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STATIC SIMULATION OF E-BIKE TILTING THREE-WHEELED FRAME STRUCTURE USING THE FINITE ELEMENT METHOD

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Abstract. The purpose of the present study was to estimate the static strength of the frame structure developed from the initial tilting three-wheeled electric bike design using the Finite Element Analysis (FEA) assisted by the Static SOLIDWORKS Simulation software with a configuration of two wheels located at the front and one wheel at the back position. The main consideration of structural strength was seen from the point of view of the distribution of static loads using three types of materials (6061-T6 aluminium, AISI 1020 Steel and CFRP). The minimum factor of safety resulting from the initial design simulation was estimated to be 1.84.

Keywords: Urban vehicles, three-wheeled tilting, frame, finite element analysis

1. Introduction

Numerous models of three-wheeled vehicles with varying sizes have been produced in the past century, with two wheels serving to bear the load and one wheel serving to steer. The use of three-wheeled vehicles has become very popular since it is capable of reducing the area and mass of the vehicle when compared to four-wheeled vehicles. Additionally, the configuration of two wheels on the front and one wheel on the rear causes the vehicle to have better aerodynamics. For this reason, it is now common to find electric vehicles that use three wheels with that configuration.

Matters to be considered when designing three-wheeled vehicles are stability, characteristics of the rider in the size determination process and load distribution. With regard to stability, the point of the center of gravity is recommended to be as close as possible to the ground and closer to the one-wheel section in order to reduce the occurrence of rollovers. But, in terms of handling, the point of the center of gravity should not too close to the one-wheel section, since it can lead the vehicle to be difficult to control at high speeds. When the design of three-wheeled vehicles has a proper stability and handling, the vehicles would offer stability and handling as good as four-wheeled vehicles, coupled with reduced size and improved aerodynamics. In addition, reduced weight due to smaller size can reduce vehicle emissions by 30–40% (Polgeest, 2011).

One result of the development of three-wheeled vehicles is the emergence of a tilting three-wheel system on a vehicle. The tilting three-wheel system offers a higher level of safety when compared to two-wheeled vehicles, which is related to a better level of stability. The high level of stability of three-

wheeled vehicles is influenced by the design of the three-wheeled vehicles. In addition, the tilting three-wheeled vehicles also have a high level of ergonomics when passing a bend. This is due to the gravitational force, centripetal acceleration and torque of the tilting. The resultant force vector that works in the tilting motion will be perpendicular to the rider's body axis, causing the rider's vestibular system to experience less lateral acceleration. As a comparison, a rider of a vehicle with a tilting three-wheel system will experience the same as experienced by aircraft passengers who are unaware of the plane's turning.

The finite element method is an important and practical numerical analysis tool. It can be found in almost all fields of engineering and applied mathematics. Therefore, the literature on finite element methods is increasing rapidly and widely. The largest benefit of FEA is its ability to overcome irregular geometric shapes. In addition, FEA has the ability to resolve conditions in general limits such as heterogeneous materials. This means that we can arrange an irregularly shaped system consisting of numerous different materials. Every material has a constant nature or spatially varying nature.

2. Methods

2.1. Element Design and Assembly Process
The initial stage to be done was to make a design using the SOLIDWORKS 2018 software features adjusted to the predetermined shape. The thing to be taken into account in designing the elements for a tilting three-wheeled electrical frame is the type of relationship among the tubes of the frame. In the present study, the relationship among the tubes was ignored or considered to be a single element (without using weld as a mate). This was done because in the present study the indicators seen were the shape of the frame and the materials used, regardless of the effect of the type of welding used.
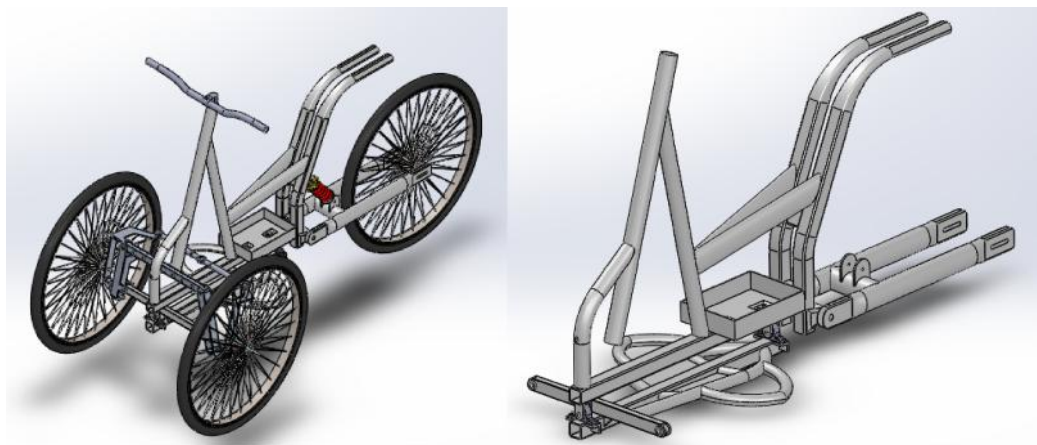

Figure 1. New model of a tilting electrical three-wheeled vehicle

The next stage was the assembly process, which was s a process of assembling the frames of the new design of a tilting electrical three-wheeled vehicle, including the top frame, bottom frame, and rear frame. The thing to be considered in the process of assembly is the type of mate among sections (surface or angle) of the elements. There are several types of mate available in SOLIDWORKS. In the present study, not all mates were used in the assembly process; there are several types of mate that are often used, such as coincident, concentric, parallel, width, screw, and others. In addition, not all elements of the electrical three-wheeled bicycle were required for assembly which would be used for simulation since it would slow down the simulation process. The parts to be assembled were upper frame, lower frame, rear frame, bearing housing, radial ball bearing, and battery holder.

2.2. Determination of Fixtures and External Loading in Assembly

In the present study, there were only two types of fixture used: fixed geometry and fixed hinge. The fixed geometry feature was located on the two slot holes connecting the lower parallel arm and the tilting arm and the slot hole in the rear frame for the rear wheel shaft. Since the tilting arm and rear wheel shaft were not included in the frame assembly, the fixture used was the fixed geometry. Additionally, this feature served to define force reaction caused by the bicycle wheels when given the load on that section. Furthermore, the fixed hinge was located on the two slot holes connecting the upper frame and the radial ball bearing and the slot hole connecting the upper frame and the rear frame. The fixed hinge feature was used since all the elements were in the assembly frame and had a rotational movement.
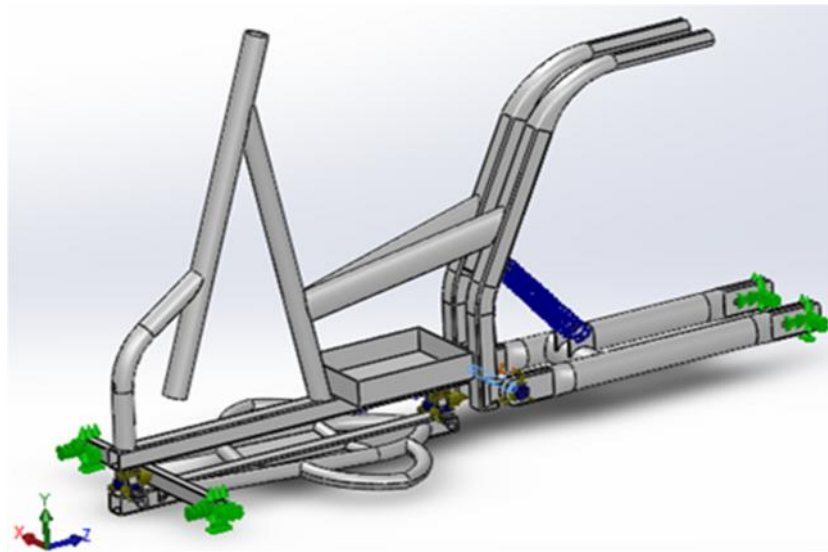

Figure 2. Fixtures used on the electrical tilting three-wheeled frame.

In the present study, there were two external loads: the rider and battery. The maximum weight assumed by the two external loads was 150 kg for the rider and 11 kg for the battery. For the rider, based on a study conducted by Soden and Adefaya (1979), the loadings would be distributed to several elements of the electrical tilting three-wheeled bikes, i.e. 50% of the rider's body weight on the seat tube, 100% of the rider's weight on the footholder, and 44% of the rider's body weight on the handlebar. In addition, the battery would be placed on the battery holder. The present study only used such features as force, remote force, and gravity. The force feature would be used to define the load from rider's body weight assumed by the bike on the seat tube and footholder, and the weight of the battery on the battery holder. The remote force was used to define the weight of the rider acting on the handlebar; however, since the handlebar was not included in the element assembly frame, it could be defined using the remote force feature. The gravity feature served to define the direction of the gravitational force acting on electrical tilting three-wheeled bike, the amount of the gravitational force acting being 9.81 m/s^2.
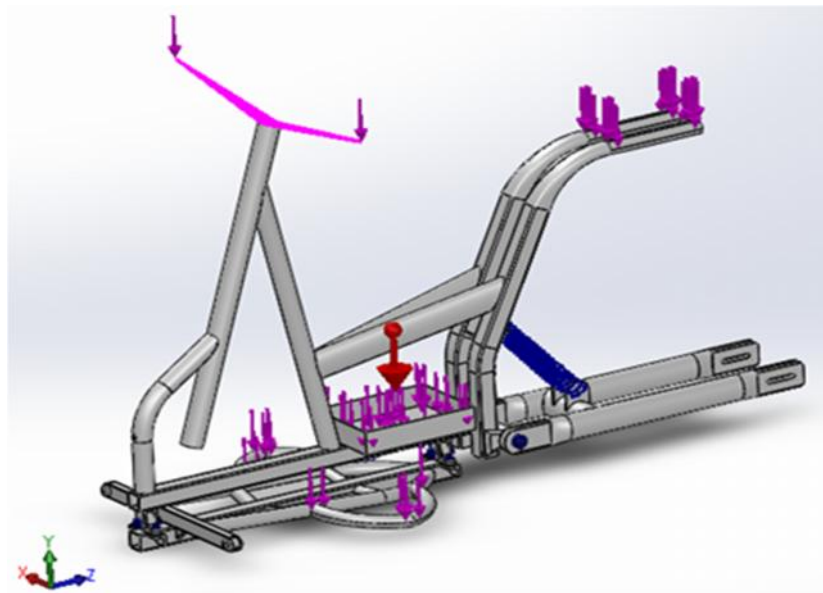
Figure 3. External loading on the electrical tilting three-wheeled frame.

2.3. Meshing process

The next stage was the meshing process. In the meshing process the thing to be considered was the size of the triangular meshing sides. The present study determined the maximum size of the triangular meshing side to be 3 mm and the minimum size to be 0.5 mm.

The meshing dimensions can be determined from the aspect ratio of the meshing. This design had a maximum aspect ratio of 83.17 and minimum aspect ratio of 1.014. It was also seen that approximately 79.7.7% of the elements had an aspect ratio below 3. This meshing process qualified as high quality meshing.

2.4. Material Selection

There were three materials used in the present study, namely the 6061-T6 aluminum, AISI 1020 steel, and CFRP. All three materials were those commonly used on bicycle frames. Here are the mechanical properties used in the simulation:

Table 1. Properties of the materials used

	Al 6061-T6	AISI 1020 Steel	CFRP
Elastic Modulus	10,000 ksi	27,000 ksi	14,793.84 ksi
Poisson's Ratio	0.33	0.29	0,433
Shear Modulus	3,770 ksi	10,400 ksi	623.66 ksi
Mass Density	0.975 lb / in^3	0.284 lb / in^3	0.051 lb / in^3
Tensile Stength	45,000 psi	60,900 psi	130,679 psi
Yield Strength	40,000 psi	50,800 psi	156,640.75 psi

3. Results and discussion

3.1. Results of Frame Design Simulation Using the Al 6061-T6 Material
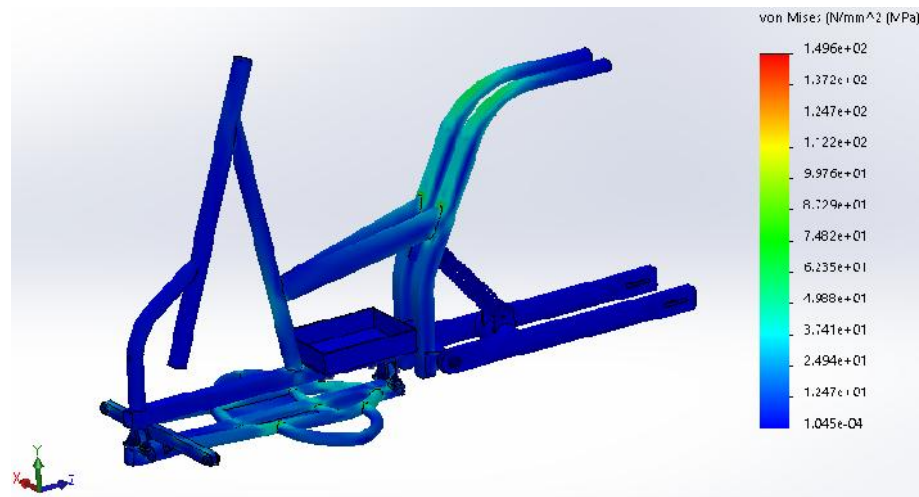

Figure 4. Results of simulation of von Mises stress of the new frame using the Al 6061-T6 material
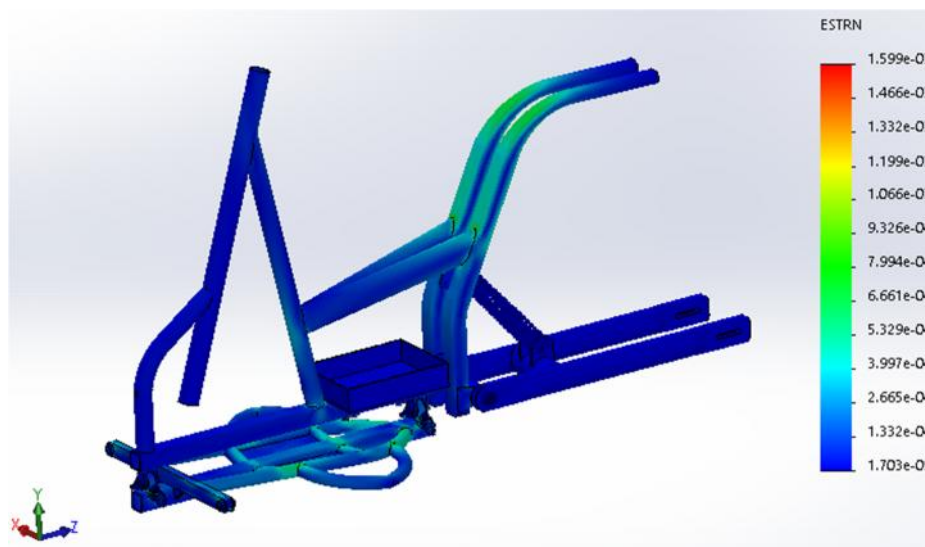

Figure 5. Results of simulation of strain of the new frame using the Al 6061-T6 material

In the static testing using the Al 6061-T6 material on the electrical tilting three-wheeled design, the results analyzed using the Static SOLIDWORKS Simulation were the von Mises stress, maximum displacement, strain and factor of safety. Based on the simulation results, the maximum value of von Mises stress was 149.6 MPa and the minimum value of von Mises stress was 1.045×10^{-4} MPa. The point of the maximum stress was on the footholder that connected the lower tube connector to the square tube (lower frame). This was due to the fact that the footholder supported 100% of the load given by the rider (on condition that the rider stands on a bicycle). The maximum displacement occurred was 5.98 mm. Additionally, the electrical tilting three-wheeled design using the 6061-T6 aluminum material had a maximum deformation of 1.59×10^{-3} located on the section experiencing the

maximum stress and the minimum deformation occurred was 1.70×10^{-9}. The maximum displacement was located on the seat tube section which was subject to the rider's load of 150 kg. The smallest factor of safety was 1.84. Furthermore, the mass of the electrical tilting three-wheeled frame design using the 6061-T6 Al material was 4.46 kg.

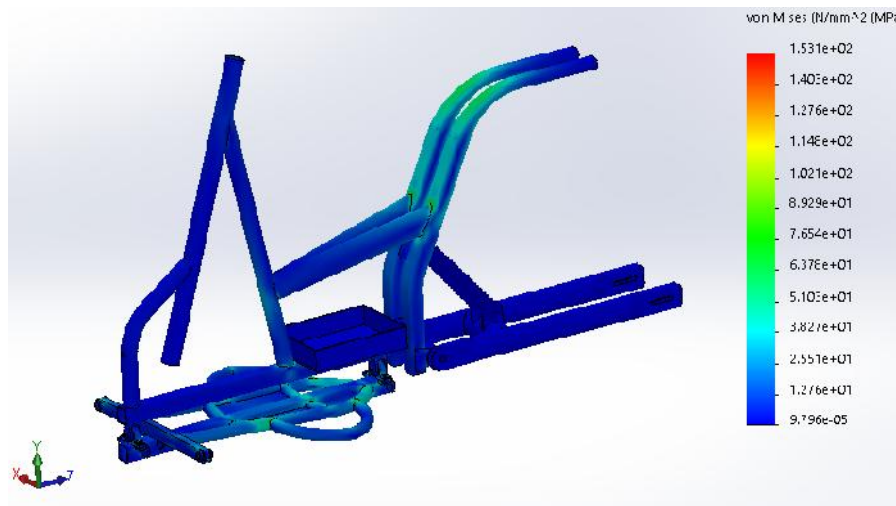*3.2. Results of Frame Design Simulation Using AISI 1020 Steel Material*

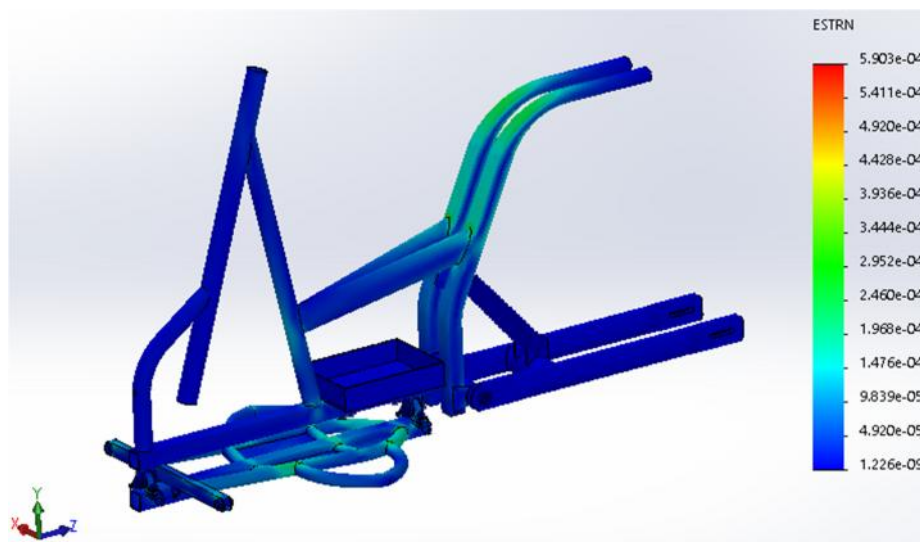**Figure 6.** Results of simulation of von Mises stress of the new frame using the AISI 1020 Steel.

Figure 7. Results of simulation of strain of the new frame using the AISI 1020 Steel

In static testing of the electrical tilting three-wheeled design using the AISI 1020 Steel material, results of simulation indicated that the maximum value of von Mises stress was 153.1 MPa and the minimum value of von Mises stress was 9.7×10^{-5} MPa. Similar to the simulation results of the previous material, the point of maximum stress was on the footholder section connecting the lower tube connector to the square tube (lower frame). The maximum displacement occurred was 2.23 mm. In

addition, the electrical tilting three-wheeled design using the AISI 1020 Steel material had a maximum deformation of 5.90×10^{-4} located on the section experiencing the maximum stress, the minimum deformation occurred being 1.22×10^{-9}. The maximum displacement was located on the seat tube section which was subject to the rider's load of 150 kg. The smallest factor of safety was 2.28. Furthermore, the mass of the electrical tilting three-wheeled frame design using the AISI 1020 Steel material was 13.09 kg.

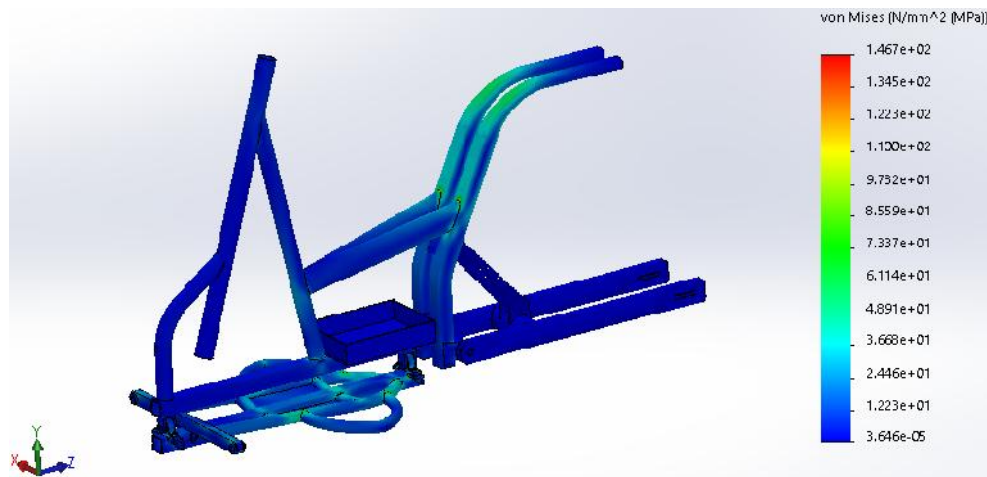### 3.3. Results of Frame Design Simulation Using CFRP Materials

Figure 8. Results of simulation of von Mises stress of the new frame using the CFRP material
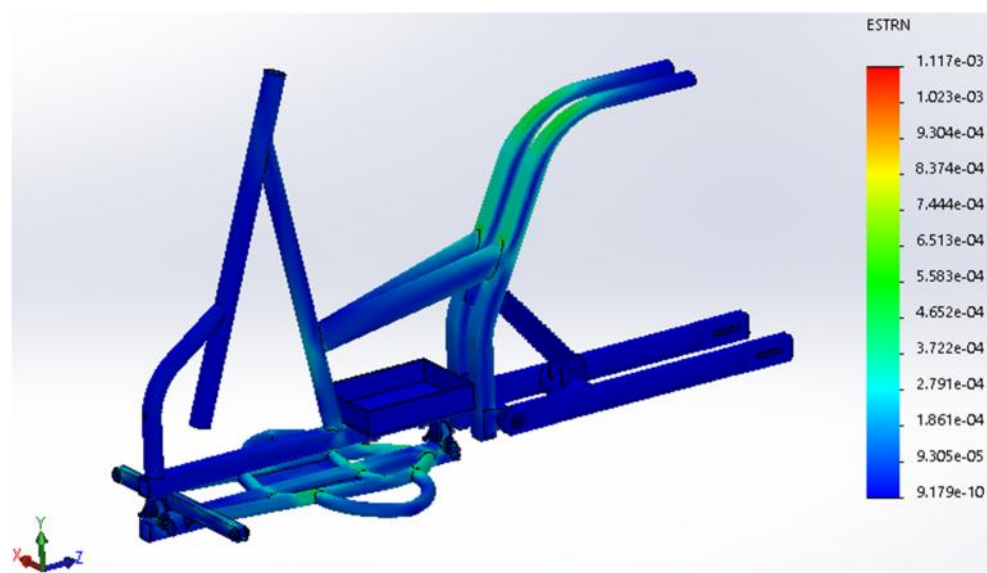

Figure 9. Results of simulation of strain of the new frame using the CFRP material

In static testing of the electrical tilting three-wheeled design using the CFRP material, the simulation results indicated that the maximum von Mises stress value was 146.7 MPa and the minimum von Mises stress value was 3.64×10^{-5} MPa. Similar to the simulation results of the previous material, the point of the maximum stress was on the footholder section connecting the lower tube connector to the

square tube on the lower frame. The maximum displacement occurred was 4 mm. Furthermore, the electrical three-wheeled design using the CFRP material had a maximum deformation of $1{,}117 \times 10^{-3}$ located on the section experiencing the maximum stress; the minimum deformation occurred was $9{,}179 \times 10^{-10}$. The maximum displacement was located on the seat tube section which was subject to the rider's load of 150 kg. The smallest factor of safety was 4.3. Furthermore, the mass of the electrical tilting three-wheeled frame design using the CFRP material was 2.38 kg.

4. Conclusions

Based on the study of the preliminary electrical tilting three-wheeled design and results of the analysis, the following conclusion can be drawn:

1. Based on the results of the analysis, the CFRP material is one with the highest minimum Safety of Factor (SoF) of 4.39, followed by the AISI 1020 steel material of 2.28, and 6061-T6 aluminum of 1.84.
2. Based on the mass, the electrical tilting three-wheeled frame design using the CFRP material has a mass of 2.38 kg, followed by the 6061-T6 aluminum of 4.46 kg, and the AISI 1020 steel of 13.09 kg.
3. In the entire simulation using several materials, the value of the maximum von Mises stress does not exceed the yield point of the material; thus, the design can be said to be capable of bearing the simulated loads.
4. It is necessary to analyze the electrical tilting three-wheeled design from the ergonomic viewpoint in order to increase the rider's comfort.
5. A cost analysis is required with regard to the manufacture of tilting electrical three-wheeled frames to create an economical and mass-production feasible design.
6. Fatigue simulation is required, aimed at determine the service life of the new electrical tilting three-wheeled frame design.
7. A dynamic testing is required.

Acknowledgment

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