On the Use of Steel and Aluminum Materials for Frame Structure of Electric Trike

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ABSTRACT

This work investigated the pros and cons of aluminum material used for electric trike frame compared with steel material. With a compact design and small dimension, e-trike is suitable to be used in many relatively small road accesses. However, the compact design can cause the frame to receive high and concentrated stress. The aluminum-based frame had lower strength, but lighter weight compared to the steel-based frame. In this study, the stress evaluation for both aluminum-based and steel-based frames is done using the finite element method. The minimum thickness of the aluminum-based frame was iterated to match the strength of the steel-based frame. The results showed that the aluminum-based frame has comparable performance to the steel-based frame but with lighter weight. However, the production cost of the aluminum-based frame might be a challenging issue to be solved.

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1. INTRODUCTION

Electric trike (e-trike) is a three-wheel electric vehicle that has been used for many purposes such as cargo delivery, tourism transportation, or garbage collection vehicle. The design of the e-trike is based on the urban city road, which has many small roads and a dense population (Arifurrahman et al., 2018). Considering the road condition, the e-trike design is preferred because of its maneuverability and compact design. The e-trike has better load capacity than the motorcycle, which is always used by freight forwarders for good delivery. The use of electric power in the vehicle also has the potential to reduce air pollution significantly (Aziz et al., 2018). For example, based on the Indonesian Environmental Agency, 75% of air pollutants come from the transportation sector (Ridwan, 2020). Using electric drive trains, the pollution from the transportation sector can be decreased, and the air quality in Indonesia can be improved (Arifurrahman et al., 2018; Aziz & Budiman, 2017).
Structural integrity is the main focus to ensure the safety aspect in a vehicle to prevent an accident (Jusuf et al., 2017). The structure’s design needs to be iterated to find the most efficient parameters, and it must be strong enough to bear the load. The frame’s performance bearing the maximum load operation could be investigated by conducting static analysis (Arifurrahman et al., 2018). The maximum operational load may come from the battery, electric motor, upper structure, and driver weights. The deformation of the frame also needs to be evaluated in the static analysis. This evaluation is essential to ensure the frame vehicle does not have plastic deformation and avoid the vehicle components colliding with each other.

Another aspect that needs to be considered is the weight of the vehicle. An electric vehicle uses a battery as the primary power source (Halimah et al., 2019). The weight of the battery used for running the electric motor may increase the vehicle’s power consumption (Kusuma et al., 2019). One solution to reduce the frame weight is to use materials with lower density (Cheah, 2010; Grabowski & Jaura, 2001; Joost, 2012; Kelly et al., 2015).

Several works investigated the usage of aluminum materials to replace steel materials as vehicle frames. Seyfried et al. discussed the weight reduction of several heavy-duty vehicle producers when replacing several parts of its frame from steel to aluminum, which successfully reduce its overall weight of the dump truck by 1900 kg and leads to reduced fuel consumption and tire wear (Seyfried et al., 2015). Saito et al. developed the vehicle body structure using an aluminum hybrid. The result showed that compared to a 3-door Civic car with a steel body, the design could reach 47% less weight (Saito et al., 2000). Several vehicle manufacturers also have produced aluminum-based frame. For example, Audi A8 reduces the body weight by 80% by using an aluminum-intensive space frame. Ford AIV uses stamped aluminum body structure which reduces the total weight of its vehicle by 320 kg. Renault and Lotus design its aluminum-based car, Spider, which has 30-50% lower weight than a steel-based car (Miller et al., 2000). Based on various research and model development that has been done in the automotive industry, which uses aluminum as the substitute for steel and provides a satisfactory result, study for aluminum usage in the e-trike vehicle has great potential to succeed.

Previous works of e-trike design in various research areas such as frame integrity, the component in drivetrain, electricity, etc., had already been conducted. Alpha-model was developed and patented as the light structure and high structural integrity of the e-trike (Budiman, 2020). The Alpha frame was designed as simple as possible so that the manufacturing process can be done with only bending, welding, and cutting. With the simple manufacturing process, the manufacturing cost and time can be reduced significantly. Faizal et al. investigate e-trike Alpha-model frame modal and static analyses (Arifurrahman et al., 2018; Arifurrahman, et al., 2018). A satisfactory result is found in the latest evolved alpha frame with minimum displacement at a safe frequency range. Furthermore, Sholahuddin et al. analyzed 5 kW electric motor used in the e-trike that focus on performance and weight reduction (Sholahuddin et al., 2016).
In this study, the static analysis of the Alpha frame using ASTM A36 Steel and aluminum 6016-T4 is conducted. By using aluminum, the weight of the vehicle can be decreased, and energy consumption will also decrease (McGregor, 2010). Static analysis is conducted using Finite Element Analysis (FEA) to reduce the computational cost significantly (Nurprasetio et al., 2017; Triawan et al., 2018). The main focus of the study was to find the design iteration of the aluminum-based frame that has minimal material usage and maximum stress with the steel-based frame as the design baseline. The maximum deflection of the frame should not exceed 3 mm to prevent damage to the e-trike component inside the frame. Two different dimension aluminum frame designs were then compared to find the optimum result based on the design criteria.

2. **FINITE ELEMENT MODEL**

2.1. Alpha Frame Geometry

Alpha frame has several versions for the design iteration. In this study, the latest version of the Alpha frame was used. The overall dimension of the Alpha frame is 2000 mm x 505 mm. The alpha frame can be divided into three subcomponents which are the handling frame, mainframe, and seat frame as shown in Figure 1.

A handling frame is used in the steering system of the e-trike. The handling frame is connected to the bottom side of the mainframe by using a welding joint. The handling frame extension will also bear the load of the battery placed under the seat frame to reduce the load concentration bore by the bottom side of the mainframe. The seat frame receives the load from the weight of the driver. The seat frame footing is connected to the bottom side of the mainframe and the upper side of the seat frame connected to the upper side of the mainframe. The mainframe is used for bearing the majority of the e-trike load. The mainframe receives a load from the upper structure, cargo box, battery, suspension system, and electric motor.

![Figure 1. Alpha frame subcomponents: (a) seat frame, (b) mainframe, and (c) handling frame.](image-url)
2.2. Material Model

In this study, the comparison for model materials was conducted for ASTM A36 Steel and aluminum 6061-T4 (Anon, 2020). Simulation for different materials was conducted to make a lighter frame design. Table 1 shows the value of several properties for each material. The table shows that steel has a higher density, elastic modulus, and strength than aluminum. Based on the material properties, the aluminum-based frame has a lower weight but higher strain than the steel-based frame with the same dimension.

2.3. Loading and Boundary Conditions

The loading was carried out according to the weight of components attached to the frame such as the weight of the driver, upper structure, battery, driving motor, and box weight of 80 kg, 100 kg, 50 kg, 30 kg, and 330 kg respectively. Thus, the total loading condition was 635 kg plus the frame weight (approximately 45 kg).

Fixed support was applied at the joint to represent the handling joint and the suspension conditions. Figure 2 shows the fixed displacement for all DOF and force placement with value. The force for each arrow indicated in Figure 2 was distributed evenly for each arrow color.

2.4. Frame thickness

In this study, the target was to find the minimum thickness (t) needed for an aluminum-based frame to bear the stress induced by loading. The frame consists of different pipe diameter (d) for each sub-component. The dimension of the frame for each simulation is shown in Table 2.

### Table 1. Materials properties for A36 steel and aluminum 6061-T4

<table>
<thead>
<tr>
<th>Property</th>
<th>Steel Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material density</td>
<td>7850</td>
<td>Kg/m³</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.26</td>
<td>N/A</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>200</td>
<td>GPa</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>250</td>
<td>MPa</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>400</td>
<td>MPa</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>79</td>
<td>GPa</td>
</tr>
<tr>
<td>Aluminum Value</td>
<td>2700</td>
<td>Kg/m³</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.33</td>
<td>N/A</td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>68.9</td>
<td>GPa</td>
</tr>
<tr>
<td>Yield Strength</td>
<td>228</td>
<td>MPa</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>239</td>
<td>MPa</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>26</td>
<td>GPa</td>
</tr>
</tbody>
</table>
The simulation was conducted for 3 cases. Case 1 is an existing frame design using steel as the material. Case 2 is using aluminum as the material and the pipe thickness is 3 mm for the seat frame, 4 mm for the mainframe, and 4.5 mm for the handling frame. The third model is using the same aluminum material with higher pipe thickness compared to the second with the value 4.5 mm for the seat frame, 5 mm for the mainframe, and 6 mm for the handling frame.

2.5. Convergence testing

In the numerical simulation, the convergence test is very important to determine if the result is valid (Hart et al., 1992; Irons & Razzaque, 1972). Convergence testing is used to find the most optimum meshing size of the model. Meshing is the discretization of the bulk model into a smaller size element. The result of the simulation becomes finer with a smaller meshing size but as the size goes down, the computation of the model is also heavier. To determine the validity of the result, the value for different meshing size is compared. When the result value of the different size mesh reached convergence value in which the variation of the value is less than 10%, the meshing size is selected for each simulation.

In this study, the convergence test was conducted by using stress value. Model 1 which used steel material was used to determine the minimum meshing size. From Figure 3, it could be seen when the size of the mesh reached 10 mm, the value approached the convergence line. The simulation for other models was using a meshing size of 10 mm.

### Table 2. Frame dimension for each simulation.

<table>
<thead>
<tr>
<th>Model</th>
<th>Materials</th>
<th>Subframe</th>
<th>Diameter (mm)</th>
<th>Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>Steel</td>
<td>Seat</td>
<td>19.5</td>
<td>2.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Main</td>
<td>31.75</td>
<td>3.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Handling</td>
<td>50.8</td>
<td>3.91</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>Aluminum</td>
<td>Seat</td>
<td>28.2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Main</td>
<td>41.6</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Handling</td>
<td>63.5</td>
<td>4.5</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>Aluminum</td>
<td>Seat</td>
<td>25.5</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Main</td>
<td>45</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Handling</td>
<td>68.8</td>
<td>6</td>
</tr>
</tbody>
</table>

3. RESULTS AND DISCUSSION

The simulation was conducted for 3 models which were explained in the previous sub-chapter. The baseline of the design was the steel-based frame due to the experimental and simulation result from previous work that has been done for the static and dynamic integrity of the existing Alpha frame (Arifurrahman et al., 2018; Arifurrahman et al., 2018). The stress distribution, deformation, strain, and weight simulation result for the aluminum frame (Case 2 and Case 3) was compared to the steel frame (Case 1) and the optimum design was chosen based on the baseline criteria and maximum displacement of 3 mm along with the frame.

3.1. First model

First model simulation was used as the baseline design and compared to the result for the 2<sup>nd</sup> model and 3<sup>rd</sup> model. First model was using steel as the material for the frame. The $a_{\text{im}}$ distribution for the 1<sup>st</sup> model is shown in Figure 4 (a).
Considering both steel and aluminum are ductile materials, the von Mises criterion is implemented to determine the frame failure. It can be seen that the maximum $\sigma_{vm}$ appearing in the frame is 167.5 MPa. This value is lower than the yield strength of steel. Thus, it can be concluded that 1st model frame design structure is safe and can be used to bear the load required.

Displacement due to loading conditions for the 1st model of the frame is also simulated (Figure 4 (b)). The maximum displacement that occurred along the frame was 1.3 mm, which was located at the seat frame. This value still far from the maximum displacement design point, which is 3mm. From the displacement perspective, the frame model design is safe.

From the safety aspect, as expected, the 1st model design is safe to be used in the e-trike operation. However, the overall weight of the frame is 41.28 kg. The weight of the frame may increase the energy consumption of the vehicle, reducing the battery performance.

### 3.2. Second model

Second model was using aluminum as the material for the frame. Aluminum has lower yield strength but has a lower density. The $\sigma_{vm}$ distribution for the 2nd model is shown in Figure 5 (a).

![Figure 5](image-url)
The maximum $\sigma_{vm}$ that occurs in the frame is 134 MPa which is lower than the aluminum's yield strength. The 2\textsuperscript{nd} model of the frame design is safe to be used for e-trike with specified loading conditions. The displacement due to loading condition was also investigated, which shows that the maximum deflection on the frame was 3.08 mm (Figure 5 (b)).

The displacement of the 2\textsuperscript{nd} model is higher than the 1\textsuperscript{st} model due to the lower modulus elasticity of the aluminum. The deflection needs to be reduced to prevent damage to the components installed on the frame, such as the battery, electric motor, etc. The weight of the 2\textsuperscript{nd} model of the frame also decreased because aluminum has a lower density than steel. From the simulation, the overall weight of the 2\textsuperscript{nd} model is 15.93 kg.

### 3.3. Third model

Third model used aluminum pipes with a larger diameter and thickness than the 2\textsuperscript{nd} model. The $\sigma_{vm}$ distribution for the 3\textsuperscript{rd} model is shown in Figure 6 (a). The maximum $\sigma_{vm}$ that occurred in the frame was 116 MPa which was lower than the 2\textsuperscript{nd} model. With lower $\sigma_{vm}$, the safety factor for the frame increases. The frame's structural integrity in the 3\textsuperscript{rd} model is also higher than in 1\textsuperscript{st} model and 2\textsuperscript{nd} model.

The displacement occurring in the 3\textsuperscript{rd} model was also investigated. From Figure 6 (b), the maximum deflection happened in the same location. Still, the value was lower than 2\textsuperscript{nd} model i.e., 2.1 mm. The weight of the frame increases by increasing the pipe diameter and thickness. The overall weight of 3\textsuperscript{rd} model was 21.85 kg.

![Figure 5. (a) $\sigma_{vm}$ and (b) displacement distribution of 2\textsuperscript{nd} model.](image1)

![Figure 6. (a) $\sigma_{vm}$ and (b) displacement distribution of 3\textsuperscript{rd} model.](image2)
As a summary, each model’s simulation result is shown in Figures 7, 8, and 9. The maximum $\sigma_{vm}$, safety factor, and maximum displacement is compared to the frame weight to find the optimum design for the e-trike frame.

![Figure 7](image1.png)

**Figure 7.** Numerical simulation result for maximum $\sigma_{vm}$ to frame mass.

From Figure 7, the lowest maximum $\sigma_{vm}$ is achieved by using 3rd model, followed by 2nd model. Note that 2nd model provides the lowest frame weight, and its maximum $\sigma_{vm}$ is lower than 1st model. The maximum $\sigma_{vm}$ is affected by the thickness of the pipe, and 3rd model has the highest pipe thickness among all models.

![Figure 8](image2.png)

**Figure 8.** Numerical simulation result for safety factor to frame mass.

Figure 8 shows the safety factor for each model. The highest safety factor is achieved by 3rd model, which uses the thickest pipe and aluminum material. The value of the safety factor is affected by the maximum $\sigma_{vm}$ value and material selection.

The displacement from the simulation result is shown in Figure 9. The frame’s displacement was investigated to prevent damage to the component inside the frame due to frame deflection. The highest displacement occurs in 2nd model, followed by 3rd model, and 1st model.

![Figure 9](image3.png)

**Figure 9.** Numerical simulation result for displacement to frame mass.

4. CONCLUSION

Numerical simulation has been conducted for three frame models: First model with steel material and 2nd model and 3rd model with aluminum material. From the $\sigma_{vm}$ distribution for the three models, all models were safe to be used for designed loading conditions. The maximum $\sigma_{vm}$ and displacement values for 1st model were 167.5 MPa and 1.3 mm, respectively. First model has the lowest pipe diameter and thickness. The maximum $\sigma_{vm}$ and displacement value for 2nd model were 134 MPa and 3 mm, respectively. The maximum $\sigma_{vm}$ and displacement values for 3rd model were 116 MPa and 2.1 mm, respectively. Thus, 3rd model had the lowest maximum $\sigma_{vm}$, whereas 1st model had the lowest maximum deflection. The comparison was also conducted on the overall weight. The frame’s overall mass values for the 1st, 2nd, and 3rd models are 41.28 kg, 15.93 kg, and 21.85 kg, respectively. Second model had the lightest weight due to aluminum’s low density and lower pipe thickness compared to 3rd model. However, the maximum displacement in the 2nd model frame reached 3 mm, which reached the maximum displacement design criteria. Third model is preferred to be the chosen design due to its weight lower than the steel frame and
has a safety factor higher than 1st and 2nd models. The displacement for 3rd model was also below the design criteria for the e-trike frame, which showed that the design is safe to be used.

Further research needs to be done by analyzing the economic improvement of the frame made of aluminum. Operation performance also needs to be conducted to verify the energy consumption for e-trike by using a lighter frame.

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