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Design and Analysis of A Stair Climbing Hand Trolley using Design of Experiment (DOE)

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Abstract: In the absence of a lift and escalator, it is difficult for users to transport heavy loads from the ground level to the higher floors of a building. Human effort is the best solution to transport heavy loads by using a stair climbing hand trolley. Thus, this study can be the basis or benchmark for prospective researchers for knowledge on the state. To begin, this study focuses on design improvement using SolidWorks software and analysis of a stair climbing hand trolley using Design of Experiment (DOE). The aim of this study is to identify the significant parameters and optimum setting for the stair climbing hand trolley. For the design improvements, the basket trolley and basket mounting were added using SolidWorks software to increase the efficiency of a stair climbing hand trolley. SolidWorks Simulation was used to analyze the design of this study and the results obtained from the Finite Element Analysis (FEA) which are yield strength and displacement. This study is expected to achieve several outputs such as yield strength, and displacement from the three parameters, which are material, ply angle and ply thickness. In addition, the parameters were applied to generate Design of Experiment (DOE) by using Minitab software. Full factorial design was conducted which the number of experiments required for this study (3 factors) is $3^3 = 27$. As a result, alloy steel was chosen since the material has the highest yield strength where the failure will happen much longer than stainless steel and aluminum alloy. Apart from that, the best ply thickness was 0.4 or 0.5 which produces consistent level whereas it was found that 0 or 90 degrees has the best ply angles. In a nutshell, Design of Experiment by using optimum parameters such as material, ply thickness and ply angle has proven to increase the efficiency of a stair climbing hand trolley by improving its material and mechanical properties.

Keywords: Design of Experiment, Finite Element Analysis, SolidWorks

1. Introduction

A stair climbing hand trolley is useful for moving heavy loads from one location to another [1]. Users who live in apartments or flats will benefit from a trolley that can lift loads while climbing the

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stairs. It is crucial for lifting loads [2]. The support frame of a hand trolley, there are usually two wheels and two handles. The device is pushed and pulled using these handles. It stands upright in an L-shape, with handles reaching out from the top back of the edge, or one handle bending from the back. Furthermore, products will be stacked on the platform, which is tilted backward to keep the platform and support frame balanced. In today's market, there are a variety of trolleys made of steel, aluminum, and durable plastic.

This type of trolley is commonly built with six wheels and mild steel, which is suitable for carrying moderate loads for stair climbing purposes. A six-wheel trolley can help people load and unload heavy items quickly in buildings without elevators or escalators. Since the trolley has a manual hand winch at the loading port, people can easily lift items from the ground to a table or something higher than the trolley, reducing back pain and musculoskeletal disorder issues [3].

Most hand trolleys are designed to transport products on a flat surface or at ground level. When it comes to moving products above ground level, however, there are constraints where a hand trolley cannot be used, such as rough surfaces or any up level from ground level is not an easy job, especially if there are no lifting facilities such as elevator, and conveyer. As a result, the aspect of transport from lower ground to higher ground or vice versa is limited. The hand trolley could be attempted to climb the staircase, but there is a higher risk of failure during the lifting process, such as the hand trolley sliding out of control and causing accidents and injuries [4]. Therefore, a design improvement of the stair climbing hand trolley was constructed to improve the efficiency of a trolley design as well as to recognize the significant parameters and optimum setting for the stair climbing hand truck.

2. Materials and Methods

2.1 Materials

There are several materials that were applied before running the Finite Element Analysis using SolidWorks Simulation. Firstly, is alloy steel. The proportions of alloying components might range from 1 to 50%. Alloy steels are divided into two categories: low alloy steel and high alloy steel [5]. The 5 % alloying element is usually considered as the border between low alloy and high alloy steel. In the oil and gas business, alloy steel is identical with low alloy steel. Low alloy steels typically have less than 8% non-iron elements, while high alloy steels contain more than 8% non-iron elements. Table 1 illustrates mechanical properties for alloy steel.

Table 1: Mechanical properties for alloy steel [6]

Mechanical Properties	Value
Yield Strength	450 MPa
Tensile Strength	595 MPa
Hardness	89 Vickers - HV
Elongation (in 200mm)	16% minimum

Next, stainless steel was used before performing a simulation. Grades 304 and 304L are stainless steel types 1.4301 and 1.4307, respectively. The most versatile and widely used stainless steel is Type 304. As a result of these properties, 304 has become the most popular grade for sinks and saucepans. Stainless steel 304L has a lower carbon content than Type 304. It is used to improve the weldability of heavy gauge components. Table 2 illustrates mechanical properties for 304 stainless steel alloys.

Table 2: Mechanical properties for 304 stainless steel [7]

Mechanical properties	Grade	
	304	304L:
Tensile Strength (MPa)	520 - 720	500 - 700
Proof Stress (MPa)	210 Min	200 Min
Elongation A50 mm	45 Min %	45 Min %

In addition, aluminum alloy grade 3003 was applied to conduct for a simulation. Aluminum alloy 3003 is a medium strength alloy with very good resistance to atmospheric corrosion and very good weldability as well as good cold formability. It is commonly used in the manufacture of sheet metal, fuel tanks, and other products that require moderate strength and good formability. Aluminum alloys are ideal when engineers want to lower the weight of a product. Table 3 illustrates mechanical properties for aluminum alloy grade 3003.

Table 3: Mechanical properties for aluminum alloy grade 3003 [8]

Mechanical properties	Value
Tensile strength	95 – 135MPa
Proof stress	35 Min MPa
Hardness Brinell	28 HB

2.2 Methods

Figure 1 illustrates the whole process of determining the best setting for each parameter in the stair climbing hand trolley design.

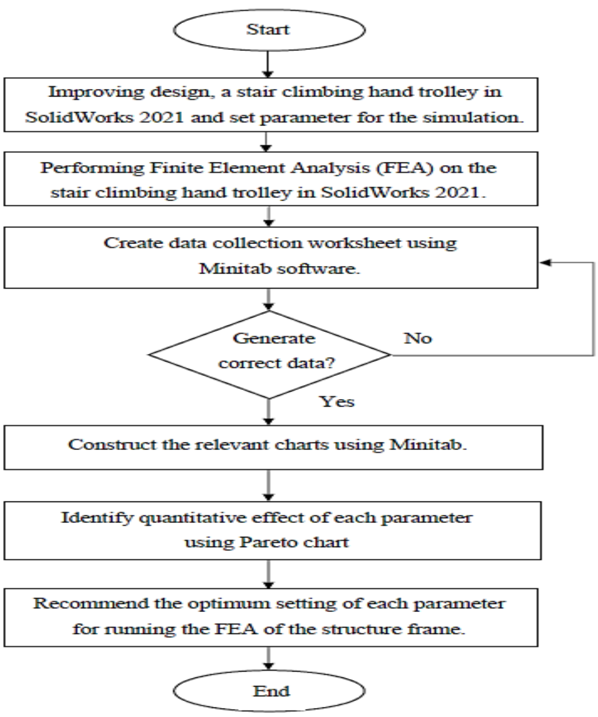


Figure 1: Flowchart of research methodology

The procedures begin with the creation of a design improvements of a stair climbing hand trolley in SolidWorks 2021. To increase the effectiveness of the stair climbing hand trolley, a basket and basket mounting were added to the design. Figure 2 shows the design of the basket and basket mounting.

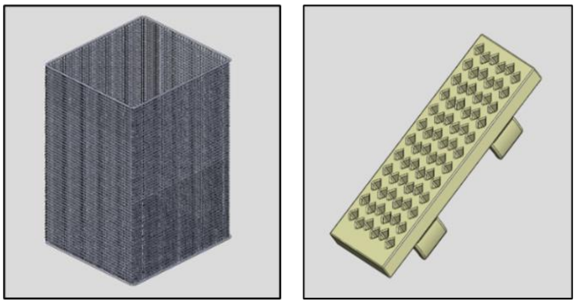
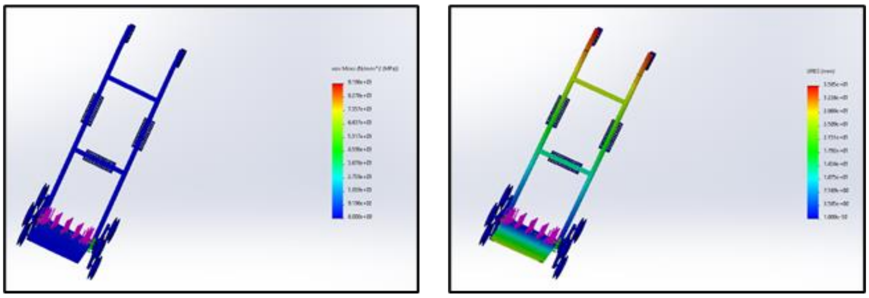


Figure 2: Design of the basket and basket mounting

Then, performing Finite Element Analysis was conducted after improved design of a stair climbing hand trolley. After running the simulation, the stress, and displacement results are obtained. Figure 3 illustrates the simulation results for the three parameters of material, ply angle, and ply thickness respectively.



a) b)

Figure 3: a) Stress b) Displacement

Next, Figure 4 illustrates the data collection worksheet was tabulated into a table in Minitab software which obtained the results of the simulation such as stress, and displacement as well as significant parameters that were applied.

↓	C1 StdOrder	C2 RunOrder	C3 PtType	C4 Blocks	C5 Material	C6 Ply Thickness	C7 Ply Angle	C8-T Stress	C9-T Displacement
1	2	1	1	1	1	0.4	45	2.308e+09	1.097e+02
2	15	2	1	1	2	0.5	90	2.399e+09	3.940e+01
3	12	3	1	1	2	0.4	90	2.403e+09	4.065e+01
4	4	4	1	1	1	0.5	0	2.330e+09	1.064e+02
5	6	5	1	1	1	0.5	90	2.332e+09	1.064e+02
6	24	6	1	1	3	0.5	90	2.396e+09	3.590e+01
7	9	7	1	1	1	0.6	90	2.308e+09	1.036e+02
8	26	8	1	1	3	0.6	45	2.384e+09	3.496e+01
9	3	9	1	1	1	0.4	90	2.331e+09	1.097e+02
10	11	10	1	1	2	0.4	45	2.392e+09	4.065e+01
11	19	11	1	1	3	0.4	0	2.397e+09	3.704e+01
12	5	12	1	1	1	0.5	45	2.312e+09	1.064e+02
13	1	13	1	1	1	0.4	0	2.329e+09	1.097e+02
14	18	14	1	1	2	0.6	90	2.370e+09	3.838e+01
15	21	15	1	1	3	0.4	90	2.396e+09	3.704e+01
16	13	16	1	1	2	0.5	0	2.398e+09	3.940e+01
17	8	17	1	1	1	0.6	45	2.292e+09	1.036e+02
18	25	18	1	1	3	0.6	0	2.370e+09	3.496e+01
19	7	19	1	1	1	0.6	0	2.306e+09	1.036e+02
20	23	20	1	1	3	0.5	45	2.414e+09	3.590e+01
21	10	21	1	1	2	0.4	0	2.402e+09	4.065e+01
22	22	22	1	1	3	0.5	0	2.397e+09	3.590e+01
23	27	23	1	1	3	0.6	90	2.369e+09	3.496e+01
24	17	24	1	1	2	0.6	45	2.363e+09	3.838e+01
25	14	25	1	1	2	0.5	45	2.390e+09	3.940e+01
26	20	26	1	1	3	0.4	45	2.418e+09	3.704e+01
27	16	27	1	1	2	0.6	0	2.369e+09	3.838e+01

Figure 4: Data collection worksheet

The Minitab software then generates data collecting spreadsheets based on the design parameters, which include material, ply thickness, and ply angle [9] using full factorial design. Figure 5 illustrates the creation of full factorial design in Minitab 21.

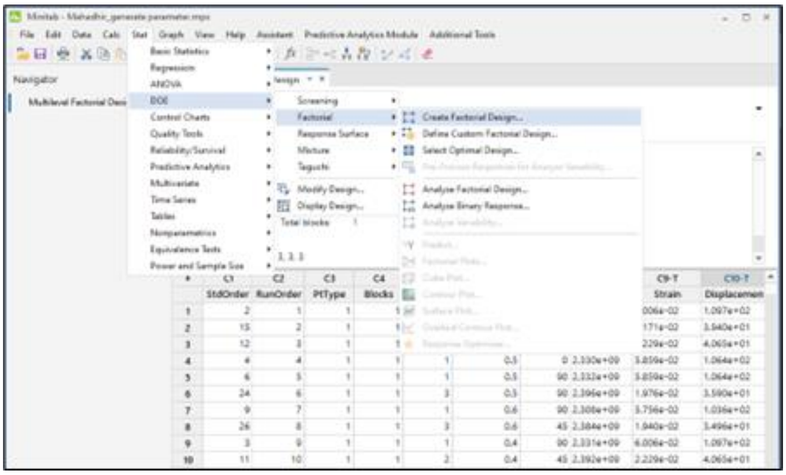


Figure 5: Create full factorial design in Minitab 21

Following that, the Design of Experiments (DOE) outcome will be determined. A Pareto chart is used to determine the quantitative influence of each parameter [10]. Finally, the optimum setting of each parameter for conducting the FEA for the stair climbing hand trolley will be recommended in the result and discussion.

2.3 Equations

In DOE, evaluation criteria are referred to as factors. Moreover, the results of the optimization process are known as responses. In this study, three parameters factor will be explored. Therefore, a significant number of experiments (runs) are required. The formula for determining the required number of experiments is as follows in Equation 1 [11].

$$N = 3f \quad Eq. 1$$

Where:

N: Number of experiments

f: Number of factors

According to Equation 1, the number of experiments required for this study (3 factors) is $3^3 = 27$. As a result, Minitab 21 software was used in this study to conduct the DOE analysis to reduce the number of treatments to be executed in an experiment.

3. Results and Discussion

3.1 Results

The DOE Analysis technique was utilized to evaluate the ideal results for the parameters of the structural frame. The study is focused on two response variables, specifically yield strength, and displacement.

3.1.1 Interaction plot for yield strength

Figure 6 illustrates a line graph showing that alloy steel has the highest yield strength, followed by stainless steel and aluminum alloy. The strength of alloy steel is likely due to its composition and manufacturing process. The line graph on the top right shows that aluminum alloy has the lowest strength at angles of 0, 45, and 90 degrees, while material 2 has the highest strength at angles of 0 and 90 degrees but lowest at 45 degrees compared to alloy steel. The bottom right graph shows that alloy steel and stainless steel have consistent strength at angles of 0, 45, and 90 degrees, while aluminum alloy has the lowest strength.

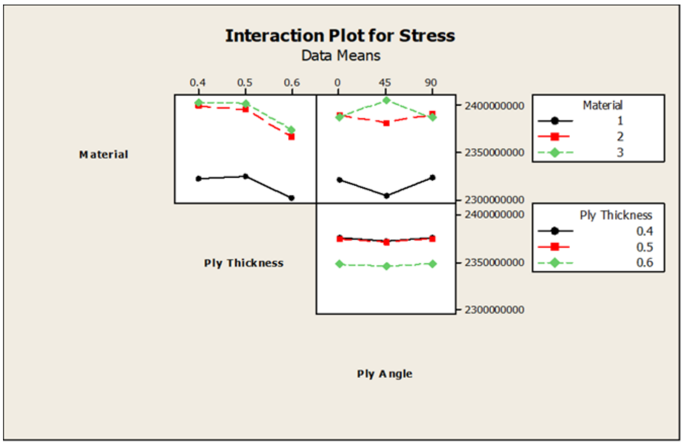


Figure 6: Interaction plot for yield strength

3.1.2 Main effects plot for yield strength

Figure 7 illustrates that alloy steel has the highest yield strength among the materials shown, followed by stainless steel and aluminum alloy. For a ply thickness of 0.4 shown the lowest yield strength, however for the thicknesses of 0.5 and 0.6 it has the same yield strength. In terms of ply angle, at angle of 45 degree has the lowest yield strength, but the angles of 0 degrees and 90 degrees have the same yield strength. The best setting for alloy steel would be at a thickness of either 0.5 or 0.6 and with a ply angle of either 0 or 90 degrees, which results in the same yield strength for both the thickness and angle. A study by Kalteremidou, Hajikazemi, Paepegem, Hemelrijck & Pyl shows that a thicker off-axis layer results in a lower strain and fails at a lower crack density, and a larger off-axis angle in the off-axis layers leads to a lower strain and higher crack density [12].

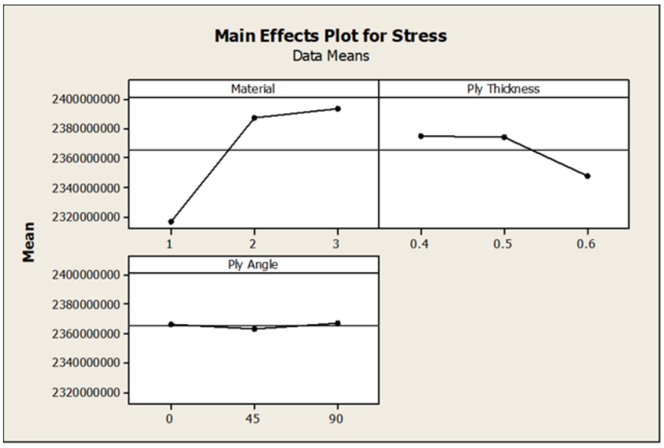


Figure 7: Main effects plot for yield strength

3.1.3 Surface plot of yield strength correlates ply thickness and ply angle

As illustrated in Figure 8, the yield strength remains constant across various ply angles and ply thicknesses, except for a slight decrease in yield strength at a ply angle of 0 and 45 degrees and a ply thickness of 0.6.

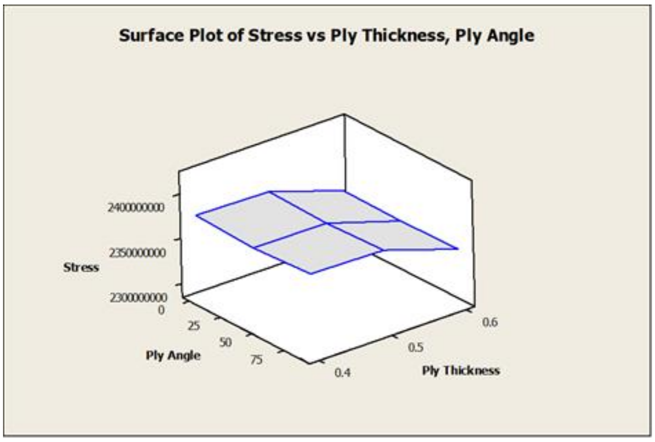


Figure 8: Surface plot of yield strength correlates ply thickness and ply angle

3.1.4 Interaction plot for displacement

Figure 9 shows an interaction plot of displacement corelates material and ply thickness. It was found that aluminum alloy has the highest displacement at a ply thickness of 0.4, while stainless steel and alloy steel have slightly different displacement regardless of ply thickness. Thus, changes in ply thickness can have a significant impact on the degree of splitting and delamination in brittle materials such as aluminum alloy. The plot also illustrates the correlation between material and ply angle, where aluminum alloy has a large amount of displacement when the angle is set to 0, 45, and 90 degrees. Meanwhile, the interaction plot at the bottom right side of the figure demonstrates the correlation between ply thickness, and ply angle. As the angle increases, the modulus and failure stress decrease, while a decrease in angle results in a higher initial modulus. Additionally, ply thicknesses 0.4, 0.5, and 0.6 show consistent displacement values at all angles. According to Vidyashankar & Murthy [13] this may be attributed to the fact that as the fibers in the laminate are aligned at a larger angle to the primary load path, it results in lower interlaminar stresses, reducing the risk of failure.

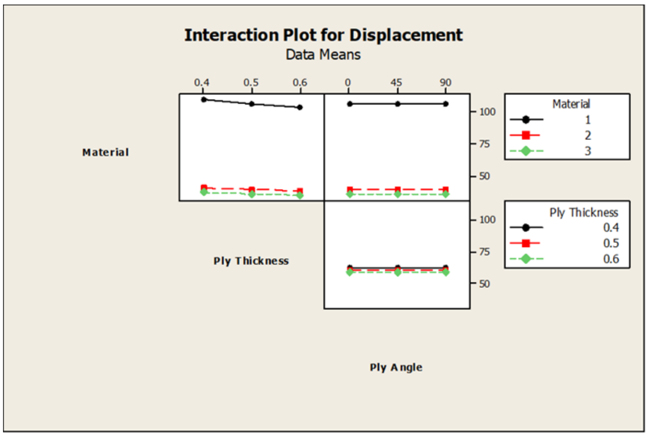


Figure 9: Interaction plot for displacement

3.1.5 Main effects plot for displacement

As shown in Figure 10, aluminum alloy has the highest displacement value among the materials shown, followed by stainless steel and alloy steel. For a ply thickness, there are slightly different between 0.4, 0.5, and 0.6 in which aluminum alloy has the highest displacement compared to stainless steel and alloy steel. In terms of ply angle, at angles of 0, 45 and 90 degrees generated the same results at 60. Thus, the ply angle does not influence the changes of the displacement and material.

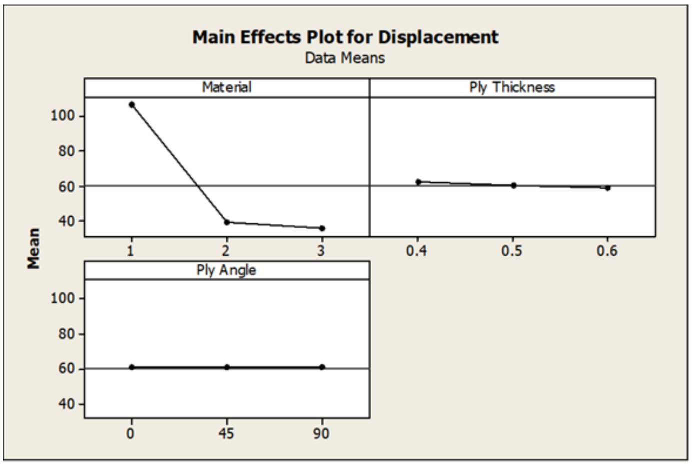


Figure 10: Main effects plot for displacement

3.1.6 Surface plot of displacement correlates ply thickness, ply angle

As shown in Figure 11, the displacement remains constant across various ply angles and ply thicknesses, in which the result obtained at the same displacement magnitude.

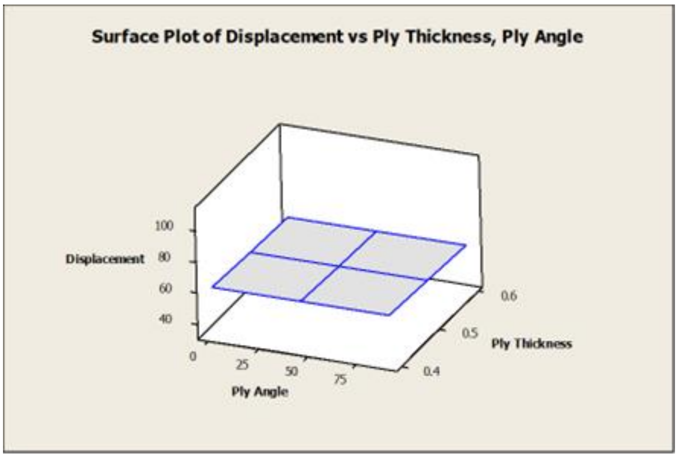


Figure 11: Surface plot of displacement vs ply thickness, ply angle

3.2 Discussion

Table 4 presents data on the yield strength of various materials, ply angles, and ply thicknesses. Alloy steel has the strongest yield strength, followed by stainless steel and aluminum alloy. In terms of ply thickness, a thickness of 0.6 has the lowest yield strength, while 0.4 and 0.5 thicknesses have the same yield strength. For ply angle, at 45-degree angle has the lowest yield strength, while 0 and 90 degrees angles have the same yield strength.

Table 4: Comparison for yield strength with different parameters

Material		Ply thickness		Ply angle	
Aluminium alloy	Lowest	0.4	Same	0˚	Same
Stainless steel	High	0.5	Same	45˚	Lowest
Alloy steel	Highest	0.6	Lowest	90˚	Same

Table 5 presents the results of an analysis of different materials, ply angles, and ply thicknesses on displacement. The data shows that alloy steel has the lowest displacement, with stainless steel and aluminum alloy coming in next. In terms of ply thickness, the analysis shows that a thickness of 0.4 has the most displacement, while 0.5 and 0.6 have similar but less displacement. Additionally, it shows that at angles of 0, 45, and 90 degrees, the displacement values are constant level.

Table 5: Comparison for displacement with different parameters

Material		Ply thickness		Ply angle	
Aluminium alloy	Highest	0.4	Highest	0˚	Same
Stainless steel	High	0.5	High	45˚	Same
Alloy steel	Lowest	0.6	Lowest	90˚	Same

4. Conclusion

In short, all the objectives were successfully achieved in which to improved design a stair climbing hand trolley in SolidWorks software. A stair climbing hand trolley had chosen to make an analysis on a structural frame using Design of Experiment (DOE). There are a few features have been added to the stair climbing hand trolley which are basket and basket mounting. Thus, it will help this product become sturdy as well as improve the efficiency of this project. Next, Finite Element Analysis (FEA) was conducted to obtain the data such as yield strength, and displacement before performing Design of Experiment (DOE) by using Minitab software. The chosen materials such as alloy steel, AISI 304, and aluminum alloy 3003 were applied to make comparisons between these materials before running a simulation. Besides, there are several parameters that were applied on a stair climbing hand trolley which are ply thickness and ply angle. The reason for this occurrence, to recognize the significant parameters and optimum setting for the stair climbing hand trolley by using SolidWorks.

In addition, the parameters were applied to generate Design of Experiment (DOE) by using Minitab software. Full factorial design was conducted which the number of experiments required for this study (3 factors) is $3^3 = 27$. Then, the obtained information will be tabulated on a data worksheet. The plot of main effects, and the plot of interaction were displayed to give a visual representation of the data, making the interpretation process more efficient and organized.

As a result, the data were analyzed and evaluated in which alloy steel was chosen as the optimum material due to high value of yield strength compared to stainless steel and aluminum alloy. The study found that alloy steel has the highest yield strength, followed by stainless steel and aluminum alloy. Additionally, it was determined that angles of 0 and 90 degrees resulted in the best yield strength, while 45 degrees had the lowest. The study also found that ply thicknesses of 0.4 and 0.5 had consistent levels of yield strength, but the lowest was found at 0.6. Therefore, alloy steel is the best material for this research study as it exhibits the highest yield strength and failure occurs much longer compared to the other materials. As a result, Design of Experiment (DOE) by using optimum parameters (material, ply thickness and ply angle) has proven to increase the efficiency of a stair climbing hand trolley by improving its material and mechanical properties.

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