred and given a positive rating. The second attribute that will be compared in the screening process is the strength of the materials. Materials have played an essential factor in this comparison. 2 materials will be compared in this project which are stainless steel and low-carbon steel. Mechanical properties such as tensile and yield strength will determine the strength between two materials. The tensile strength and yield strength of stainless steel are 685×10^6 Nm^2 and 292×10^6 Nm^2, respectively, which is higher than the tensile and yield strength value for low-carbon steel. Tensile and yield strength for low carbon steel is 399.83×10^6 Nm^2 and 220.59×10^6 Nm^2 respectively b[6]. The following characteristic is the load capacity of linear guide motion. This project has two types of linear guide motion, which are from base models (1) and (2). NSK Corporation has designed a linear guide from the base model (1), while Rollon has designed a linear guide from the base model (2). A linear guide from the base model (1) can hold a load until 2260 N, while a linear guide from the base model (2) can withstand a load of 10000 N. Last criteria is weight of test rig model. The test rig should be flexible and easy to move or store. If the test rig has a high weight, it will be difficult for the model to move from one place to another. Weight is also closely related to size. If the model is large, it needs ample space to store the test rig. The material used is also a factor test rig that has a high weight. In this project, Stainless steel has higher mass density compared with low-carbon steel.

The rating will be given in numerical methods, which are -1, 0, and 1. which represents it is worst compared to the benchmark, it is the same as a benchmark, and it is better than the benchmark, respectively. The marks will be totalled up, and the test rig model with the highest score will continue with the scoring process. Based on the Screening process, five designs can continue to the next procedure, which is a scoring process. The design that was selected is F2 M1 L1 D2, F2 M1 L2 D2, F2 M3 L1 D2, F2 M3 L2 D2 and F3 M3 L2 D2.

2.3 Equations

There are two equations used because it has two values of forces needed to determine this project, which are forces during the static condition and the cornering condition. Each condition has different types of equations, but it still uses the vehicle dynamic fundamental. Equations (1) and (2) below are the final equations for force in static and cornering conditions. This calculation only focuses on a front tire. In order to find the force value, both equations need to be filled using parameters from a specific car [4][5].

$$Fz_1 = \frac{1}{2} mg \frac{c}{L} \tag{1}$$

$$Fz_1 = \left(\frac{c}{L}\right) W - \left(\frac{h}{L}\right) M \times a \tag{2}$$

2.4 Vehicle Parameter

In order to complete the equation, the Parameters of specific vehicles are required. Perodua Myvi has been chosen for this project. Perodua Myvi is one of the class's leading local vehicles. However, when it comes to ride and handling, it has its share of problems as many complaints were circulating saying that the Myvi is not so comfortable for both passengers and drivers [5]. Table 2 below shows the parameters applied in the vehicle dynamic equation.

Table 2 *Perodua Myvi Parameter [6]*

Definition	Values
Sprung mass, *m*	573 Kg
Unsprung mass front right & left, *m*	114.9 Kg
Length from the center of gravity to the front end, *c*	0.75 m
Length from the center of gravity to the rear end, *b*	1.85 m
Length of the center of gravity to the right & left end	0.715 m
Wheelbase, *L*	2.5 m
Wheel Center	1.43 m
Center of gravity to the ground, *h*	0.61 m

2.5 FEA Simulation

Finite element analysis (FEA) is a numerical method for solving problems in engineering and mathematical physics. It is beneficial for problems with complicated geometries, loadings, and material properties where analytical solutions can be obtained. FEA is the method of using virtual simulation technology to test how a product design reacts to physical effects, including bending, heat, vibration, fluid flow, and other impacts. With FEA simulation tools, the design has been evaluated early in the design cycle, including what will cause premature failures, quick design changes to reduce cost and weight, and the product's factor of safety.

As stated before, the analysis will be conducted in 2 conditions, which are in static condition and cornering condition. The vehicle dynamics fundamentals and parameters of Perodua Myvi, as stated in Table 2 above, have been used to find a value of force that will be applied in both conditions. After the calculation made, the load applied in the static condition is 2496.87 N, which is lower than the load applied during the cornering condition, which is 4342.47 N. Both forces will be applied to the part where the tire is placed.

3. Result and Discussion

As stated before, the value of the force that will be applied in static condition is 2496.87 N. The analysis of the simulation will include the maximum stress of the design, the maximum displacement of the design, and the minimum safety factor for the design. All the designs that will go through the scoring process will undergo this simulation. However, models F2 M1 L1 D2 and F2 M1 L2 D2 have the same simulation result because the only component that is different between the two models is the linear guide motion. The simulation does not affect the component because the force was applied to the other part. The simulation result of all the designs will be compared with the base model.

3.1 FEA Result for Static Condition

Figure 3 below shows the result of maximum stress for all the designs. If the maximum stress is less than the value of the yield strength of the materials, it means the structure is safe to use [7]. So, the maximum stress of the base model is the lowest compared with the other model, which is 4.209× 104 N/m2, followed by the F2 M1 L1 D2 and F2 M1 L2 D2 model, which has maximum stress of 4.850e+04 N/m2.Next is model F2 M3 L1 D2 and F2 M3 L2 D2, which has 4.965× 104 N/m2, and lastly is model F3 M3 L2 D2, which has a maximum stress of 1.097× 105 N/m2, which is the highest compared with other design. Even though all the designs have different values of maximum stress, all the designs are safe to use because the value of maximum stress of each design is not more than the yield strength of the materials applied. There are two materials used in this project, which are stainless steel and low-carbon steel. The yield strength of both materials is 292× 106 Nm2 and 220.59× 106 Nm2, respectively.

Even though F2 M3 L1 D2 and F2 M3 L2 D2 have used stainless steel as a material, the maximum Stress of the model is higher compared with the base model, F2 M1 L1 D2, and F2 M1 L2 D2 model. This is because stainless steel has less value of elastic modulus than low-carbon steel, which is 2.07×10^{11} N/m^2 and 2.11×10^{11} N/m^2, respectively. Having low elastic modulus materials makes it floppy and stretch a lot when the force is applied [8]. Therefore, in this case, this design can absorb more force that has been applied to the structure. However, even if the model F3 M3 L2 D2 case uses stainless steel, the maximum Stress is still high since the model's structure differs from that of the F2 M3 L1 D2 and F2 M3 L2 D2 models. For the maximum stress outcome, the frame construction will also be a crucial element.

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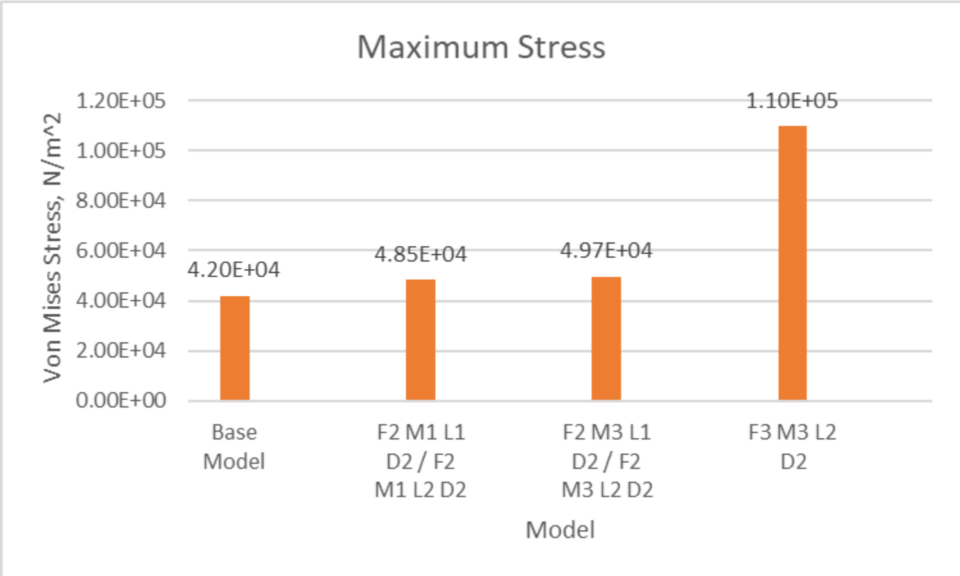

Fig. 3 *Maximum Stress Graph for Static Condition*

Figure 4 below shows the result of maximum displacement for all the designs. Displacement in FEA simulation can be defined as the movement of individual points on a structural system due to various external loads [9]. So, if the deformation of the design is high, it will affect the testing activity that is performed by the design. The graph of displacement also shows that the maximum displacement is directly proportional to maximum stress. The lowest maximum displacement is from the base model, which is 7.624×10^{-6} mm, followed by model F2 M1 L1 D2 and F2 M1 L2 D2, which has 7.873×10^{-6} mm of maximum displacement. Next is model F2 M3 L1 D2 and F2 M3 L2 D2 has a maximum displacement of 8.122 × 10-6 mm. Lastly, model F3 M3 L2 D2 has a maximum displacement of 1.38× 10-6 mm, which is the highest compared with another model.

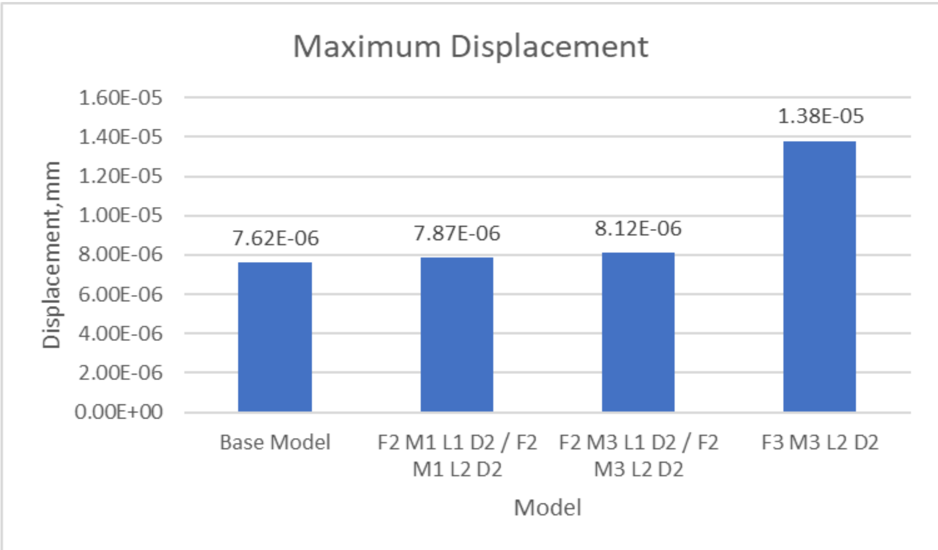

Fig. 4 *Maximum Displacement Graph for Static Condition*

Figure 5 below shows the result of a factor of safety (FOS) for all the designs. FOS is how much a system can withstand beyond the expected loads or actual loads. The smaller the Factor of Safety, the higher the chance that the design will be a failure [10]. Model F2 M3 L1 D2 and F2 M3 L2 D2 have the highest FOS compared with another model, which is 5881. It means this design has the highest safety rating. Next, the base model has the second highest FOS, which is 5200, followed by F2 M1 L1 D2 and the F2 M1 L2 D2 models, which has 4500. Lastly, model F3 M3 L2 D2 has the lowest FOS, which is 2700. Despite having varying FOS values, all of the designs are still far from failing and may be used safely in real-world applications.

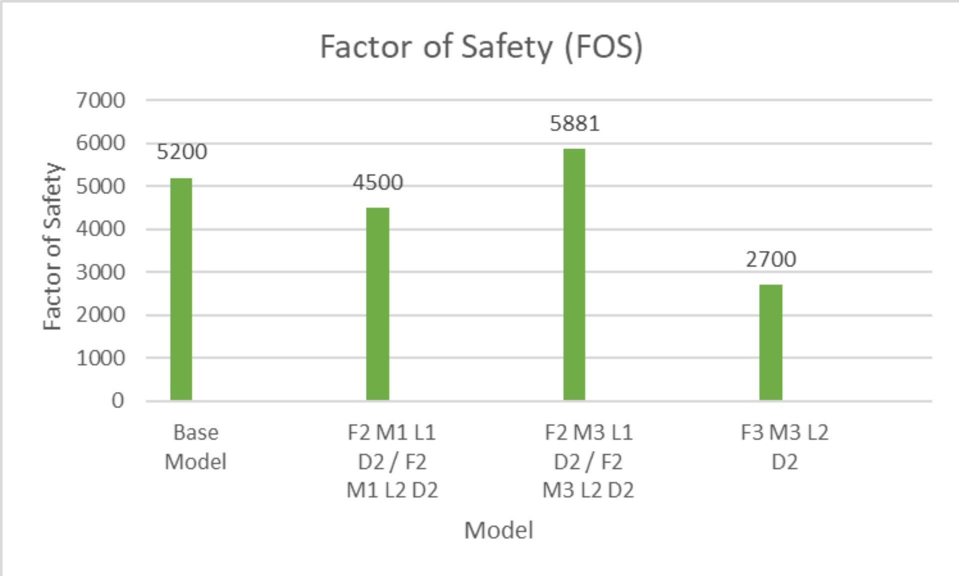

Fig. 5 *Minimum Factor of Safety Graph for Static Condition*

3.2 FEA Result for Cornering Condition

Analysis of the cornering condition is vital in this project because the force applied in this condition is much higher than in a static condition. These are the crucial elements to determine whether the structure of the test rig is safe to use or not. As stated before, the value of force that will be applied to the test rig for cornering condition is 4342.47 N. Same as static condition, the analysis will include the maximum stress of the design, the maximum displacement of the design and the safety of factor for the design. In general, the trend of the cornering condition graph and the static condition graph are comparable, but the values are not the same.

Figure 6 below shows the result of maximum stress for all the designs in cornering conditions. So, same as the static condition, the maximum stress of the base model is the lowest compared with the other model, which is 7.32×10^4 N/m^2, followed by the F2 M1 L1 D2 and F2 M1 L2 D2 model, which has maximum stress of 8.44×10^4 N/m^2.Next is model F2 M3 L1 D2 and F2 M3 L2 D2, which has 8.64×10^4 N/m^2, and lastly is model F3 M3 L2 D2 that has maximum stress of 1.91×10^5 N/m^2, which is the highest compared with other design.

Similar to static conditions, all the designs have different values of maximum stress. However, all the designs are safe to use in real-world applications because the value of the maximum stress of each design is not more than the yield strength of the materials applied.

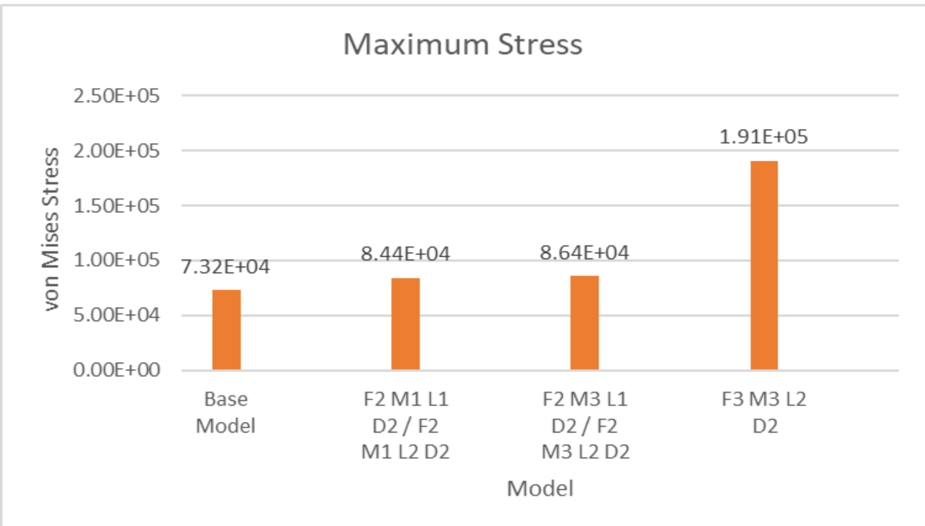

Fig. 6 *Maximum Stress Graph for Cornering Condition*

Figure 7 below shows the result of maximum displacement for all the designs in cornering conditions. The trend of the graph is similar to the graph's maximum displacement for static conditions, where it shows that the graph is directly proportional to the maximum stress value. The lowest maximum displacement is from the base model, which is 1.33×10^{-5} mm, followed by models F2 M1 L1 D2 and F2 M1 L2 D2, which have 1.37×10^{-5} mm of maximum displacement. Next is model F2 M3 L1 D2 and F2 M3 L2 D2 has maximum displacement of 1.41×10^{-5} mm. Lastly, model F3 M3 L2 D2 has a maximum displacement of 2.40×10^{-5} mm, which is the highest compared with another model.

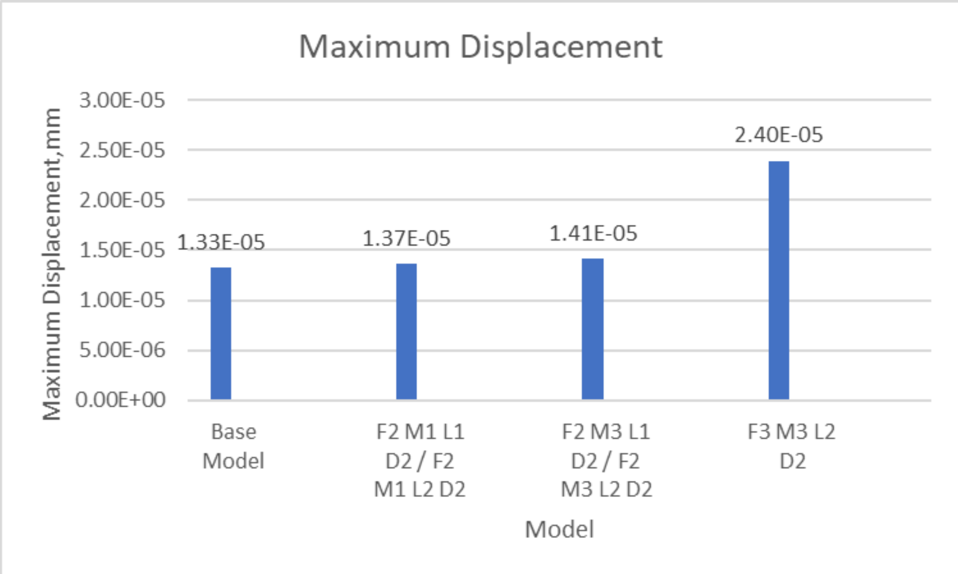

Fig. 7 *Maximum Displacement Graph for Cornering Condition*

Figure 8 below shows the result of a factor of safety (FOS) for all the designs in cornering conditions. Fos can show whether this structure can hold the force applied or fail during cornering conditions. As stated before, the force applied in this state is much higher than in static conditions. Model F2 M3 L1 D2 and F2 M3 L2 D2 have the highest FOS compared with another model, which is 3381. It means this design has the highest safety rating. Next, the base model has the second highest FOS, which is 3014, followed by F2 M1 L1 D2 and F2 M1 L2 D2 models, which has 2615. Lastly, model F3 M3 L2 D2 has the lowest FOS, which is 1530. Despite having varying FOS values, all of the designs are still far from failing and may be used safely in real-world applications.

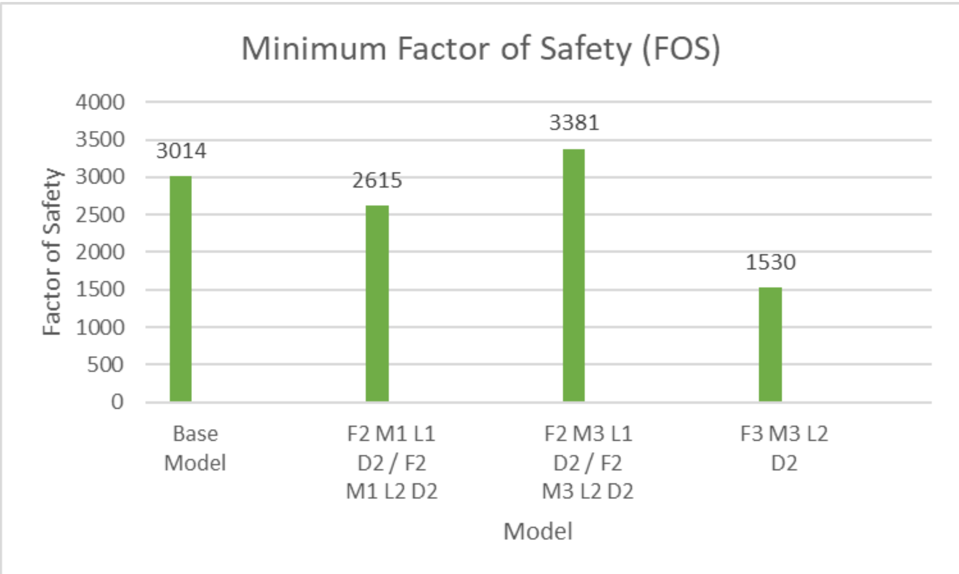

Fig. 8 *Minimum Factor of Safety Graph for Cornering Condition*

The model F2 M3 L1 D2 and F2 M3 L2 D2 are the strongest and safest structures out of all the designs, according to the graph analysis for both situations. It cannot only hold the load for static and cornering conditions but also withstand higher loads without breaking or failing.

4. Scoring Process

From the screening process, five designs get the highest marks, and to find one final design, a scoring process is used. The criteria that will be compared are FEA Analysis Result, strength, ease of build, weight, and cost. All the criteria have their weightage, which is 30%, 25%, 20%, 15%, and 10%, respectively. All the designs will be compared with the base model, and the rating will be given in a numerical method, which is from 1 to 5. If the design quality is much worse and worse than the base model, the rating will be 1 and 2, respectively. If the quality of the design is the same as the base model, the rating will be 3. However, if the design quality is better and much better than the base model, the rating will be 4 and 5, respectively.

Table 3 *Scoring Table for Quarter Car Test Rig Model*

Selection Criteria	Weight (%)	**F2 M1 L1 D2**		**F2 M1 L2 D2**		**F2 M3 L1 D2**		**F2 M3 L2 D2**		**F3 M3 L2 D2**	
		Rating	Weight Score	Rating	Weight Score	Rating	Weight Score	Rating	Weight Score	Rating	Weight Score
FEA Analysis Result	30	2	0.6	2	0.6	4	1.3	4	1.3	1	0.3
Strength of Materials	25	3	0.75	4	1	4	1	5	1.25	5	1.25
Parts of Frame Structure	20	5	1	5	1	5	1	5	1	2	0.4
Weight	15	4	0.6	4	0.6	4	0.6	4	0.6	5	0.75
Cost	10	4	0.4	4	0.4	1	0.1	1	0.1	2	0.2
Total	100										
	Total Score	3.35		3.6		4.0		4.25		2.9	
	Rank	4		3		2		1		5	
	Continue	NO		NO		NO		**YES**		NO	

So, the best design that was selected based on the scoring table is the F2 M3 L2 D2, which has a total score of 4.25. The figure of model F2 M3 L2 D2 is shown below. The rank was followed by design F2 M3 L1 D2, F2 M1 L2 D2, F2 M1 L1 D2, and F3 M3 L2 D2, which have total scores of 4.0, 3.6, 3.35, and 2.9. Of all the five designs, only the F3 M3 L2 D2 design gets a total score below three, which means the specifications of the entire design are below compared with the base model.

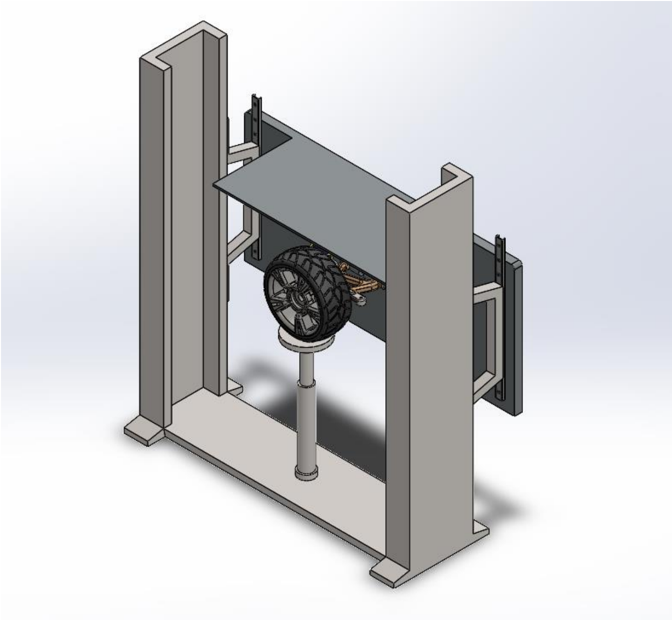

Fig. 9 *F2 M3 L2 D2 Quarter Car Test Rig Model*

Conclusion

Five designs of the new quarter car test rig model go through the scoring process and have been designed based on fundamental vehicle dynamics using simulation software. The three-base models have also been designed using the same software so that the data from the base model can be compared with the new test rig model.

The improvement of existing test rig model already in the market has been suggested using a design tree, screening, and scoring process. Some of the criteria of the test rig model, such as weight and cost, have been improved compared with the existing model. Even though the criteria such as cost and weight have been reduced, the safety level of the test rig does not decrease, and it can function as needed.

The test rig's mechanical performance and safety level have been analyzed and discussed. The performance and safety parameters such as maximum stress level and maximum displacement are better than the base model. So, it will make the test rig do much testing, especially the testing that produces a greater force.

Acknowledgement

The authors would like to thank the Faculty of Engineering Technology, Universiti TunHussein Onn Malaysia for its support.

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