American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN : 2320-0936
Volume-6, Issue-3, pp-131-138
www.ajer.org
Research Paper Open Access

Design and Finite Element Analysis of Double - Acting, Double - Ends Hydraulic Cylinder for Industrial Automation Application

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ABSTRACT: *The design and analysis of safe hydraulic cylinders have become a great concern because of the important role it plays in the automation of industrial equipment and systems. Hydraulic and pneumatic systems are fluid power systems that are commonly used in the industry nowadays. Most failures experienced in hydraulic systems are failures associated with the linear actuator (hydraulic cylinder). Most of these failures are design, materials and structural integrity related one whereby safety standards are not fully satisfied. This paper address the issue of deploying and implementation of acceptable design codes for the design and structural analysis of a double acting double ends hydraulic cylinder basically for industrial automation applications. The maximum force is estimated to be 11 KN. The combination of Analytical and finite element analysis (FEA) methods was utilized for the development of the cylinder. These are to give credibility to the design for the purpose of future manufacture of the cylinder. The bursting pressure, longitudinal stress piston rod and piston diameter, barbell thickness was determined and analyzed. The methods used for this design work could provide significant knowledge and skill for young design engineers, and this cylinder product may be readily available to industrialist for manufacture.*

Keywords: *Design, Hydraulics, Cylinder, Industrial, and Automation*

I. INTRODUCTION

Over the years, man has recognized and accepted fluid as a source of power. Hydraulic power has been used over the years as the primary source of power to propel boats and turn water wheels.However hydraulic has found greater applications today more than its initial use as it has gained more acceptability in different fields. It is now used on land moving vessels, in the aviation industry, process automation, robotics and very numerous engineering branches. Now it is known traditionally as force transmission through pressurized fluids. Hydraulic power came into existence in 1648 when a Frenchman named Pascal made a publication on hydrostatics, which included his law that stated that pressure in a fluid is transmitted equally in all directions [2]. This principle was later used to generate fluid force in the industry, not just water alone as in the Bramah's press [2]. Bramah was able to demonstrate that a small force on a long stroke, small diameter piston could produce a relatively large force on a short stroke, large diameter piston. This force amplification was very impressive. However, his observation that there was a way to transmit power, as well as the force, was more important because he showed a way to change power from mechanical to hydraulic and then back to mechanical very efficiently [1].

Fundamentally, every hydraulic system should in its basic form consist of a reservoir, valves, pipe hoses, and actuators. The reservoir contains fluid, a pump or motor which pressurizes this fluid in the hydraulic system. The Valves are responsible for the control of fluid flow and pressure in the system. The pipes or hoses transmits fluid with or without pressure to the desired parts of the system. The actuators (also called hydraulic cylinders) are used to convert the fluid energy to mechanical energy that can be used to do work [6, 10]. The output power developed always depends on the flow rate, the pressure drop and accompanying velocity increase across the actuator and its overall efficiency.

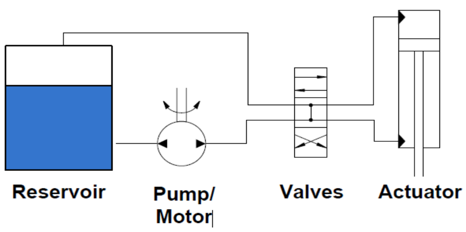

Figure 1: Schematic showing the main components of a hydraulic system [5].

Seeing, therefore, the importance of hydraulic cylinders in hydraulic systems, over the years there has been deliberate efforts to develop the different types of cylinders.Apart from the telescopic and tandem cylinders, it has the single acting and double acting hydraulic cylinders which are very efficient and may be used based on the desired application. Double-acting hydraulic cylinders are of two types as well, the Double - acting hydraulics cylinder with piston rod on one end and Double - acting hydraulic cylinder with piston rod on both ends which will be the focus of this work. This research work used a CAD tool (Solidworks) to carry out finite element analysis (FEA) on a typical double acting hydraulic cylinder with double ends that can withstand a pressure of 200 bars and produce a force of up to 11kN.

II. MATERIALS AND METHODS

The For this research work, the materials adopted include a high-speed computer and a CAD- tool (Solidworks) used for the simulation and FEA [8, 9]. The figure below shows the procedure followed in the carrying out of this study.

2.1 Double acting double ends hydraulic cylinders.

Double acting cylinders are normally designed such that pressure can be applied in either inlet or outlet port, providing linear power in both directions [11]. Furthermore, since the exposed areas in the cylinder are unequal during extract and retract operations (forward and return stroke) there is a difference in operation speed and force.The double acting double ends hydraulic cylinder which is the subject of this research is not in any sense different in principle of operation from every normal hydraulic cylinder but it produces both fluid flow and pressure in both directions, and both ends of the piston can be connected to the point of application where work is needed to be done.

2.2 Parts design consideration

The following assumptions were taken into the consideration of the design of the cylinder, piston, piston rod and seals in the hydraulic cylinder.

- Working fluid is mineral oil
- Available pressured P_a =200bar= 200* 10^5pa
- Atmospheric pressure = 1.0135 * 10^5pa
- Stroke length= 60mm+80mm =140mm = 0.14m
- Cylinder output force =11KN = 11000N
- Cutting stroke=1.5m/s
- Material for cylinder calculation low carbon steel BS970 070M20
- Tensile stress of material is = 430mPa
- Yield stress of material is = 215mPa
- Factor of safety = 3
- Young modulus of the material used is = 210GPa, for BS 970 070M20 (low carbon steel)
- End fixing factor = K = 0.7 is chosen because of maintenance purpose, in a case of adjustment i.e. in the case of increasing stroke length.

2.2.1 Design of piston rod

The piston rod of a hydraulic cylinder is highly stressed, and therefore it should be able to resist the bending, tensile and compressive forces that it may encounter during the operation without buckling. In practice, the rod is more likely to fail by buckling under the compressive load than by bending. In this case, the rod behaves like a column and is subjected to buckling. The rod diameter can be related to critical load. Therefore Euler's formula in the equation below for long column can be used to obtain the piston rod diameter.

$$P = \frac{\pi^2 . E . I}{L^2 . K^2} \quad (1)$$

Where:
P = Buckling load (N)
L = the column length (m)
I = Moment of inertia (m^4)
E = Young's Modulus of Elasticity for the column material (Pa)
K = the end fixing factor
E = Young's modulus of the material used in this design calculation is 210 (Gpa) for BS 970 070M20 (Low carbon steel).
P = cylinder force * factor of safety = 11000 * 3 = 33 * 10^3N
L = total stroke length =140mm = 0.14m
K = 0.7, Reason for choosing k = 0.7 is for maintenance purposes in case of adjustment i.e. in case of increase in the stroke length of the rod.
Substitute into the equation 2.1

$$33 * 10^3 = \frac{\pi^2 * 210 * 10^9 * I}{0.14^2 * 0.7^2}$$

$$I = 1.528742837 * 10^{-10} m^4$$

The moment of inertia and the maximum permissible stress to avoid buckling is dependent on the type of end fixing of the cylinder. The moment of inertia (I) can be found from the formula below

$$I = \frac{\pi d^4}{64} \qquad (2)$$

Therefore:

$$1.528742837 * 10^{-10} = \frac{\pi d^4}{64}$$

Making d^4 the subject we have

$$d^4 = \frac{9.783954156 * 10^{-09}}{3.142}$$

$$\boldsymbol{d = 8mm}$$

Hence diameter of the piston rod required, **d = 8 mm**. Finally, for other calculations and in a case of construction, the diameter of the piston rod used will be **12mm**, for safety and because from Baym Hydraulics Corporation catalog of metric rod wipers and piston seals the nearest standard rod seal diameter is **12mm**.

2.2.2 Design of the piston

The hydraulic piston design must not be complicated. It must be designed for ease of assembly and disassembly for maintenance purposes. A study was done to find out if a solid piston can withstand the compressive force that a piston rod is subjected to. The main failure point was the edges of the piston and kind of seals used at tolerances between the piston and the cylinder wall. They all have minimum factor of safety of 3. Let **A** be the full area of the piston and **a** be the cross sectional area of the piston rod. Since the design is a double acting double ended hydraulic cylinder, pressure is acts on both sides of the rod, hence the area which the pressure is acting on is given by **(A-a)**. The force produced is given in the equation below.

$$\boldsymbol{F = P(A - a)} \qquad \textbf{(3)}$$

Since the piston and the piston rod are circular in nature, therefore area of the pressurized part is given by

$$\boldsymbol{A - a = \frac{\pi D^2}{4} - \frac{\pi d^2}{4} = \frac{\pi (D^2 - d^2)}{4}} \qquad \textbf{(4)}$$

Where:

F = force = assume force * factor of safety (3) = 11000 * 3 = 33 * 10^3N

P = pressure, 200bar = 200 * 10^5 Pa

D = diameter of piston

d =diameter of piston rod, 12mm = 0.012m

By substituting the above value into those equations, we have,

$$\boldsymbol{D = 47mm}$$

Hence diameter of piston required **d = 47 mm**. Finally, for other calculations and construction, the diameter of the piston is taken to be **48mm**. Because from Baym Hydraulics Corporation catalog of metric rod wipers and piston seals, the nearest standard rod seal diameter is **48mm.**

2.2.3 Design of the cylinder

Let OD = outside diameter of the cylinder.

Tensile stress of BS 970 070M20 = 430mpa

Factor of safety (N) = 3

Determine the maximum working stress (σ_m) is given as

$$\sigma_m = \frac{\text{Tensile stress of material}}{FOS} = \frac{\sigma_t}{N} \qquad (5)$$

σ_m = 143.3 * 10^6pa

Applying lame's equation to determine OD

$$\textbf{OD}^2 = \frac{D^2(\sigma + P)}{(\sigma - P)} \qquad (6)$$

$$OD^2 = \frac{0.048^2 (143.3 * 10^6 + 200 * 10^5)}{(143.3 * 10^6 - 200 * 10^5)}$$

OD = 0.055m = 55mm

2.2.3.1 Cylinder Tube thickness

The tube thickness of a cylinder barrel is a very important factor in the design of a hydraulic cylinder. The strength of the cylinder tube is proportional to its wall. If a cylinder is too thick or too thin may pose serious safety, and operational problems and hence the tube thickness of the cylinder has to be carefully chosen. The wall thickness required for the cylinder can be calculated from the formula in equation (3.9).

Thickness (t) = $\frac{OD-d}{2}$

Where:

OD, is the cylinder external diameter, 55mm and small "d" is the piston seal diameter (cylinder internal diameter), 48mm.

t = $\frac{55-48}{2}$

Thickness (t) = 3.5mm

2.2.4 Bursting stress

- To determine the bursting stress of the cylinder we need to apply lame's equation for thick cylinder because the ratio of inside diameter t/d is > 1/20.
- When a thick-walled tube or cylinder is subjected to internal and external pressures, hoop and longitudinal stresses act on the wall.
- The bursting stress can be referred to as the amounts of hoop stress and longitudinal (axial) stress that are produced in the wall of the cylinder when subjected to internal and external pressures that may cause the material which the cylinder is made from to fail. This happens if the hoops stress exceeds the tensile strength of the material.
- In this design calculation, the hoop stress must be lower than a tensile strength of the material which the cylinder is made from to ensure the safety of the cylinder and personnel during actual operation.

Material of the cylinder BS 970 070M20 (low carbon steel) Tensile stress = 430 * 10^6pa. The hoop stress (σ_H) of a cylinder can be determined from the Barlow formula as shown in the equation below.

$$\sigma_H = p.\frac{d_o^2 + d_i^2}{d_o^2 - d_i^2} \qquad (7)$$

Where:

p= oil pressure, 200bar = 200 * 10^5Pa

d_o= outer diameter of cylinder, 55mm

d_i = inner diameter of cylinder, 48mm

Substituting into equation 10

$$\sigma_H = 200 * 10^5 .\frac{55^2 + 48^2}{55^2 - 48^2}$$

$\sigma_H = 147.8m$Pa

Also the longitudinal stress is given by:

$$\sigma_l = \frac{P_1 R_1^2 - P_2 R_2^2}{R_2^2 - R_1^2} - - - - - - (8)$$

Where P_1 = Internal pressure (200 * 10^5pa)

P_2 = External pressure (atmospheric pressure = 1.0135 * 10^5pa)

R_1 = Internal radius

R_2 = External radius

Therefore;

σ_l = 63.4 * 10^6Pa

σ_l= 63.4 Mpa.

2.3 Material for the hydraulic cylinder

In the design of mechanical systems, the choice of material plays a huge role in the functionality of the system. There are various types of materials used for constructing hydraulic cylinder, and the selection largely depends on the requirement of the hydraulic cylinder. But in the case of this research, **low carbon steel (BS 970 070M20)** as shown in was chosen as the material for the hydraulic cylinder because it combines the required light weight with very good yield strength, tensile strength, corrosion resistance and good surface hardness for wear resistance.

It has minimum yield strength of 215 Mpa, minimum tensile strength 430 Mpa, 21% elongation, with a composition of 0.2% of carbon(c) and 0.7% of manganese (Mn) and normalized condition. BS 970 070M20 is a very common form of steel because of its low price and its acceptable material properties notwithstanding. It is neither brittle nor ductile and low carbon steel has a relatively low tensile strength, but it is cheap and malleable. Its surface hardness can be improved by carburizing. It is mostly used for large quantity needs, for example, structural steel. The density of low carbon steel has been found to be approximately 7.85g/cm^3, and Young's modulus is 210,00Mpa.

The material chosen will be used for the construction of the hydraulic cylinder components such as the cylinder, piston rod, piston, the end caps and tie rods. The method adopted for the selection of the material was from (Materials selection in mechanical design, Prof. M F Ashby.) First and foremost, it took into account the basic parameters of Materials selection in mechanical design-which are, strength, toughness, and weight. The basic function for designing the system (double acting double ends hydraulic cylinder) is for it to be able to produce a shearing force from 10KN to 11KN and that velocity of cutting stroke should not exceed 1.5m/s. The Constraint of the cylinder is the performance and limiting factor i.e. strength of the material BS 970 070 M20 (low carbon steel) -if it can be able to withstand the high pressures built up inside the cylinder.

2.4 Finite element analysis (FEA) of the hydraulic cylinder

The initial design of the cylinder was made of paper with sketches and with design calculations provided. The various parts/components were reproduced using Solidworks. These components were then fitted together in an assembly to make sure they fit together and that the required motion trajectories were possible without problems. Static simulations were done on the key parts to make sure they would be able to handle the maximum stresses during operation and to help in optimizing weight. The analysis was also used to verify the rate of deformation and principal stresses acting on each component. A safety factor of 3 was used for the design. This was done because the stresses are well defined, and weight of the assembly was very important. The requirement for low weight was the biggest reason for not using a larger safety factor.

III. RESULTS AND DISCUSSION

The All the components and parts of the double acting double-end hydraulic cylinder were carefully developed and modeled using Solidworks workspace. The 3D models of the parts and the pictorial simulation results for both the stress analysis and deformation will be represented below.

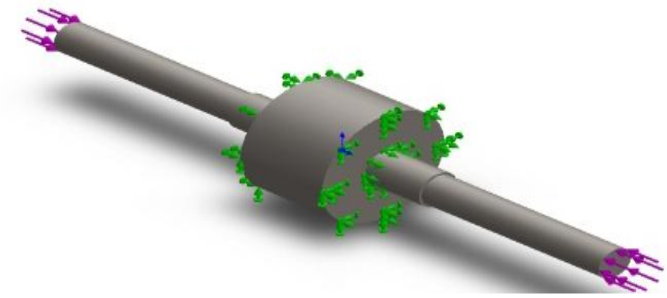

Figure 2: Piston and piston rod configuration.

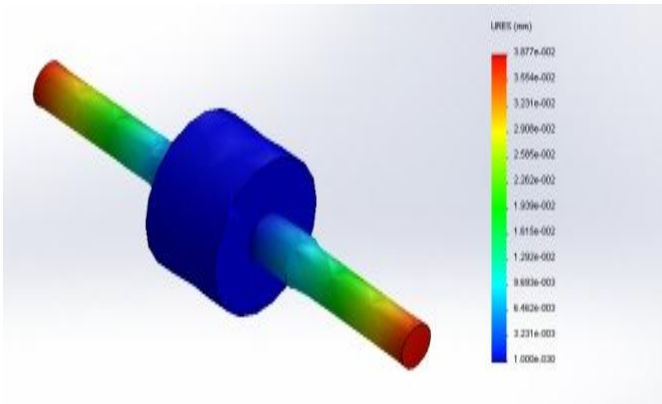

Figure 3: Deformation of piston and piston rod assembly under maximum load of 11kN.

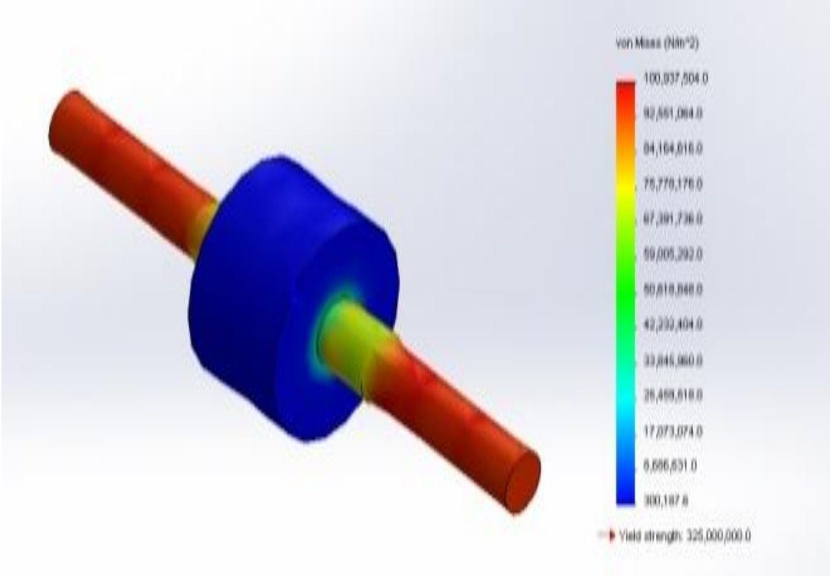

Figure 4: Stress analysis for piston and piston rod under maximum load of 11kN.

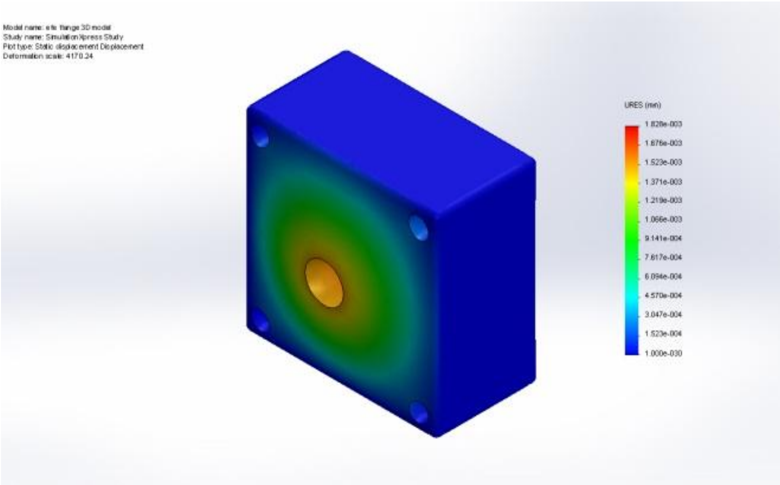

Figure 5: Deformation tests under 11kN force

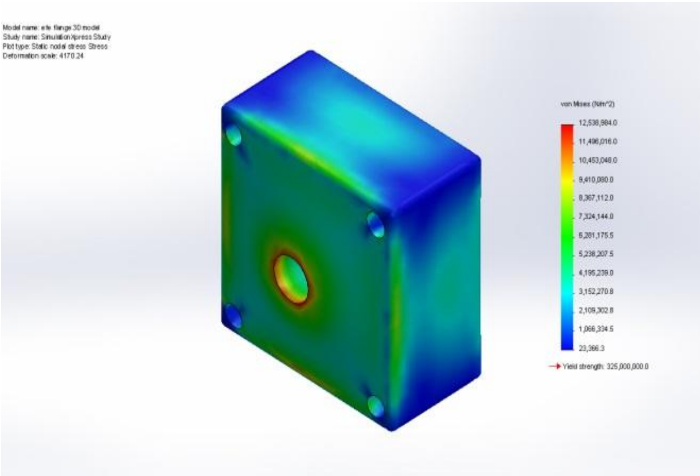

Figure 6: Stress test on flange 11kN force under static simulation.

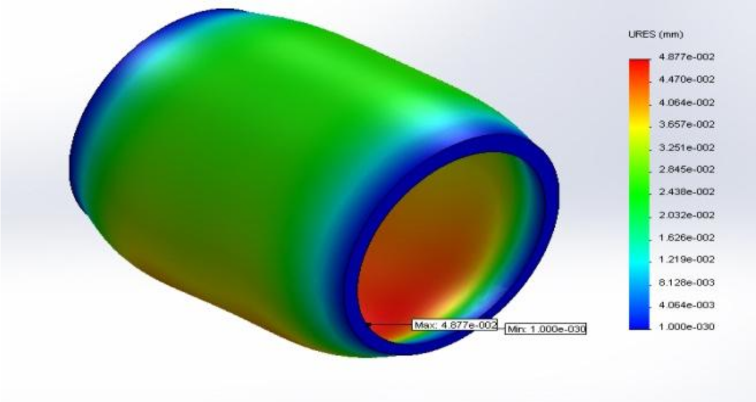

Figure 7: Deformation analysis of cylinder with 200bar internal pressure.

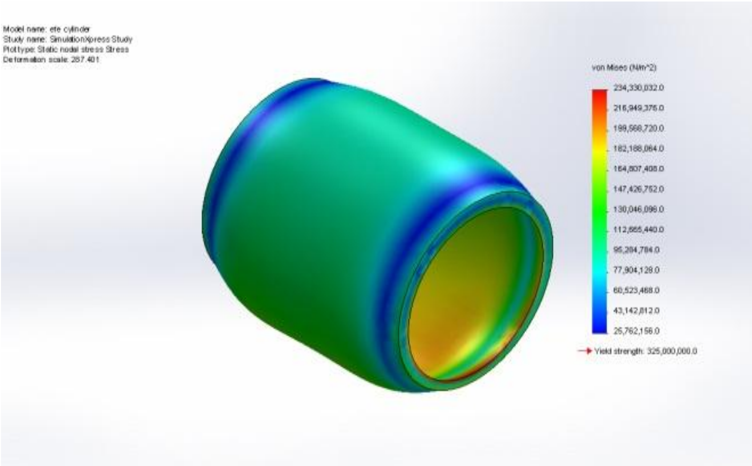

Figure 8: Stress analysis of cylinder under 200bar internal pressure.

A 3D model of a double acting double ends hydraulic cylinder with the following specifications was designed usingBS 970 070M20 (Low carbon steel) and from the simulation results as can be seen in fig. 8 even when subjected to an internal pressure of 200bar, the maximum stress experienced at the ends will be way less than the yield strength of the material. It can as well be seen from the stress analysis results that the von Mises stress on both the flange and piston and piston rod assembly do not exceed the yield strength of BS 970 070M20 (Low carbon steel). This implies that using this material with the following specifications will yield optimum results without failure. The results can as well be extrapolated.

Table 1

S/N	PARTSDIMENSION	SYMBOL	VALUES	UNIT
1	Piston rod diameter	D	12	mm
2	Piston diameter	D	48	mm
3	Cylinder Outside diameter	OD	55	mm
4	Cylinder wall thickness	T	3.5	mm
5	Stroke length	L	140	mm
6	Cylinder port diameter	_	10	mm
7	Width of cylinder end flange	_	75	mm
8	Length of cylinder flange	_	30	mm
9	Tie rod diameter On flange	_	8	mm
10	Flange Edge fillet radius	_	3	mm
11	Cylinder port diameter	_	10	mm
12	Length of tie rod	_	220	mm
13	Hoop stress	σ_H	147.8	mm
14	Longitudinal stress	σ_L	63.4	mm
15	Extension/retractionforce	F	11000	N
16	Pressure	P	200	Bar

IV. CONCLUSION

A double acting double ends hydraulic cylinder was successfully designed and analyzed. Relevant standards and codes were used in the material selection process, and choosing of seals also follows. Therefore the design of double acting double end hydraulic cylinder was achieved and is ready for manufacturing. The cylinder external and internal diameters were determined to be 55mm, and 48mm, piston diameter with a seal is 48mm, piston rod diameter is 12mm and the stroke length is 140mm. The FEA analysis carried out on the hydraulic cylinder provided credible validation for the reliability, functionality, and safety of the hydraulic cylinder designed.This designed double acting double end hydraulic cylinder can be effective employed when manufactured for industrial automation such as hydraulics system for cutting and crimping of hydraulics pipe hoses, power steering for earth moving vehicles among others industrial applications.

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