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Design and Fabrication of A Single Acting Hydraulic Crane

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Abstract: *In this present work, the designed and fabrication of a single acting hydraulic crane was carried out. The hydraulic crane is made up of the following main components; the hydraulic actuator or actuating cylinder, the master cylinder, the fluid reservoir, pumps, seals, valves and conductor. The basic design elements and parameters considered in the design of the actuating cylinder are; the piston (diameter and cross-sectional area), and the barrel or cylinder (thickness, force and pressure developed). The fabricated machine was tested for performance using different loads. The time required for lifting each loads and retraction time were monitored and recorded. The results obtained reveal that the machine is capable of lifting loads up to 5000N at a time of 58.00sec. Also, it was observed that the performance of the machine was satisfactory and reliable since the correlation values were close to 1 for load plot against lifting time and retraction time. However, to improve more on its performance, it was recommended that motorized hydraulic systems should be incorporated into subsequent designs.*

Keywords: *Design; Fabrication; Hydraulic Crane; Loads; Correlation Values*; Performance

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I. Introduction

The need to develop an efficient hydraulic machine is paramount for industries and designers. With the wide usage of hydraulically driven machines, specifically the hydraulic crane machines with large power, more research interest has been taken in energy-saving measures and strategies owing to energy cost, environmental legislation, etc. [1]. A crane is a machine equipped with a hoist, ropes or chain that can be used to lift and lower materials, and to move them horizontally. It is mainly used for lifting heavy materials and transporting them to required destination. It applies one or more simple machines to create the mechanical advantage needed to move the load beyond normal capability of man [2-3]. It is defined as a machine used for moving heavy objects, typically by suspending them from a projecting arm or beam [4]. Generally, cranes can be classified as; jib crane, overhead bridge crane, telescopic handler's crane, and the travelling gantry crane [5].

A hydraulic system is used for transmitting force or motion by applying pressure on a confined liquid. Hydraulic cranes are usually multi-degree-of-freedom (multi-DOF) mechanical booms. Their main function is to move and lift heavy load from a given position to another one using hydraulic drive [6]. A hydraulic system consists of an assemblies of valves, cams, operating cylinder, etc., which have close fitting tolerance to obtain maximum efficiency from the system and protect intricate parts [7]. I t is of utmost importance that the oil to be used must suit the system been developed. The hydraulic oil to be used must be able to perform two important functions which are [8].

1. It must be able to transmit the required power efficiently
2. It must be able to provide adequate lubrication

Hence, for the hydraulic oil to perform the above-mentioned functions, it must possess the following characteristics;

1. Film strength and lubrication, to provide adequate lubrication between closely fitted sliding parts
2. Resistance to emulsification, so as to separate quickly from any water which may have entered into the system
3. Resistance to corrosion and rusting so as to prevent damage to the closely fitted parts
4. Adequate viscosity to ensure a steady flow of oil at all times and to minimize leakage

At certain point in the system, mechanical devices must be used to control the fluid. A hydraulic system is a collection of mechanical parts linked together by connecting rods and in many cases by fluid levers. Pascal's law defines the basis of hydraulic system [9]. Pascal's Law or principle of transmission of fluid-pressure defines the basis of hydraulic systems. It states that the pressure exerted anywhere in a confined incompressible fluid is transmitted equally in all directions throughout the fluid such that the pressure ratio remains the same [10]. Hydraulic systems make use of incompressible fluids. The pump moves the fluid in the system and the intake of the pump is connected to a fluid source called the reservoir. Atmospheric pressure acting on the fluid in the reservoir forces the fluid into the pump. When the pump operates, it forces the fluid from the tank into a discharge pipe at a suitable pressure. The flow of the pressurized fluid is categorized into three control functions which are;

1. Control of the fluid pressure
2. Control of the fluid flow rate
3. Control of fluid flow direction

A cylindrical tube fitted with a moveable piston called a hydraulic cylinder is often used when the pressurized fluid moves the piston, the piston rod impacts a force on the object through a desired distance. Restricting the movement of the piston in a hydraulic cylinder, as when the piston carries a load, creates a specific pressure relationship within the cylinder. The output force produced is the pressure of the pressurized fluid multiplied by the piston area, measured in Newton at the end of the piston rod. A seal is placed around the rod as it passes through the cylinder to prevent leakage of the fluid.

This present work is expected to provide lifting capability required for lifting heavy objects especially in most mechanical workshops in Nigeria where servicing and repair of automobile engines are being done using primitive techniques such as using the hand to lift the engine out during overhauling. It will also be of great important in installation of machine tools, generators and so on. It is expected that the ease and comfort associated with the use of this machine in lifting and transporting loads, it will be helpful to industries, workshops in their day to day activities. This study is therefore undertaken to look for ways to improving on the local ways of lifting loads with aim of improving performance, safety and reliability of the device.

II. Research Methodology

The following processes were followed;

(i) Critical study and analysis of the working principle of the machine
(ii) Detailed study and analysis of the machine component
(iii) Visit to places where similar machines are in use to know the similarities and differences in design and the problem associated with their uses

The hydraulic crane is made up of the following components;

(i) The hydraulic actuator or actuating(slave) cylinder
(ii) The master cylinder
(iii) The fluid reservoir
(iv) Pumps
(v) Seals, valves and conductor

2.1 Design Calculation

Hydraulic actuating cylinder is widely used in industrial hydraulic systems. It is one of the basic components of hydraulic crane. The actuating cylinder in this case is a linear actuator. An actuator is a device that converts fluid energy into a mechanical force or motion. The hydraulic cylinder consists of circular tube, sealed at both ends in which a piston and its rod move. The piston rod projects through either or both ends of the cylinder. Leakage of fluid out of the cylinder around the piston rod is controlled by a suitably designed seal usually containing packing. The basic design elements and parameters considered in the design of the actuating cylinder are;

(i) The Piston (Diameter and Cross-sectional area)
(ii) The Barrel or Cylinder (Thickness, Force and Pressure developed).

The following data were used in the design of the actuating cylinder;
Diameter of the actuating cylinder piston, d_1= 100mm
Assuming a clearance between one side of the piston and one side of the wall as 0.25mm
Thus, clearance on each side = 2(0.25) mm= 0.5mm
Internal diameter of the actuating cylinder = Piston diameter (d_1) + Clearance on each side = 100mm + 0.5mm= 100.5mm.

2.1.1 Determination of the Pressure Developed in the Cylinder

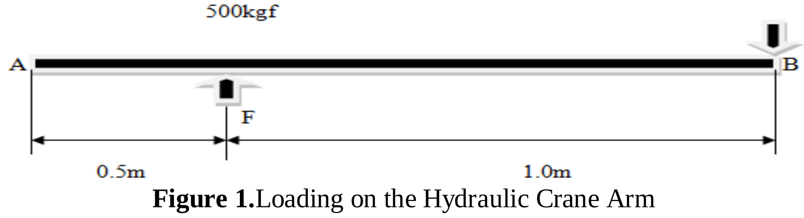

Figure 1. Loading on the Hydraulic Crane Arm

F= Force exerted on the arm by the actuator
Assumption;
Clockwise moment = Anticlockwise moment
F × 0.5mm = 500kgf × 1.5m
Thus,
F = 1500kgf = 15000N

$$P = \frac{F}{A} \quad (1)$$

$$A = \frac{\pi d_1^2}{4} \quad (2)$$

where,
P = Pressure developed in the cylinder
F = Force (F) exerted on the arm by the actuator
A = Area of the actuating

$$A = \frac{3.142 \times 0.1^2}{4} = 0.0079m^2$$

$$P = \frac{1500kgf}{0.0079m2} = 1.91 \times 105kgf.m - 2\ (1.91 \times 106N.m - 2\ or\ 1.91MPa)$$

Therefore, from Pascal's law, the same pressure will act at both the actuating and master cylinder.

2.1.2 Thickness (t_1) of the Actuating Cylinder
Let the thickness of the actuating cylinder wall be represented by t_1
where:

$$t_1 = \frac{d_1}{2}\sqrt{\left\{\frac{\delta_t + P}{\delta_t - P}\right\}} - 1 \quad (3)$$

t= d_1= Diameter of Actuating Cylinder Piston
P= Pressure Developed in the Cylinder
t = Tensile Strength of Grey Cast Iron
d_1= 100mm (or 0.1m)
P = 1.91MNm^{-2} (or 1.91MPa)
$\delta_t = 210MNm - 2$
Therefore

$$t_1 = \frac{0.1}{2}\sqrt{\left\{\frac{210 + 1.91}{210 - 1.91}\right\}} - 1 = 0.0068m\ (6.8mm)$$

2.1.3 External Diameter (D_a) of the Actuating Cylinder
External Diameter (D_a) = Internal diameter of the cylinder (d_a) + 2 × Thickness (t_1)
= 100.5 mm + (2 × 6.8mm)
D_a= 114 mm (0.114 m)

2.1.4 Circumferential Stress on the Cylinder

$$\delta_c = \frac{P \times d_2}{t_1} \quad (4)$$

where,
δ_c =Circumferential stress on the cylinder
P =Pressure developed in the cylinder
d_2 = Internal Diameter of actuating cylinder
t_1 = Thickness of the actuating cylinder

$$\delta_c = \frac{(1.91 \times 10^6) \times 0.1005m}{2 \times 0.0068m} = 14.1 \times 10^6 Nm^{-2} = 14.1MPa$$

2.1.5 Test for Cylinder against Internal Pressure
Cylindrical pressure vessel, hydraulic cylinder and pipes carrying fluids at high pressure develop both radial and tangential stresses with values, which are independent upon the radius of the equipment under consideration.
Let the internal radius of the cylinder be designated as "a"
Let the external radius of the cylinder be designated as "b"
Let the pressure developed in the cylinder be designated as "P"

The tangential and radial stresses have magnitude (δt) which is given by Equation (5)

$$\delta_t = \frac{a^2 P}{b^2 - a^2}\left(1 + \frac{b^2}{r^2}\right) \quad (5)$$

$$\delta_t = \frac{a^2 P}{b^2 - a^2}\left(1 - \frac{b^2}{r^2}\right) \quad (6)$$

Minimum stress occur at the inner surface
where,
r = a

$$\delta_{max} = P \times \frac{b^2 + a^2}{b^2 - a^2} \quad (7)$$

P = 1.91 MPa
b = 54.55mm (0.05455m)
a = 50.25mm (0.05025m)

$$\delta_{max} = 1.91MPa \times \frac{0.05455^2 + 0.05025^2}{0.05455^2 - 0.05025^2} = 23 \times 10Nm^{-2}$$

Let the factor of safety be 3 for steady/varying load.

$$Allowable\ Stress = \frac{Maximum\ Stress\ (\delta_{max})}{Factor\ of\ safety} \quad (8)$$

$$= \frac{23MPa}{3} = 7.7MPa$$

2.1.6 Test of the Ram against Buckling Load

The ram is typically a hard chrome-plated piece of cold-rolled steel which attaches to the piston and extends from the cylinder through the rod-end head. The piston rod connects the hydraulic actuator to the machine component doing the work. When the ram is under axial load, it is considered to be a column with both ends fixed. The minimum load under which the ram will fail is called the buckling load

$$For\ a\ solid\ round - section\ column, the\ second\ moment\ of\ area\ (I) = \frac{\pi D^2}{64} \quad (9)$$

where;
D = Ram Diameter = 54 mm (0.054m)
I = Second Moment of Area
Therefore,

$$I = \frac{\pi D^4}{64} = \frac{\pi \times 0.054^4}{64} = 4.17 \times 10^{-7}\ m^4$$

$$Radius\ of\ gyration\ (K) = \frac{D}{4} \quad (10)$$

$$\frac{0.054}{4}$$

K = 0.0135 m

$$Slanderness\ Ratio = \frac{l}{k} \quad (11)$$

l = Effective Length
Effective Length (l) = 0.7 × L
L = Total Length of Ram = 180 mm (0.18 m)
Therefore; l = 0.7 × 180 mm
l = 126 mm (0.126m)
For mild steel, modulus of elasticity E = 207 × 10^9 Nm^{-2} (Table 1, Appendix)
From Euler's equation

$$P_{cr} = \frac{4\pi^2 EI}{L^2} \quad (12)$$

P_{cr} = Euler's Crippling Load

$$Pcr = \frac{4 \times \pi^2 \times 207 \times 10^9 \times 4.17 \times 10^{-7}}{0.18^2} = \frac{3407737.529}{0.0324}$$

P_{cr} = 105 MN

Since maximum load is far lesser than the crippling load, the ram is safe against buckling.
That is,
$P_{max} << P_{cr}$

Also from Euler's column

$$\frac{4l}{D} - \frac{1}{K} \geq 0 \qquad (13)$$

Therefore,

$$\frac{(4 \times 0.126)}{0.054} - \frac{0.126}{0.0135} = 0$$

Since,

$$\frac{4l}{D} - \frac{1}{K} = 0$$

The diameter of the ram is appropriate according to Euler's column.
Let the Factor of Safety be 3 for steady/varying load.

$$Safety\ Load = \frac{\text{Crippling Load}}{\text{Factor of Safety}} \qquad (14)$$

$$= \frac{105\ \text{MN}}{3}$$

Safe Load = 35 MN

2.1.7 Determination of Diameter of the Shaft Hinging the Arm to the Column

The shaft is fixed at both ends and the force is acting at the centre and it is a solid shaft. From Figure 2, it was calculated that a force of 1000kgf acts on the shaft hinging the arm to the column.

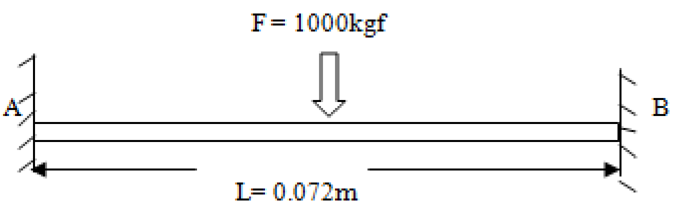

Figure 2. Schematic diagram of shaft hinging on the arm to the column

Considering a solid cylindrical section as shown in Figure 3

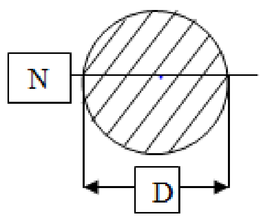

Figure 3. Solid cylindrical shaft section
where;
D= Shaft Diameter
N= Neutral Axis
Y_{max}= Position of Neutral Axis
For a solid circular section, the moment of inertia (I) about the neutral axis (N) is

$$I = \frac{\pi D^4}{64} \qquad (15)$$

$$Y_{max} \frac{D}{2} \qquad (16)$$

$$Z = \frac{I}{Y_{max}} \qquad (17)$$

Section Modulus (Z)

$$= \frac{\pi D^3}{32}$$

But,
Yield Strength/Stress of Structural (Mild) Steel = 240 MNm^{-2}

$$S_n = \frac{\text{Maximum Bending Moment (M)}}{\text{Section Modulus (Z)}} \qquad (18)$$

$$240 \times 10^6 \times \frac{32 \times \text{Maximum Bending Moment (M)}}{\pi D^3}$$

$M = \frac{FL}{8}$

M= Maximum Bending Moment

$M = \frac{10000 \times 0.072}{8}$

M = 90.00 Nm

Therefore,

$D^3 = \frac{32 \times 90.00}{\pi \times 240 \times 10^6}$

$= \frac{2880}{753982236.9}$

= 0.000003819719

$D = \sqrt[3]{0.000003819719}$

D = 0.016m (16 mm).

Since shafts have standard sizes, 20mm shaft diameter is appropriate but a 25mm shaft diameter was used

2.2 Materials Selection

2.2.1 Material for Piston and Ram

The material used in constructing the piston and ram are mild steel and aluminium cast alloys. Mild steel was used because it possesses strength and toughness, readily available and possesses greater strength in tension, ductile and resists wear. The material is easy to polish in order to allow the piston have easy movement in the cylinder.

2.2.2 Selection of Material for the Crane's Arm

The material used in constructing the arm which is of a hollow circular section is cold rolled steel. Cold rolled steel was used because like any other steel it has properties which make it suitable for this application. Some of these properties are; good weld ability, good ductility, and high strength in tension, easy formability, smooth and clean surface.

2.2.3 Material for Seals

For hydraulic crane to be able to perform well, the type of seal used plays an important role. Modern hydraulic equipment use variety of seals which are in large selection of different seal materials. In this research work, neoprene was used. Neoprene is a product of Elastomer, which are resilient and possess rubber like qualities.

2.2.4 Selection of material for the crane's column

The material used in constructing the column which is of a hollow circular section is galvanized iron. Galvanized iron was used because like any other construction material, it is cheap, readily available and has properties which make it suitable for this application.

2.3 Fabrication of the machine

The fabrication of the machine involves cutting operation, welding operation, drilling operation, machine operation, etc. The processes are shown in Figure 4.

Plate 1. Drilled Hole on one end of the crane's arm

Plate 2. Grinding of the ram rest on the arm

Plate 3. Welded hook holder

Plate 4. Fitting of the arm to the hydraulic crane assembly

Plate 5. Crane assembly with hydraulic jack fixed

Plate 6. Fabricated hydraulic crane

III. Results and Discussion

After successful fabrication of the machine, it is imperative to test or evaluate the machines performance. Hence, the test was conducted as follows;

(i) Selection of standard loads to be lifted (1000N, 2000N, 3000N, etc.)
(ii) Hook the selected load to the arm of the crane
(iii) Lock the control valve
(iv) Raise the load and take note of the maximum height and the time it takes to reach the height
(v) Allow the loads to stay at different time interval
(vi) Then check if there is a drop in height

After various loads have been loaded on the crane, the correlation for the load versus time graph is gotten to be 0.9923. Also, a high correlation value close to 1 was obtained for the plot of load (N) against retraction time (s). This simply shows that the hydraulic crane is reliable and also in a very good working condition. Table 1 presents the time taken to raise each load, maximum height to which each load can be lifted to, and the retraction time.

Table 1. Performance Evaluation Test Results

Loads (N)	Time taken to raise load (s)	Loaded arm's height (m)	Retraction time(s)
1000	30.00	0.175	20.00
2000	35.00	0.175	17.00
3000	42.00	0.175	15.00
4000	50.00	0.175	12.00
5000	58.00	0.175	10.00

Figure 5 presents the graph of time taken (s) to raise load (N). It was observed that increase in loads brings about increase in time taken to raise the loads, and vice-versa. However, this was the opposite in plotting the loads against retraction time (Figure 7). The smaller loads took a longer retraction time unlike the heavy loads.

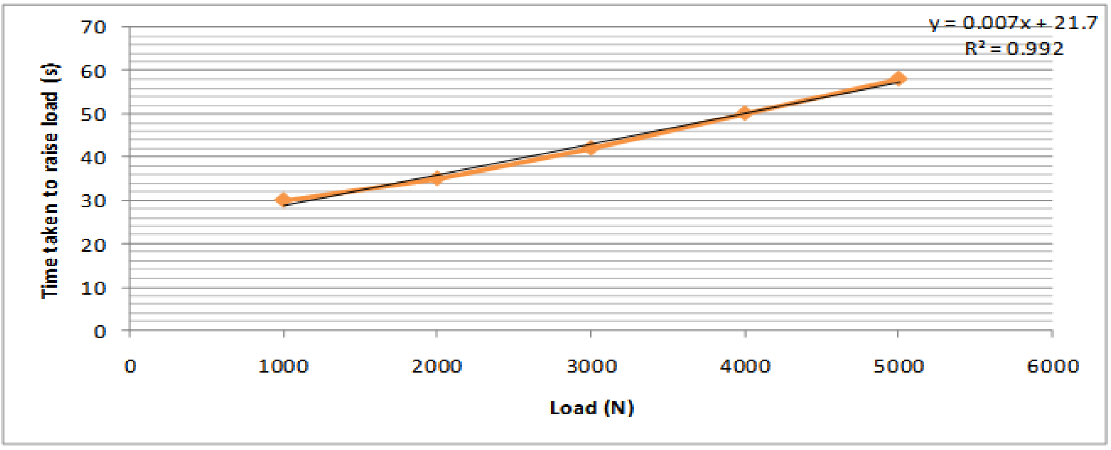

Figure 5. Graph of time taken to raise load (s) against load (N)

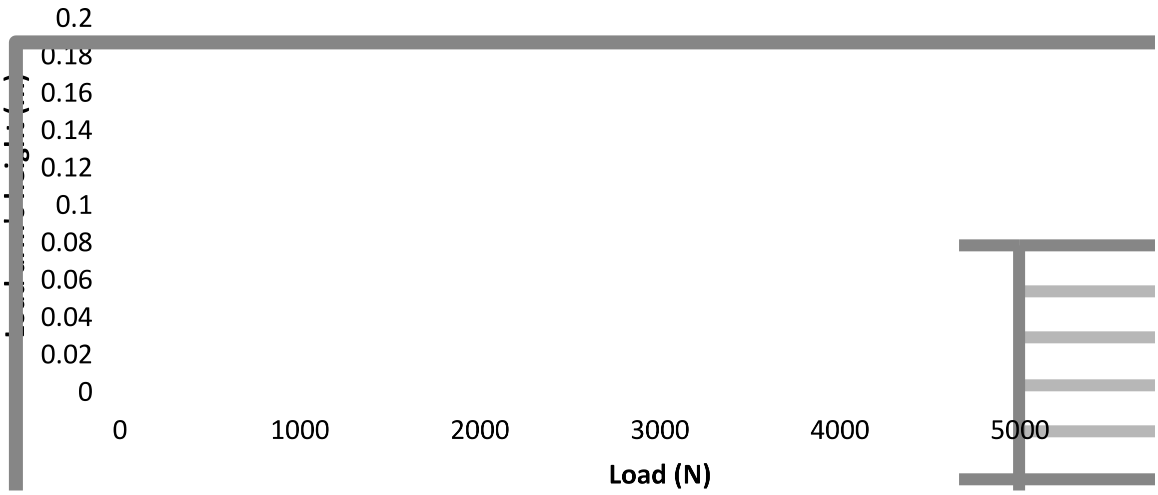

Figure 6. Graph of load arm's height (m) against load (N)

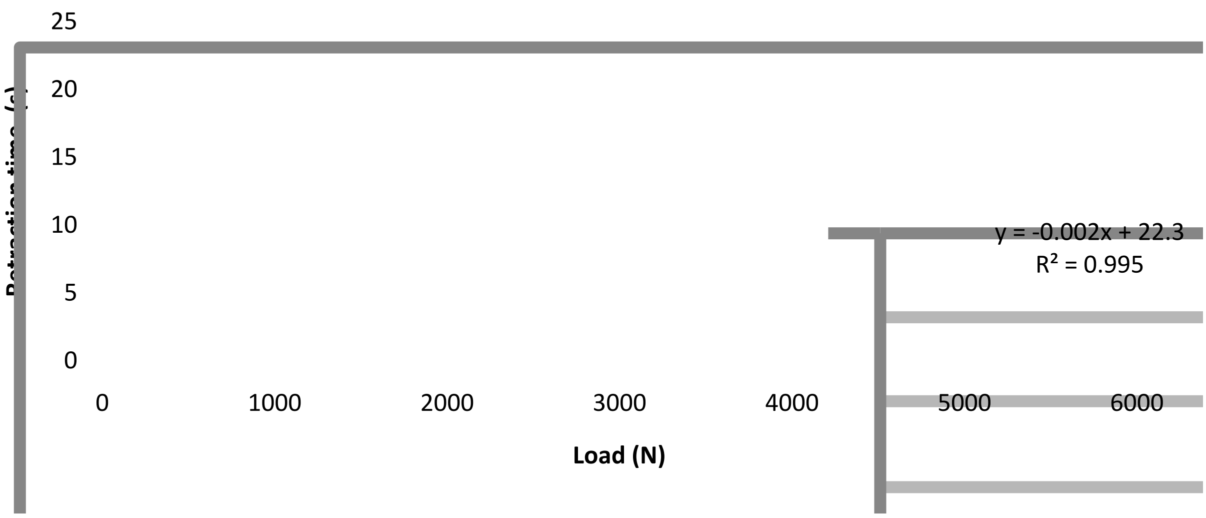

Figure 7. Graph of retraction time (s) against load (N)

IV. Conclusion

In this research work, critical study and analysis of the working principle of a hydraulic crane was carried out with detailed analysis of the machine component. From the study, the design was based on ways of improving safety, weight, ergonomics, aesthetics, cost and durability. From the result obtained, it can be conclude that the hydraulic crane will do a lot of good to technicians and maintenance engineers at local automobile and plant repair workshops, because it would save the time and energy which might be expended on the crude way of lifting and moving heavy loads within the workshop. Circular irons were used to improve the strength of the crane and also add to its aesthetic values. The machine developed is capable of lifting loads up to 5000N at a time without fracture. The tyres used were of larger diameters and this ensured easy movement of the crane forward or side-ways when it is loaded or unloaded without stressing the user of the crane.

V. Recommendation

Considering all limitations, delay and additional cost, experienced during the design and fabrication of this work; it is therefore recommended that a motorized hydraulic systems should be incorporated into subsequent designs as this will better the performance of the hydraulic crane. Also, since the machine constructed is hand operated, some amount of time and energy is wasted when applying effort in order to lift a load. Therefore, subsequent development can make use of motorized hydraulic or pneumatic systems as this will help save a lot of energy and reduce work time.

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