PARAMETRIC ANALYSIS AND STRUCTURAL OPTIMISATION OF A MINI-CRANE

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Abstract - *This article presents a novel design and analysis of a semi-automatic mini-crane mechanism. The main objective of the work is to help load and unload spare tyre into the boot. The crane system is fit into boot of the car. First, a basic CAD model is designed using Solidworks to fit the necessary requirements. Then, selection of material is carried out based on attainment of maximum possible factor of safety, minimum displacement and minimum stress developed in the component by performing parametric analysis.*

Key Words: Crane, Autodesk Inventor, spare tyre, lifting, parametric analysis.

1. INTRODUCTION

Wheel replacement in an automobile is a physically challenging task, especially when it comes to an elderly person or a handicapped person. The most challenging part of the process is the unloading of the spare tyre from the boot and the loading of the damaged tyre into the boot space. Aside from mechanical failures, around 27% of all roadside emergencies are tyre related. Statistics show that on an average, upto 5 Flat tyres may occur in a person's life time. Surveys have shown that, majority of the US citizens attain license after the age of 35.

We aim to create a solution for current wheel replacement system. We have devised a system that aids in the replacement of a damaged wheel by reducing the effort and fatigue.

Crane is a hoisting machine used to lift heavy and bulky objects. The objects are hoisted using a crane hook attached to a wire rope or a metal chain, operated by a pulley system, driven by a motor. We have created a miniature version of a crane, such that, it can be easily Fitted into and folded in the boot space of a car without taking up too much space. The crane is also Fitted to the side of the boot space using hinges, so as to provide additional support and stability while lifting objects.The motor is powered by the battery of the automobile.

The crane is operated using an electric motor. The motor is attached to a gear box using a belt to control the torque provided by the motor. Lifting of a tyre requires a high torque and low speed. The gear box is provided so as to achieve this high torque. It also aids in the change of direction of the crane mechanism.

The crane can also be rotated in the horizontal direction using hand, which is aided by a ball bearing at the crane joint. It can be folded and placed on the boot space Floor when not in use. This prevents blockage of rearview of the driver. For the stability of the crane, the total moment about the base should be equal to zero. The magnitude of load that is permitted to be lifted is some value less than the load that will cause the crane to tip, thus providing a safety margin.

We focused on the material selection for the crane, so that it provides maximum strength to the design and prevents the collapse of the crane while loading and unloading of the tyre.

The concept of crane originated from pulley systems that were first utilised by ancient Mesopotamians as early as 1500 BC. But, it was not until 1834 that hydraulic cranes came into use with the development of hydrodynamics. The industrial revolution made the use of cranes in harbours and industries for loading objects more common. In 1838, William Armstrong developed the first water-powered hydraulic cranes.

Modern crane are of two types: Mobile and Fixed. There are four principal types of mobile cranes: truck mounted, rough-terrain, crawler, and floating. Fixed cranes have the ability to carry greater loads and greater heights due to their increased stability. The most commonly used fixed crane is the tower crane. It consists of varies parts such as the mast, slewing unit, jib, counter jib, hoist winch and hook. Mast is the main supporting tower of the crane. It is usually made of steel trussed sections. Slewing unit is placed on top of the mast and contains the motor that runs the crane. Jib is the extended operating arm with rotated along the vertical axis. Hook is used to connect the material to the crane.

G. Sun, M. Kleeberger, and J.Liu [1] give a method for the dynamic calculation for a hoisting device. Based on this method, the Finite element model of crane structure will be coupled with the model of drive system. W. Sochacki [2] focuses on the dynamic stability of a laboratory model of a truck crane. His study shows that, for each of the studied examples, there exists such a rope length for which the critical value of the coefFicient a in the Mathieu equation is obtained. Y. Sakawa, and A. Nakazumi [3] derive a dynamical model for the control of a rotary crane, which makes three kinds of motion (rotation, load hoisting, and boom hoisting) simultaneously. B. Jerman, and J. Kramar's

[4] study provide us with the maximum horizontal inertial forces in a radial direction that are acting on a load suspended from the jib during a crane's slewing motion.

2. COMPONENTS OF THE MINI-CRANE

2.1 ELECTRIC MOTOR

We have used a DC Geared motor (12V 4.8A) in our device. A DC geared motor is an all-in-one combination of a motor and gearbox. The addition of a gear head to the motor helps to control the speed while increasing the torque provided by the motor. If voltage is continuously applied to the motor, it could heat up and reduce the life of the motor. Therefore, it is necessary to use the motor within the safety specifications. The motor's basic rating point is slightly lower than its maximum efficiency point. Load torque is determined by measuring the current drawn when the motor is attached to a machine whose actual load value is known.

Different types of gear mechanisms are used in DC geared motors: Standard gear mechanism, Metal bearing gear mechanism and planetary gear mechanism. Standard gear mechanism is used to support intermittent duty, where the motor is used for 2sec or less. In Metal bearing gear mechanism, all gears, including the output gear, are attached to the shaft and supported by non-lubricated metal bearings. This type of mechanism is used for medium load applications and continuous duty cycle operation. Planetary gear mechanism is a heavy duty which uses 3 mating gears to transmit torque to the output shaft.

2.2 CRANE FRAME

The crane has a lightweight, portable frame which can be Fixed to the boot of a car using bolts. The crane has a foldable design, which ensures the minimum usage of boot space in the car and also ensures the rearview of the driver is not blocked when not in use. The crane is unfolded and a latch is used to lock the frame to the side of the car so as to provide additional support and stability. The frame consists of two components of cylindrical and rectangular cross-section. Sheet metal is used for designing the rectangular component and steel pipe of cylindrical cross-section is used for the second component. The frame is assembled using nut and bolt. The length of the horizontal components can be adjusted using a slider mechanism.

2.3 WIRE ROPE

A wire rope is used to lift the materials. A concentrated wire rope is constructed using number of wire strands by passing through coiling wheels which compress and shape each of the wires to form consolidated structures or it decreases diameters before wounding strands around the core. A hook is attached to one end of the wire rope and the other end is wound on the shaft attached to electric motor. The no. of wire ropes used is determined by considering the weight of the material raised, the weight of the wire rope, and the force due to acceleration of the material and the wire rope.

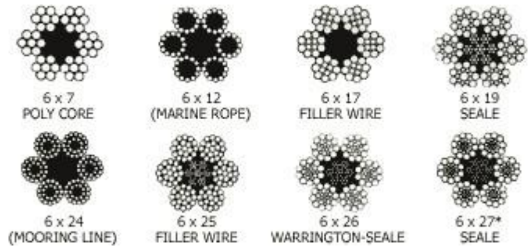

Fig 1: Cross Section of Wire Rope

2.4 HOOK

Hooks are one of the most important components of a crane. The hook is used to attach the material raised to the wire rope. The material selection for the hook is very important, so as to prevent the early failure of the hook due to stresses acting on it. Formation of crack may occur due to the application of tensile stress, bending stress etc.

2.5. PULLEY

A pulley is a system that consists of a wheel and a Flexible rope or cable. It is used to support the wire rope in the crane. It helps easily change the direction of motion and makes the movement of the wire rope smoother by decreasing the frictional forces acting on it. The dimensions of the groove in the pulley depends on the diameter of the wire used.

3. CALCULATIONS

3.1. ELECTRIC MOTOR

Diameter of spool shaft, D = 3cm

$\therefore$ Required Torque, $T_{load} = M.g.R_{shaft}$

$$T_{load} = 20 \times 9.8 \times 1.5 = 294 \times 10^{-2} Nm \text{......... (1)}$$

Considering, DC Geared Motor (12V 4.8A),

Rated Torque of Motor, T_m = 40 kg.cm = 40 x 0.09807Nm

$$T_m = 3.9228 Nm \text{......................... (2)}$$

From (1) and (2), the Torque required is less than the Rated Torque of the motor, $\therefore$ the selected motor is suitable.

Speed of Motor, N = 60rpm

Velocity of load during lifting,

$V_{up} = R_{shaft} \times \omega_{shaft} = 1.5 \times 10^{-2} \times 60 \times \frac{2\pi}{60}$

$V_{up} = 0.0628$ m/s = 6.28cm/s .... (3)

Power required to operate motor,

$P_{Required} = V \times I = 4.8 \times 12 = 57.6$ Watts

Car Battery Specification: 12V 35Ah

$P_{battery} = 12 \times 35 = 420$Wh

Maximum Operation Time = 420/57.6 = 7.291 Hours

Since the motor is to be used for only a short period, it is safe to use on the car battery.

3.2.WIRE ROPE

The forces acting on the wire rope are the weight of the material to be raised, the weight of the wire rope and the force due to the acceleration of the material and the wire rope.

Total weight of material raised = 10 x 20 = 200 N ....(4)

Wire cable of diameter 1mm is used for creating the wire rope. Assume 'n' wire cables are used for the wire rope.

Wire of diameter 10mm has a minimum breaking load of 440N.

Since wire of 1mm of length 3.3m is considered, the weight of wire can be neglected.

From (3), Acceleration, $a = \frac{V^2}{2s} = \frac{(0.0628)^2}{2*2}$

$= 9.859 \times 10^{-4}$ m/s^2......(5)

Mass of material raised $= \frac{200}{n x 9.81}$ kg $= \frac{20.3873}{n}$ kg

Weight due to acceleration on one cable = m * a

$= \frac{20.3873}{n} \times 9.859 \times 10^{-4}$

$= \frac{0.02}{n}$ N.......(6)

Breaking load of wire = 440 N

Assume a factor of safety of 10.

(4) & (6) $\Rightarrow \frac{200}{n} + \frac{0.02}{n} = 44 \quad \Rightarrow \quad n = 4.54 \approx 5$.........(7)

So 5 wire cables of φ1 mm are taken in to account. The diameter selected is on the much safer side, considering the maximum tension in the wire rope is 200 N. The mechanical properties of wire ropes according to IS 280: 2006[8] is considered.

4. DESIGN

For this project, we considered the average car dimensions of a city car from table and created a basic model using CAD (Fig 2). The crane has a foldable design which ensures the usage of minimum boot space as well as it prevents blocking the rearview of the driver. It consists of a vertical and a horizontal component. The vertical component has a cylindrical cross-section and helps in the easy rotation of the crane.

Average length of boot = 104 cm
Average height of boot = 90.2 cm

The height of boot from the collected data is the height up to the top of the seat. Therefore, the available height in the boot is more. The height of crane is selected by taking this into consideration.

Height of crane = 90cm

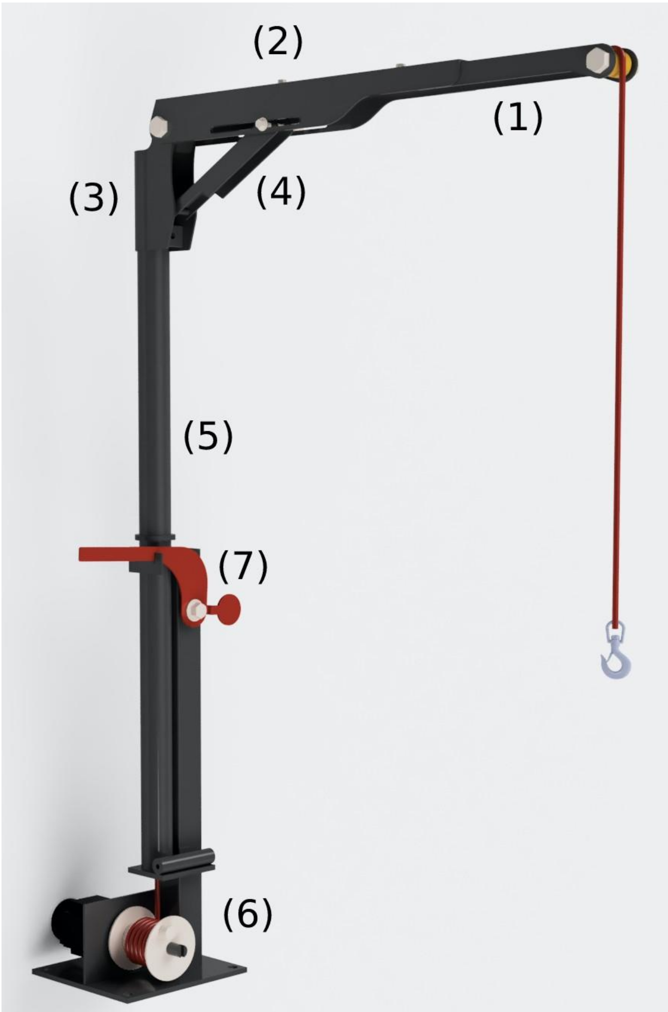

Fig 2: CAD Model of Mini-Crane

Length of horizontal component is calculated by taking half of the boot length. Due to the limitation in the sample space, an average length for component was selected.
∴ Length of horizontal component = 59cm

5. MATERIAL SELECTION AND PARAMETRIC ANALYSIS

Material selection is done by conducting parametric analysis on the CAD model (Fig 2) of the crane. Three suitable materials were selected on the basis of market availability and cost. These materials were added to the CAD model, and three different loads were applied to each of these materials. These provided us with 9 different sets of results when structural analysis was conducted. The material providing the best set of results was finalised as the material for the crane frame.

The following parameters were applied to the CAD model:

Component No	Feature Name	Parameter Name	Values
2	Extrusion1	Width	36 – 39:3
2		uniThickness	3 – 4:3
4	Extrusion1	Width	20 – 23:3
4		uniThickness	3 – 4:3
5	Extrusion1	pipeThickness	2 – 5:3

Table 2: Dimensional Attributes of Components subjected to Parametric Analysis

5.1. PARAMETRIC ANALYSIS RESULTS

5.1.1. STAINLESS STEEL 440C

Mechanical Properties [5]

Young's Modulus = 206.7 GPa
Poisson's Ratio = 0.27
Shear Modulus = 83900 MPa
Density = 7.75 g/cm^3

Strength

Yield Strength = 689 MPa
Tensile Strength = 861.25 MPa
Mass = 5.96087 Kg

LOAD 1 - 150 N

Factor of Safety = 2.603 (Fig. 3)
Max. Stress = 264.647 MPa (Fig. 4)
Max. Displacement = 2.974 mm (Fig. 5)

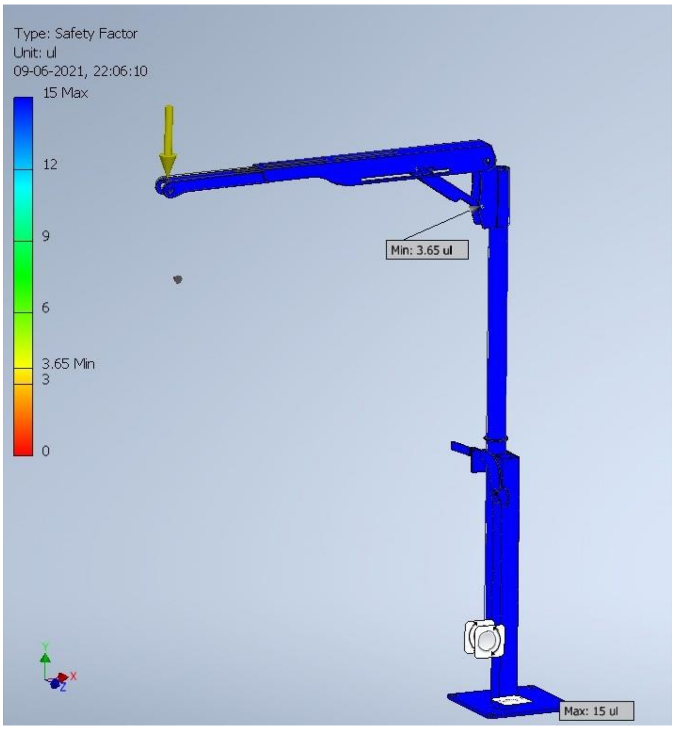

Fig 3: Factor of Safety for material 1 (150N)

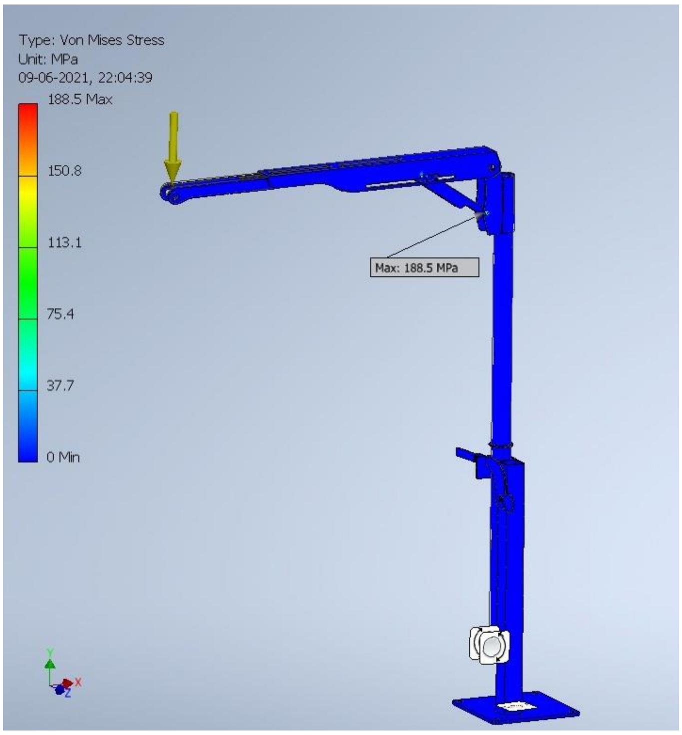

Fig 4: Max Stress Developed in the Component for material 1 (150N)

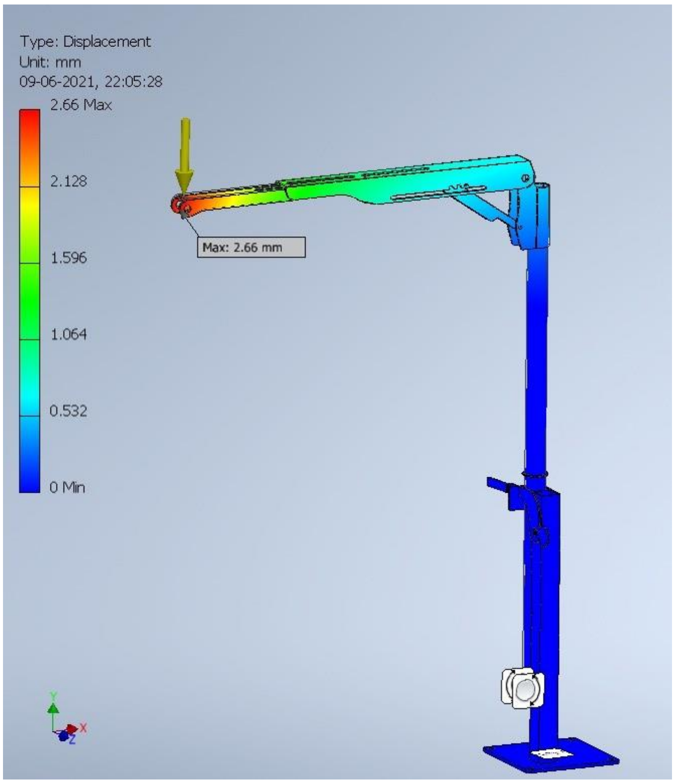

Fig 5: Max Displacement for material 1 (150N)

LOAD 2 - 175 N

Factor of Safety = 2.94 (Fig. 6)
Max. Stress = 234.609 MPa (Fig. 7)
Max. Displacement = 2.63 mm (Fig. 8)

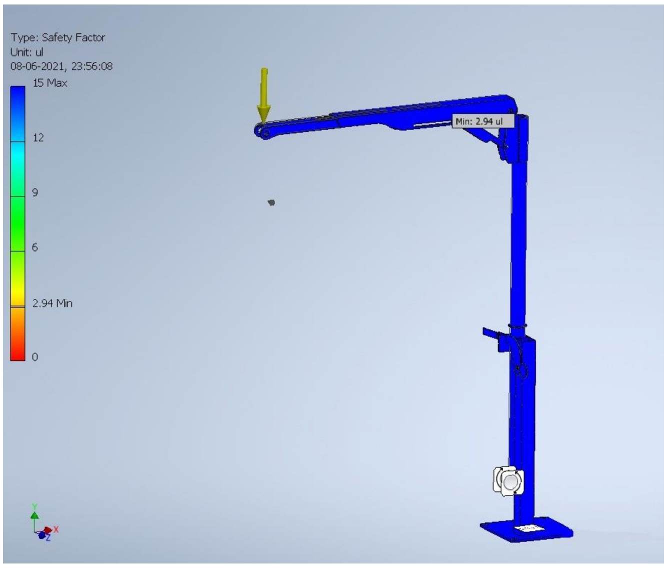

Fig 6: Factor of Safety for material 1 (175N)

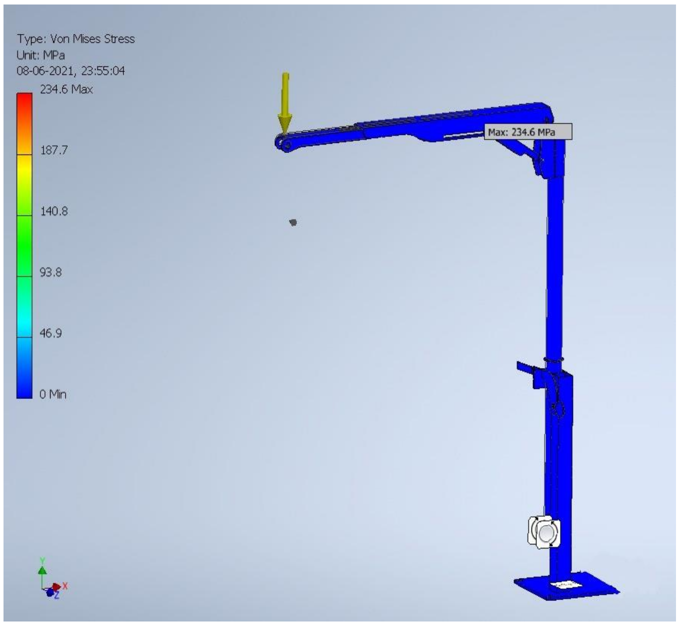

Fig 7: Max Stress Developed in the Component for material 1 (175N)

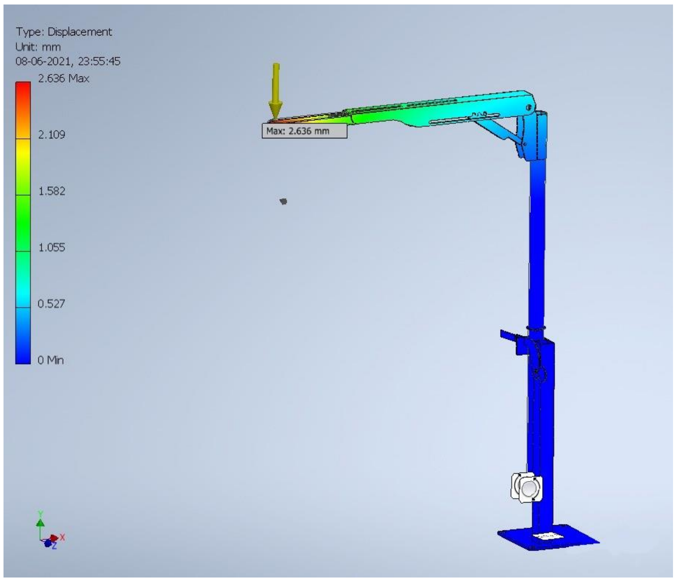

Fig 8: Max Displacement for material 1 (175N)

LOAD 3 - 200 N

Factor of Safety = 2.202 (Fig. 9)
Max. Stress = 312.852 MPa (Fig. 10)
Max. Displacement = 3.515 mm (Fig. 11)

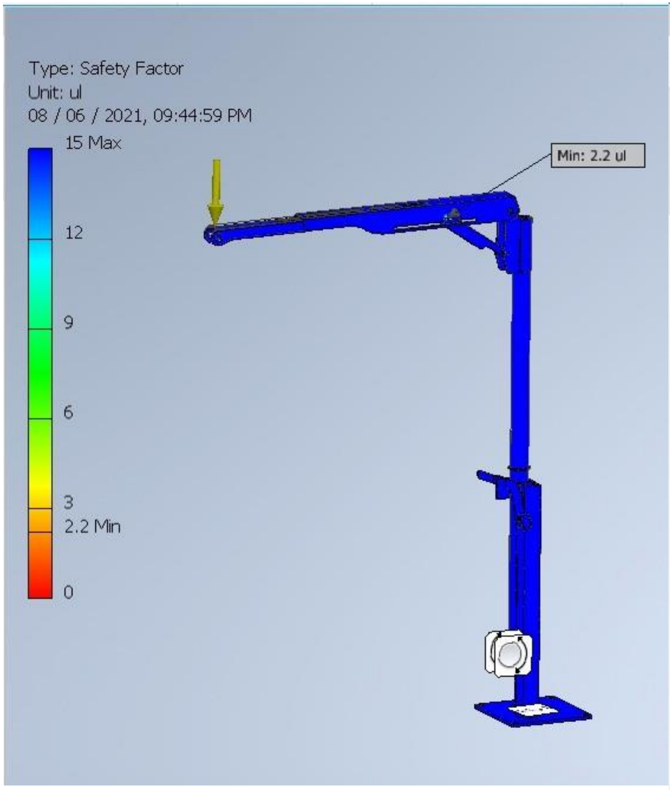

Fig 9: Factor of Safety for material 1 (200N)

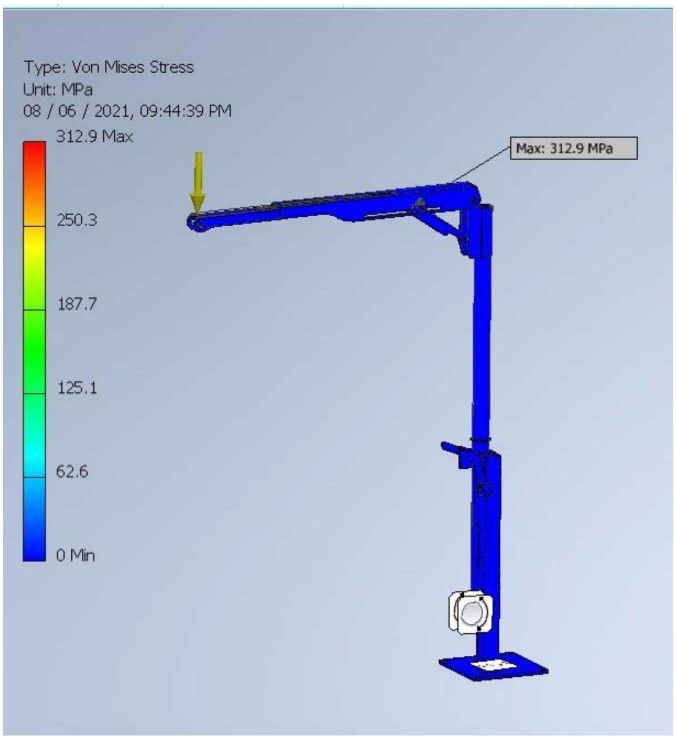

Fig 10: Max Stress Developed in Component for material 1 (200N)

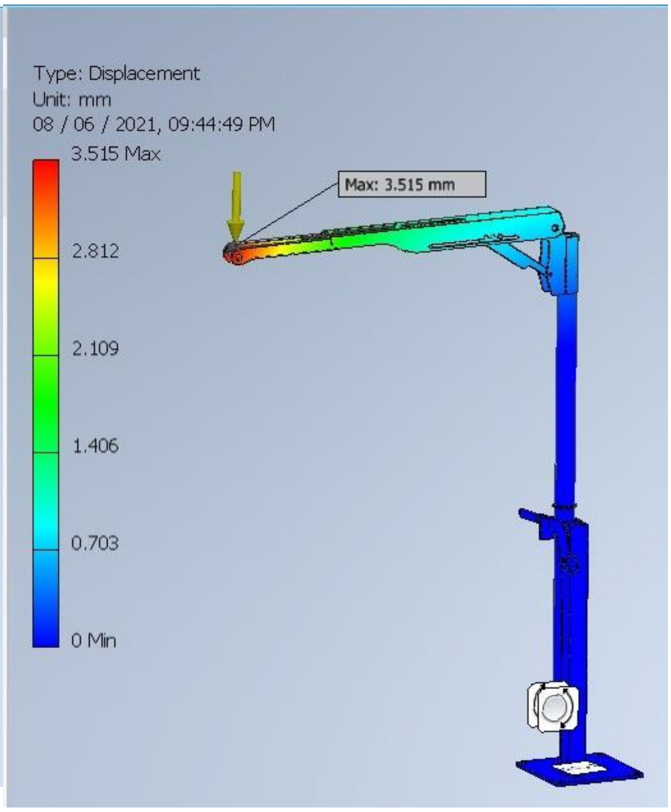

Fig 11: Max Displacement for material 1 (200N)

5.1.2. STEEL AISI 4340 409 QT

Mechanical Properties [6]

Young's Modulus = 207 GPa
Poisson's Ratio = 0.33
Shear Modulus = 77820 MPa
Density = 7.85 g/cm^3

Strength

Yield Strength = 1371 MPa
Tensile Strength = 1467 MPa

Mass = 5.43 Kg

LOAD 1 - 150 N

Factor of Safety = 5.69 (Fig. 12)

Max. Stress = 240.794 MPa (Fig. 13)

Max. Displacement = 2.632 mm (Fig. 14)

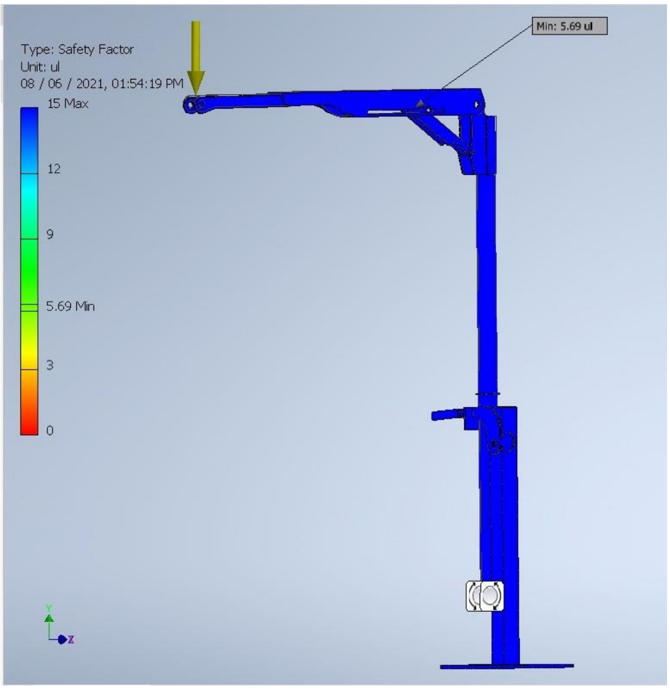

Fig 12: Factor of Safety for material 2 (150N)

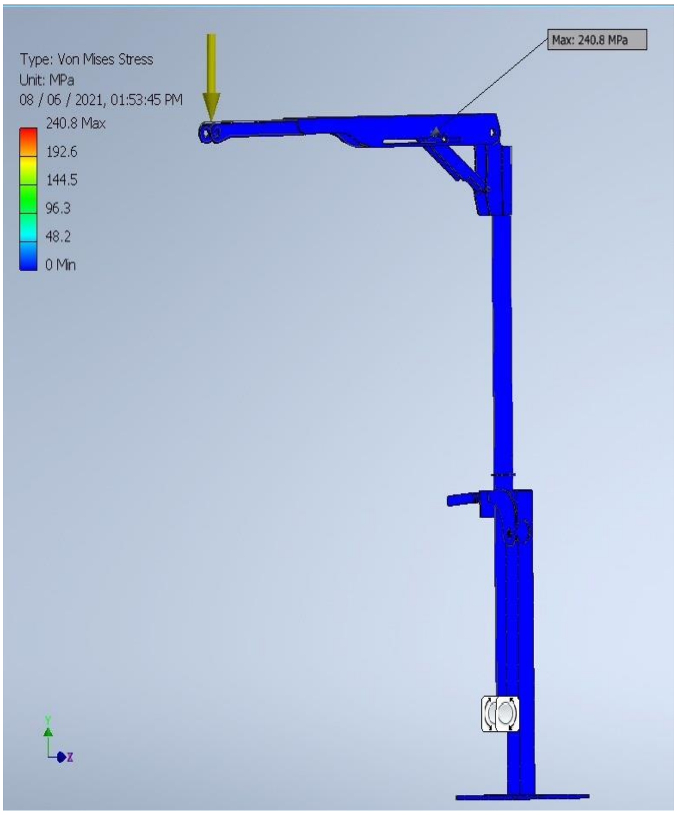

Fig 13: Max Stress Developed in the Component for material 2 (150N)

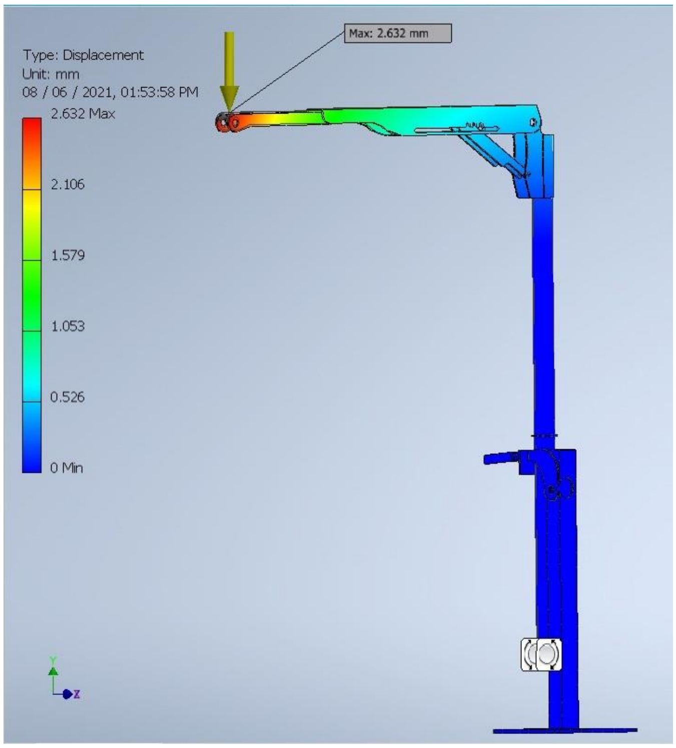

Fig 14: Max Displacement for material 2 (150N)

LOAD 2 - 175 N

Factor of Safety = 4.44 (Fig. 15)
Max. Stress = 278.8 MPa (Fig. 16)
Max. Displacement = 3.437 mm (Fig. 17)

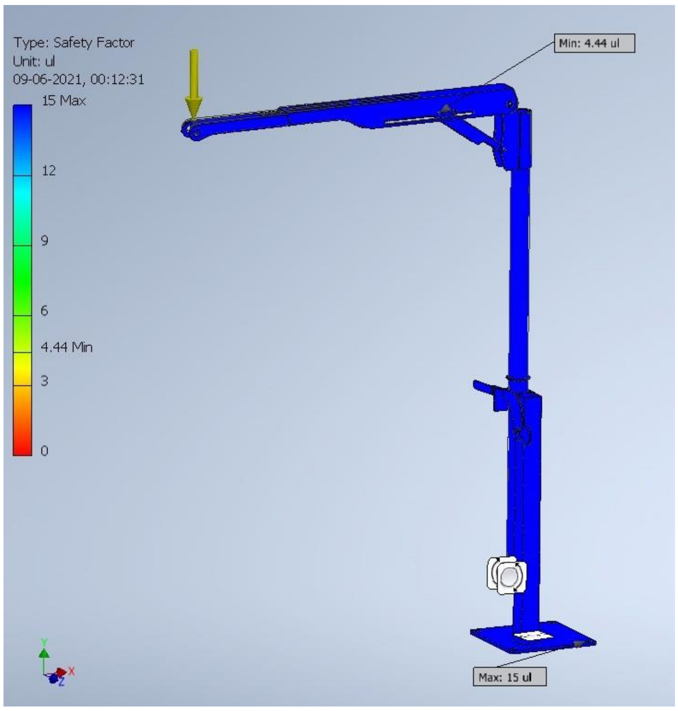

Fig 15: Factor of Safety for material 2 (175N)

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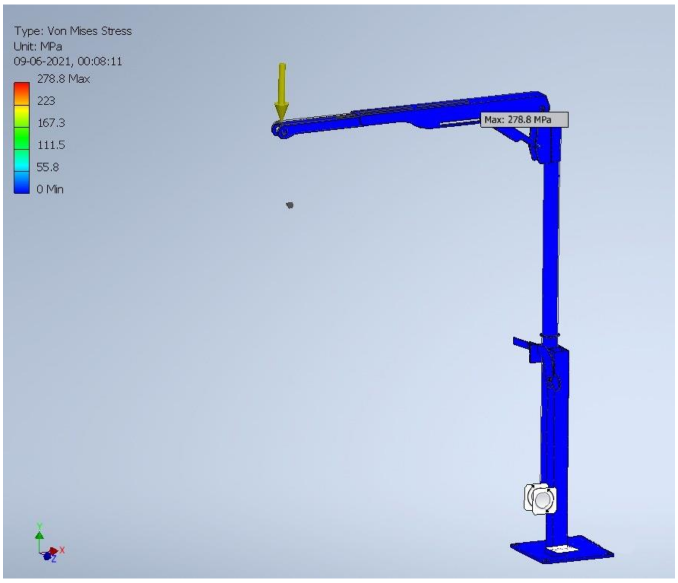

Fig 16: Max Stress Developed in Component for material 2 (175N)

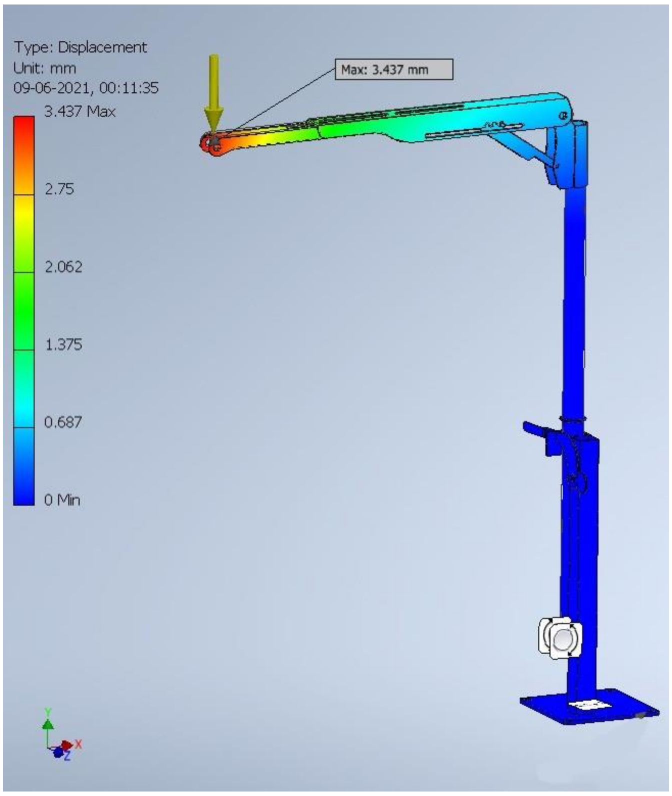

Fig 17: Max Development for material 2 (175N)

LOAD 3 - 200 N

Factor of Safety = 4.27 (Fig. 18)
Max. Stress = 321.06 MPa (Fig. 19)
Max. Displacement = 3.509 mm (Fig. 20)

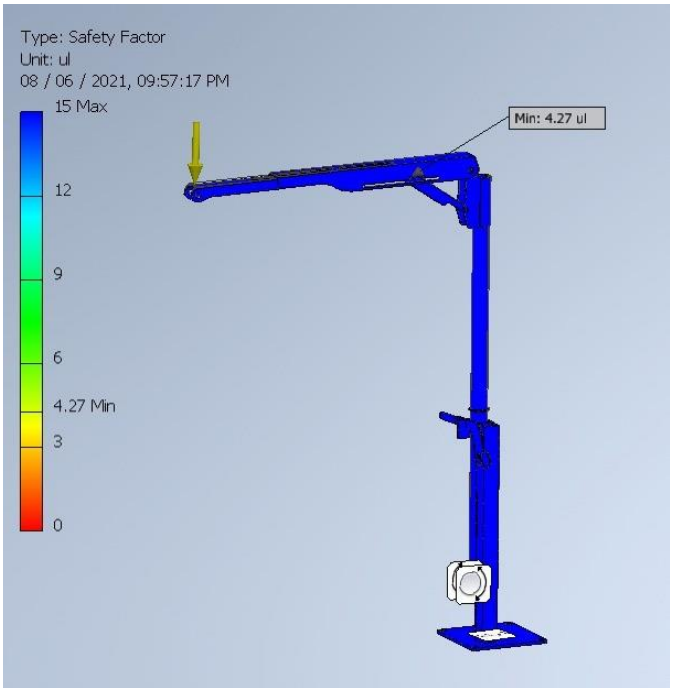

Fig 18: Factor of Safety for material 2 (200N)

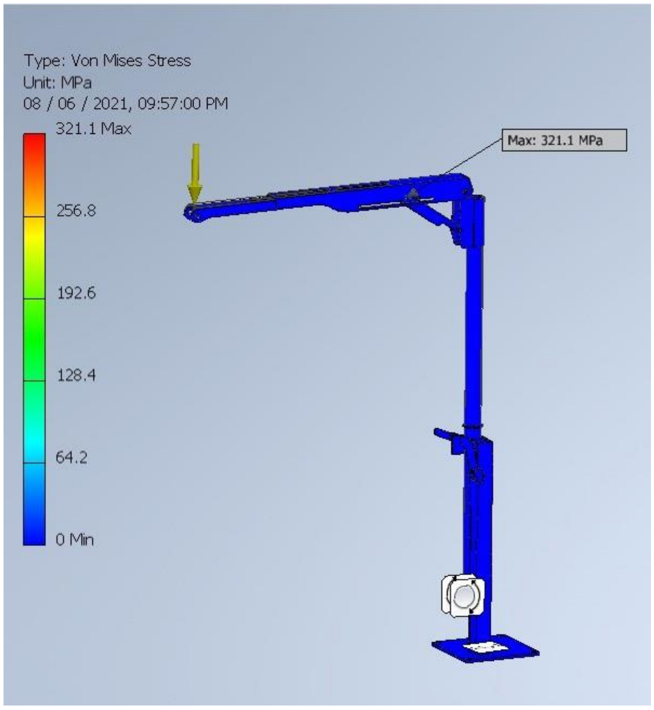

Fig 19: Max Stress Developed in Component for material 2 (200N)

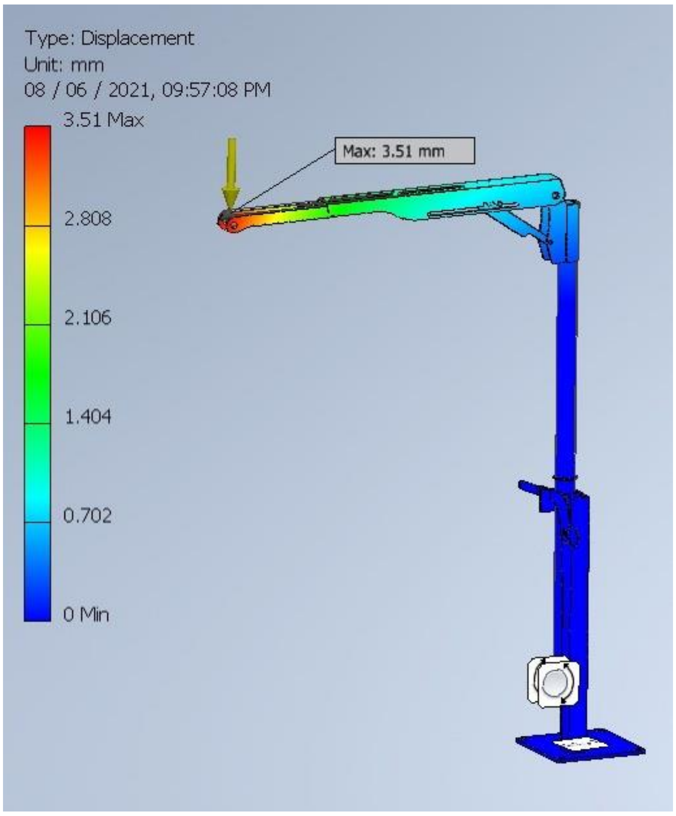

Fig 20: Max Displacement for material 2 (200N)

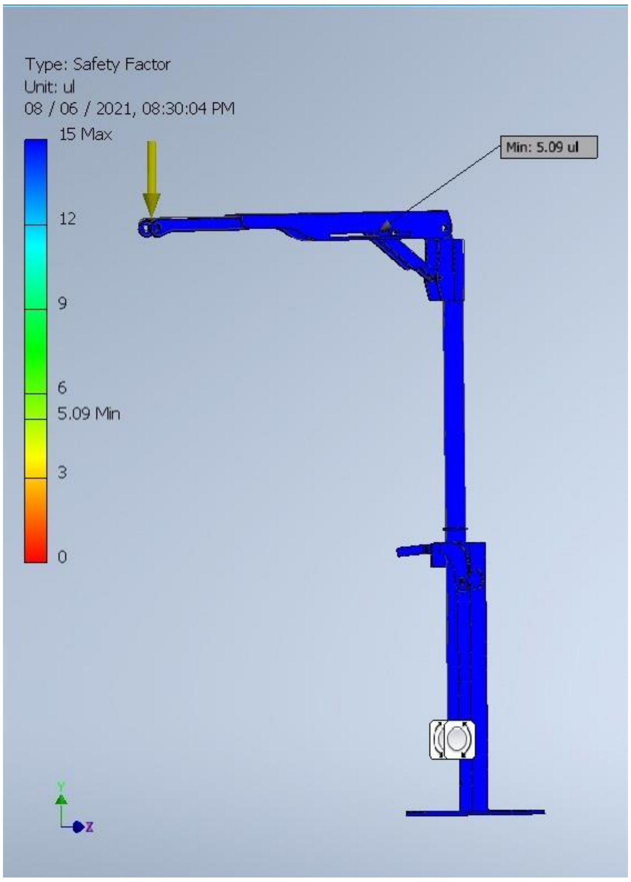

Fig 21: Factor of Safety for material 3 (150N)

5.1.3. STEEL AISI 1045 390 QT

Mechanical Properties [7]

Young's Modulus = 207 GPa
Poisson's Ratio = 0.33
Shear Modulus = 77820 MPa
Density = 7.85 g/cm^3

Strength

Yield Strength = 1274 MPa
Tensile Strength = 1343 MPa

Mass = 4.765 Kg

LOAD 1 - 150 N

Factor of Safety = 5.086 (Fig. 21)

Max. Stress = 250.488 MPa (Fig. 22)

Max. Displacement = 2.73 mm (Fig. 23)

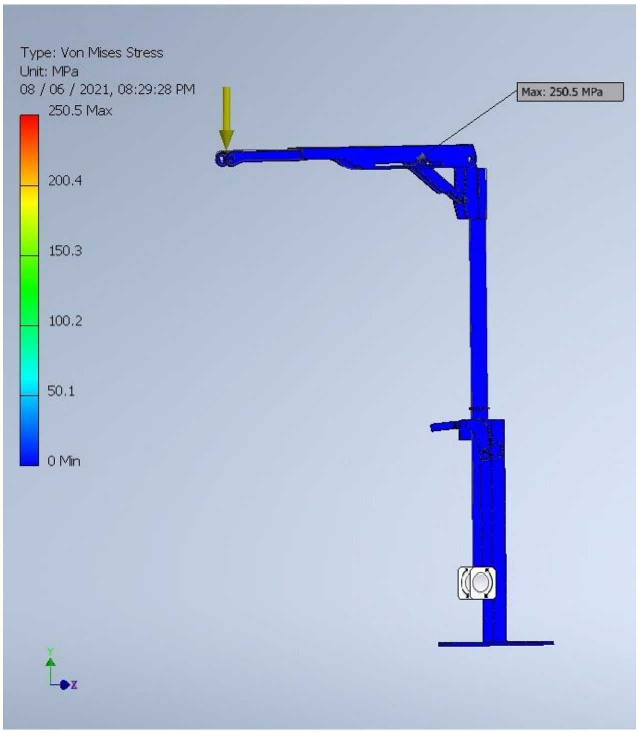

Fig 22: Max Stress Developed in Component for material 3 (150N)

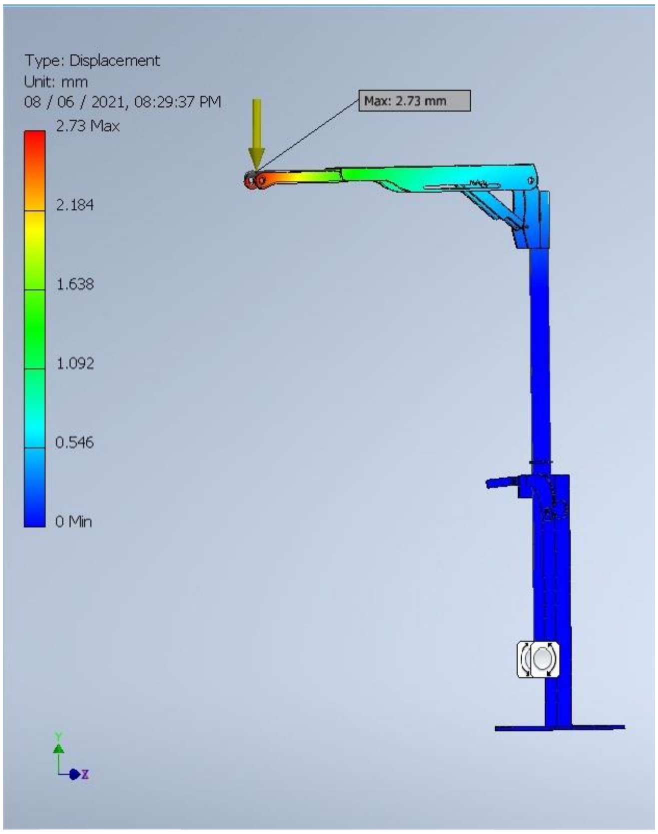

Fig 23: Max Displacement for material 3 (150N)

LOAD 2 - 175 N

Factor of Safety = 4.13 (Fig. 24)
Max. Stress = 308.8 MPa (Fig. 25)
Max. Displacement = 3.438 mm (Fig. 26)

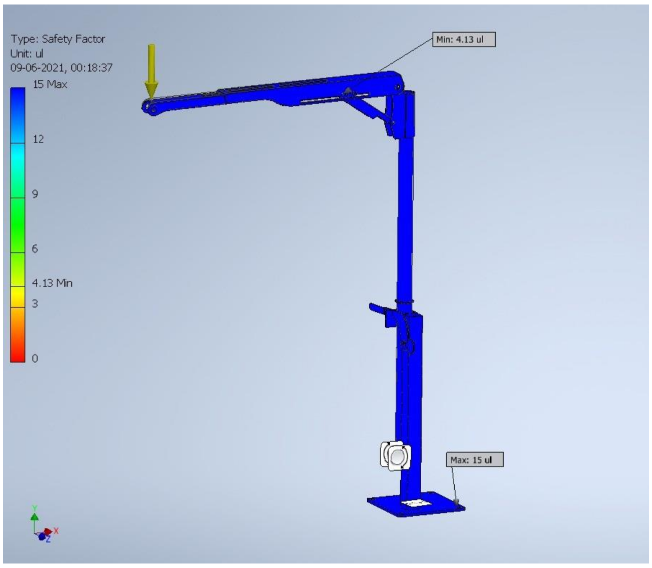

Fig 24: Factor of Safety for material 3 (175N)

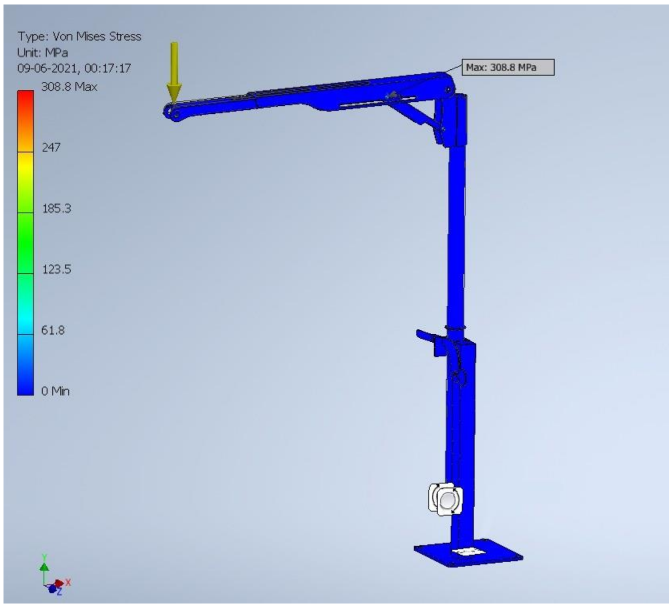

Fig 25: Max Stress Developed in Component for material 3 (175N)

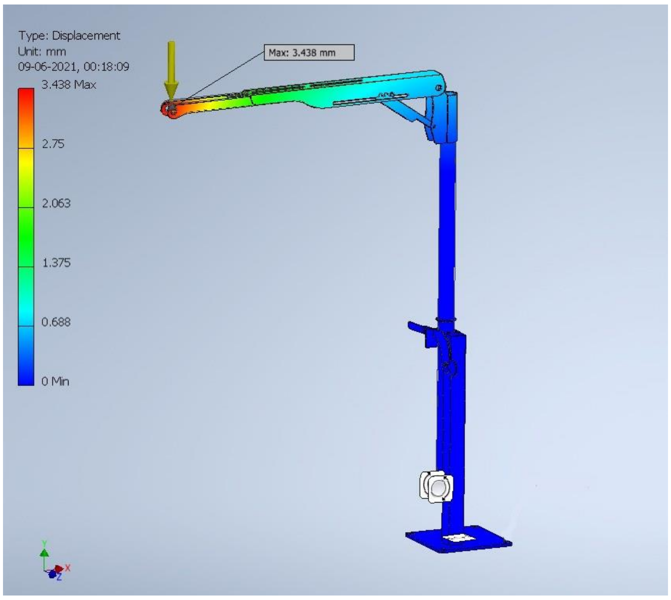

Fig 26: Max Displacement for material 3 (175N)

LOAD 3 - 200 N

Factor of Safety = 3.811 (Fig. 27)
Max. Stress = 334.293 MPa (Fig. 28)
Max. Displacement = 3.624 mm (Fig. 29)

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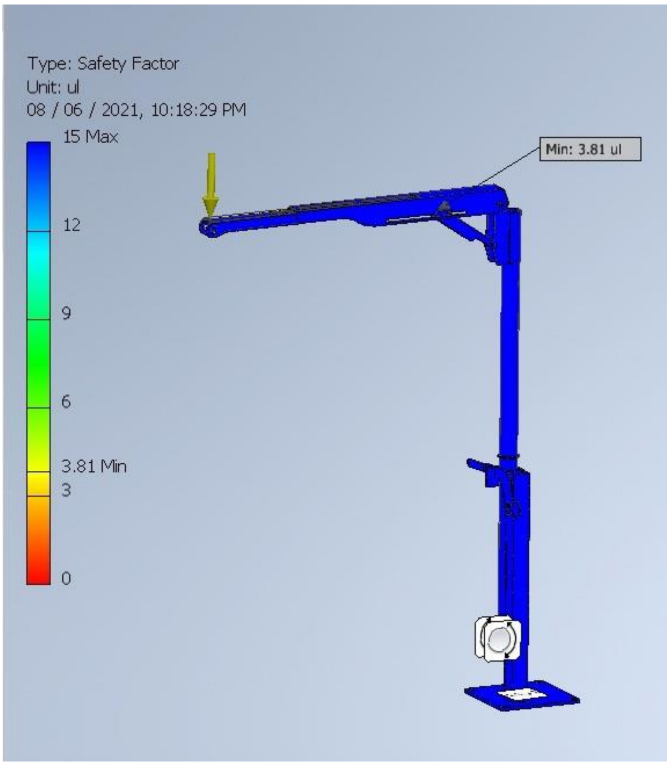

Fig 27: Factor of Safety for material 3 (200N)

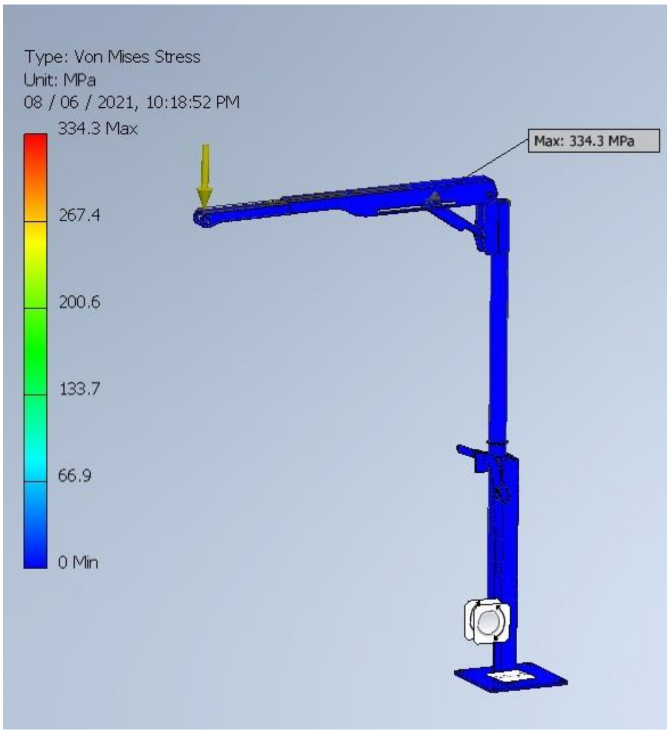

Fig 28: Max Stress Developed in Component for material 3 (200N)

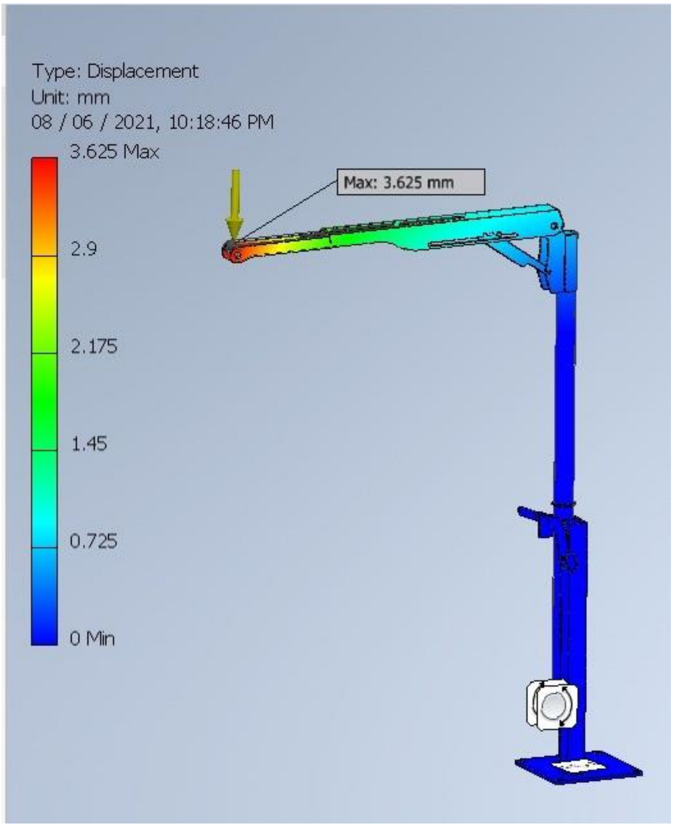

Fig 29: Max Displacement for material 3 (200N)

From the above results, it is seen that the second material, Steel AISI 4340 409 C1T, gives the most optimum result, considering the maximum stress developed in the crane and the maximum displacement that occurs in the device.

6. ELECTRICAL CIRCUIT DIAGRAM

Diagram (Fig. 30) shows a full bridge circuit with four MOSFETS, a capacitor 2200µFA and four 10kΩ resistors. The switching action is done using a slider switch. This circuit helps to run the motor in both directions. The motor used is TECH 3045 DC Geared Motor (12V 4.8A) which operates at 60rpm.

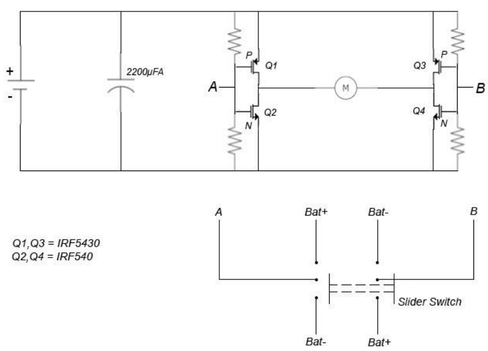

Fig 30: Electrical Circuit Diagram of Motor Control

7. COST ANALYSIS OF CRANE

The Net Diagram (Fig. 31) of the crane parts are arranged and a CNC Machining Layout is created. The gives the amount of material required for the manufacture of the crane is calculated using this.

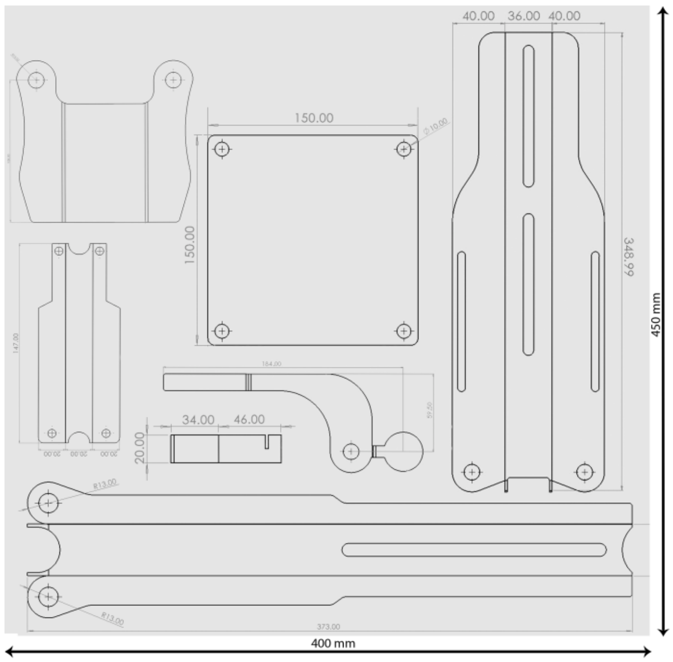

Fig 31: Net Diagram of crane parts

Area of sheet metal required = 400 x 450 = 1,80,000 mm^2
Volume of material = 1,80,000 x 3 = 5,40,000 mm^3
Density of material = 7.85 g/cm^3
Mass of material required = 5,40,000 x 7.85 = 4239000 g
= 4.239 Kg ≈ 4.5Kg
Volume of Pipe required = 122.20 cm^3
Mass of material required = 959.27 g ≈ 1 Kg
Table 3 shows the breakdown of the costs of various components of the mini-crane

MATERIAL	PRICE PER UNIT	MATERIAL REQUIRED	TOTAL PRICE
AISI 4340 (SHEET)	₹ 250/KG	4.5	₹ 1059.75
AISI 4340 (PIPE)	₹ 82/KG	1	₹ 82
WIRE ROPE	₹ 17.5/m	3.3m * 5	₹ 288.75
Miscellaneous			₹700

Table 3: Cost of Crane Materials

Total Cost = ₹ 2130.5

8. CONCLUSION

From the above study, the design attributes of a mini-crane was optimised through parametric analysis and proper material selection. Also, the total production cost of the crane was calculated by taking machining and additional costs into account. There is a significant improvement in factor of safety and displacement compared to the initial design. The overall aim of this study was completed by improving the model design by increase in its physical characteristics and reduction in weight.

The result of the parametric analysis showed that the material Steel AISI 4340 409 C1T gives the optimum conditions and therefore is used as the manufacturing material.

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