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Design Optimisation and Fatigue Analysis of Stroke Endurance Test Rig Using Finite Element Analysis

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Abstract

Stress analysis plays an important role in the machine design. Proper stress estimation helps in preventing prior failure of the structures. In the present work, a test rig used for hydraulic cylinder testing. The cylinders are checked for structural strength and for functional requirements. Initially theoretical calculations are carried out to check the strength of the designed structure. The modelled object is meshed using Hypermesh. The primary idea of the project is to optimise the pin diameter required for the given dynamic loading conditions. A function is represented for applying unequal tension and compression load on the pin structureThe analysis results shows a diameter of 220mm is required to satisfy the structural requirements. Further fatigue analysis is carried out on fixture for fatigue life estimation. Here three dimensional mesh is used for representation of the problem with sufficient number of elements for better results presentation. Three dimensional mesh is considered to accommodate small variation in the thickness of the geometry which is difficult to model with two dimensional meshing. The three dimensional analysis shows complete fatigue life for the structure for the given loading cycles. All the results are represented with necessary graphical plots.
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1. INTRODUCTION

Hydraulics is a branch of science and engineering dealing with the mechanical properties of liquids. At a very basic level hydraulics is the liquid version of pneumatics. Fluid mechanics provides the theoretical foundation for hydraulics, which focuses on the engineering uses of fluid properties. In fluid power, hydraulics is used for the generation, control, and transmission of power by the use of pressurized liquids. For example consider a basic working principle of hydraulic device .The transfer of energy takes place because a quantity of liquid is subject to pressure. A hydraulic cylinder is a linear actuator used for converting fluid energy to an output force in a linear direction. A cylinder is a hydraulic actuator that is constructed of a piston or plunger that operates in a cylindrical housing by the action of liquid under pressure. In a piston cylinder, a piston rod is connected to a piston to actuate a load. The hydraulic connections are a head end port and a rod end port (fluid supply) .

This will perform various jobs include pulling or pushing in engineering applications such as in machine tools, earth moving equipments, construction equipments and space applications.

The hydraulic cylinders are used for all fields of engineering that comprise of mining industry, construction machinery, plant engineering, defense technology, automotive engineering, textile industries, railways, power plants, agricultural machinery.

1.1 Objectives of the Study

Fatigue analysis of hydraulic testing fixture under fluctuating loads is the main definition of the problem. Here the objectives include

- Cad modelling and meshing the hydraulic fixture
- Analysis for cyclic loads
- Fatigue estimation of the base structure
- Optimisation of pin dimensions under dynamic loading conditions
- Finding the response under dynamic loads.

2. LITERATURE REVIEW

XiumeiKang et.al[1] "Recent Research on Computer-Aided Fixture Planning",Department of Mechanical and Manufacturing Engineering, University of Manitoba, Winnipeg, MB, R3T 5V6, Canada

Fixtures are used to locate, hold and support workpieces in manufacturing operations such as machining, inspection, and assembly. Designing and fabricating fixtures can take up to 10-20% of the total cost of a manufacturing system. Fixture planning is a complex activity restricted by the extreme diversity of workpiece, product batch size, product geometry, part accessibility, and working force. Computer-Aided Fixture Planning (CAFP) has been used to improve the fixture design for over 20 years. CAFP contributes to the reduction of lead-time and human interaction in fixture planning. It helps verification of the fixture quality and integration of fixture design with CAD/CAM systems. This paper summarizes constraints of fixture planning and four phases of CAFP. Various approaches to CAFP are surveyed. Application systems of CAFP including some recent patents are reviewed. The paper concludes with the research trend of CAFP.

Kulankara Krishnakumar, et.al[1] Melkote, "Machining fixture layout optimization using the genetic Algorithm" International Journal of Machine Tools & Manufacture 40 (2000) 579–598

The advantages of the GA-based method over previously reported nonlinear programming methods for fixture layout optimization are discussed. Two GA-based fixture layout optimization approaches are implemented and compared by applying them to several two-dimensional example problems.

Z. M. BIy et.al[1] Flexible ® fixture design and automation: Review, issues and future Directions" int. j. prod. res., 2001, vol. 39, no. 13, 2867± 2894

The cost of designing and fabricating Fixtures can amount to 10± 20% of the total manufacturing system costs. To reduce manufacturing costs, a fixture system is designed to be competent in fixturing as many workpieces as possible. In mass volume production, this can be achieved by flexturing a large quantity of the same kind of workpieces. In low-to-medium volume production, however, improvement of the flexibility of fixture systems becomes a favourable way to reduce the unit cost of product.This paper summarizes the latest studies in the field of flexible fixture design and automation. First, a brief introduction is given on this research area. Secondly, taxonomy of flexible fixture design activities is presented. Thirdly, the flexibility strategies based on the existing flexible fixture systems are discussed. Fourthly, the contributions on design methodologies and verifications are examined. Fifthly, advances on computer-aided design and see-up systems are summarized. Finally, some prospective research trends are presented.

Shu Huang Sun and Jahau Lewis Chen, " Knowledge Representation and Reasoning Methodology based on CBR Algorithm for Modular Fixture Design", Journal of the Chinese Society of Mechanical Engineers, Vol.28, No.6, pp.593~604 (2007)

CBR algorithm provides a better knowledge transfer and explanation than rule-based inference. It solves new problems by adapting solutions that were used to solve old problems. Based on CBR algorithm, a methodology applied in modular fixture design and focus on workpiece locating is proposed in this study. A similar solution can be retrieved from past experiences. Evaluation is applied for this retrieved case by checking degrees of freedom (DOF) to determine whether it is satisfactory for a new problem and some components would be replaced if it is not. According to this methodology, a computer-aided modular fixture design system can be established in future. In the system, three sub-bases would be included. Data base stores many function structures that are assembled by modular components to complete some functions.

3. MATERIALS USED

Material	Youngs Modulus (GPA)	Yield Strength (Mpa)	Tensile Strength (Mpa)
Pin Material EN47	200	550	880
Fixture Material EN353	210	230	370

Type of mesh for Fatigue Analysis

component	Type of mesh
Pin	Hex mesh
Fixture	Hex mesh
Bolt	Hex mesh

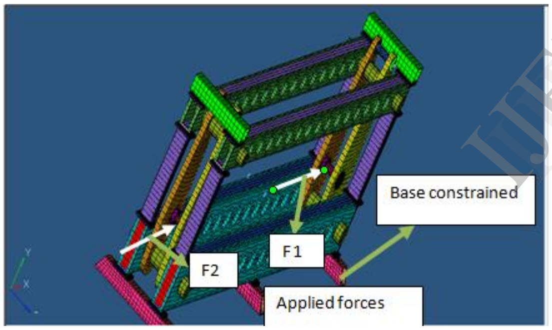
Type of mesh for pin optimisation

component	Type of mesh
Pin	Shell Mesh
Fixture	Shell Mesh
Bolt	Shell Mesh

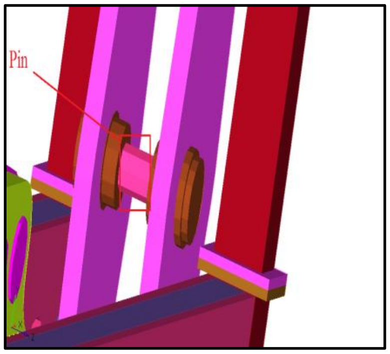
4.0 METHODOLOGY

- Three dimensional modelling of the fixture along with its components for the given specifications
- Appropriate meshing for the analysis (Shell for reduction of the mesh size and three dimensional meshing for the fatigue)
- Application of boundary conditions and analysis of the problem
- Results presentation
- Theoritical checking of the dimensions for the given loading conditions

Boundary Conditions



Theoretical Estimations :



The main loading pin will take a maximum load of 200 Tons. But totally 4 pins are used to take the load. Distributing the load on 4 pins, each pin will take a maximum load of 50tons. Generally pins are designed for shear loads. So minimum resisting area required in shear for the pin is

$$A = F/\tau$$

$$A = \pi d^2/4$$

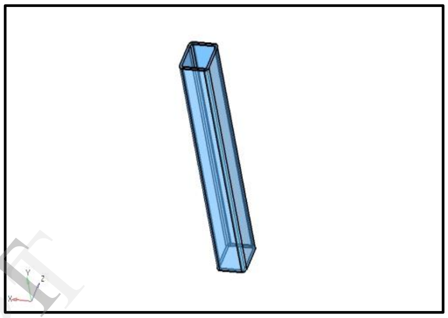
$$\pi d^2/4 = 500000/45.8$$

$$d^2 = 10917 mm^2$$

$$d = 118mm$$

Since the pin size used is 120mm, the design is safe.

Buckling Load estimates on the column:



Since 4 support columns, each column should be designed for 50 tons.

Since both the ends are hinged , the buckling load can be calculated as

$Pc = \pi^2 EI/L^2$

Here L=1143mm

From the analysis moment of inertia for the beam considered is 0.67e8mm^4.

Buckling load for the section

$Pc = \pi^2 EI/L^2$

$= \pi^2 * 2e5 * 0.67e8/1143^2$

$= 101230663N$

This particular buckling load is much higher than the applied buckling load of 50 tons.

So column structure is safe for the given load.

Area of the considered section A=11776mm^2.

So axial stress developed in the column structure

$\sigma = P/A$

$= 500000/11776$

$= 42.45 N/mm^2$.

So this axial stress developed when compared to the yield stress

FOS = YS/ DS

$= 230/42.45$

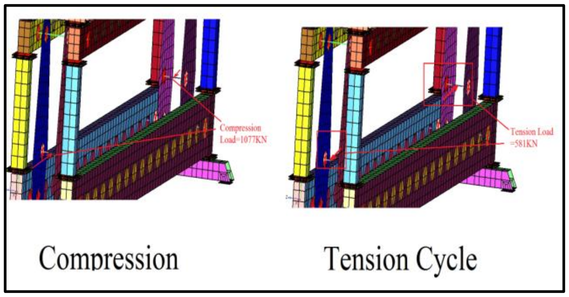
$= 5.418$

A factor of safety of 5.418 is maintained on the structure. But practically operational loads are very less compared to the maximum load considered.

5.0 RESULTS AND DISCUSSIONS

5.1 Finite element optimisation of pin Section through dynamic Response

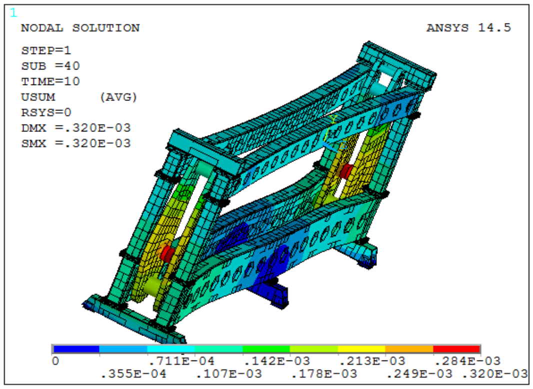
Here the problem from the company perspective is to optimise the pin under dynamic loading condition when it is subjected to a tensile load 581 KN and a compressive load of 1077KN subjected 60cycles per minute. Initial pin size is 100mm. Dynamic response study gives maximum stresses and deflection developed in the structure. But due memory and execution requirements, the problem is converted to Shell mesh. The shell mesh gives faster solution due to lesser number of elements compared to three dimensional representation of the problem. All the pins are represented by beam elements. Coupling and constraint equations are used to link the members.



Boundary Conditions diagram

The figure shows applied cyclic loads on the structure. A tension load of 581KN and a compression load of 1077KN is applied in cyclic fashion. These cyclic loads are applied on the structure for 60 seconds to find the dynamic response. Initially the beam section is taken for 100mm to find the response.

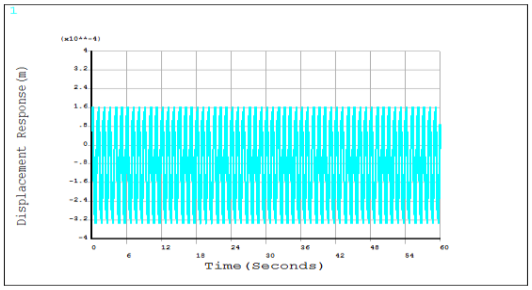
Analysis is carried out in steps to find the solution of the problem.Initially the pin diameter of 100mm is considered and dynamic analysis is carried out for 1 minute(60 seconds) load. The load is applied through functional code. Further iterations are carried out until the stress levels are within the allowable limits of pin and structure.



Overall Displacement diagram of test rig

(for 220mm pin diameter)

Response graph



The figure shows response graph for the problem. The response shows almost constant nature of response indicating no abnormal response like beats taking place in the problem. So the system is almost stable.

The results shows for pin diameter 220mm is completely safe for the given configuration. The maximum stress development of 90.8Mpa is less then the allowable stress of the Pin material 92Mpa . Similarly the displacement value is around 0.32 for the fixture. The stress value in the frame is less then the allowable stress of 38.3Mpa. So structure is totally safe for the given load. Since maximum loading condition is considered for the problem, the design is totally safe.

Results summary for Pin diameter

PinDiameter (mm)	Displacement (mm)	Pin Stress (Mpa)	Test rig Stress (Mpa)
100	0.675	402	53.3
120	0.52	245	50.9
140	0.439	165	47.5
160	0.391	137	43.5
180	0.36	123	39.2
200	0.33	109	35.1
220	0.32	90.2	31.5

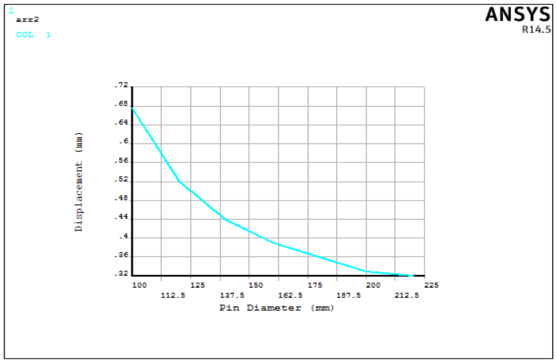
The table shows reduced displacements, stress on pin and frame with increase in the pin diameter. This can be attributed increased strength of pin moment of inertia and cross section.

Factor of safety for different pin diameters

PinDiameter (mm)	Yield Strength (Mpa)	Pin Stress (Mpa)	Factor of safety
100	550	402	1.36
120	550	245	2.24
140	550	165	3.3
160	550	137	4
180	550	123	4.47
200	550	109	5
220	550	90.2	6

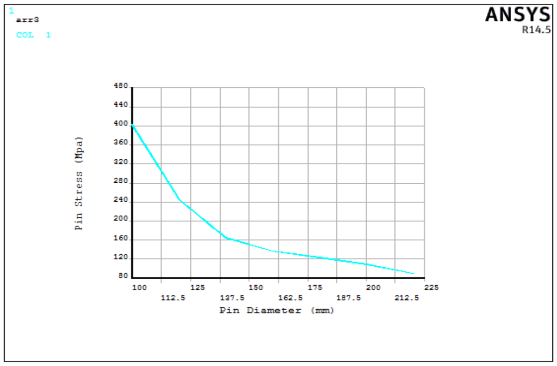
The table shows the increase in factor of safety with increase in pin diameter. Hence it concludes that 220mm of pin diameter is required for considering 6 as factor of safety.

Displacement variation to Pin diameter

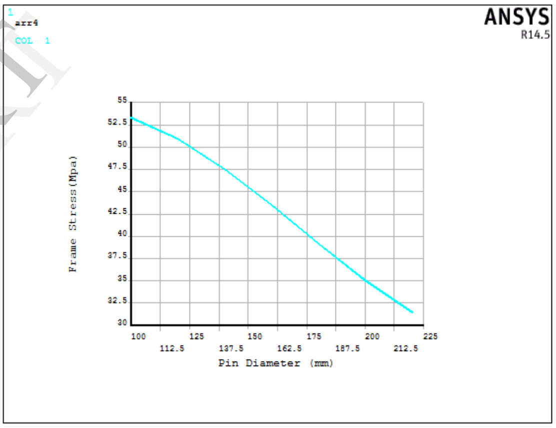


The figure shows variation of displacement with pin diameter. Almost a parabolic variation can be observed with increase of pin diameter. This can be easily understand from the basic strength of material formulation. The strength of material formulation says, the depth has higher effect on stress generation. The depth has inversely square proportion to the stress generation due to which graph is represented parabolically

Pin stress variation to Pin diameter

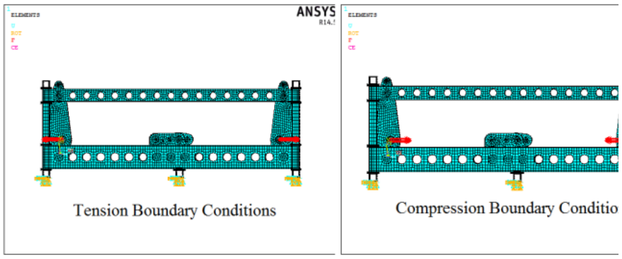


Frame stress to pin diameter



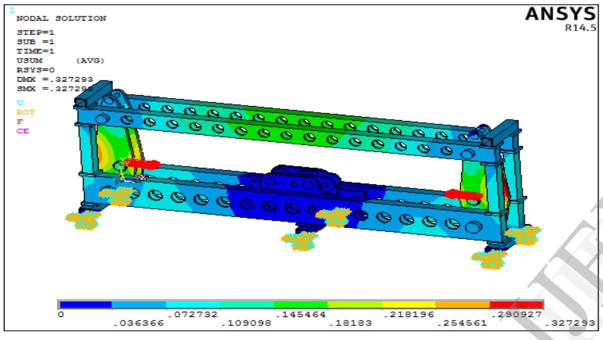
Fatigue Analysis:

The fatigue analysis is carried out in the three dimensional space with pins modelled in the three dimensional space. Three dimensional modelling is considered to get clear nature of stress development in the problem. Also unlike dynamic analysis, fatigue analysis will not take much memory space and time requirements. So three dimensional analysis is considered. Brick elements are considered for the problem. Generally brick mesh gives much better solution compared to the tetra mesh. The analysis results for fatigue are as follows.



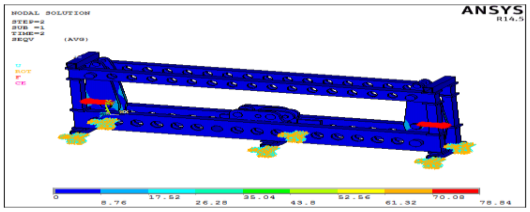
Boundary Conditions

The figure shows applied boundary conditions on the problem. Maximum tension load 581KN and Maximum compression load is 1077KN. The load is applied at the center of the pin. Two load steps are written to represent the boundary conditions. The bottom supports are constrained in all the directions. The first analysis is done to optimise the pin region. But the second analysis is done to find the fatigue life of the frame structure.

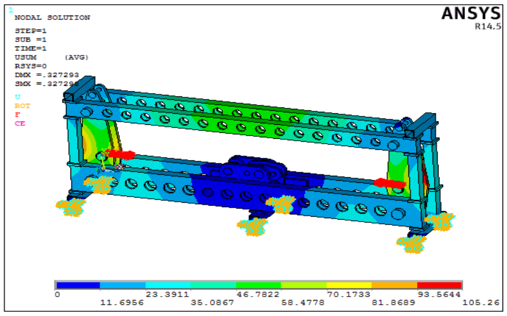


Displacement diagram of test rig

Figure shows displacement plot for the compression load. Maximum displacement is around 0.327mm. Maximum displacement is observed at the loading region. Minimum displacements at the constrained regions. The lever plates are also subjected to considerable deformation. The status bar at the bottom shows variation of displacement in the structure.



Vonmises Stress for Tension Load



Vonmises Stress for compression Load

S-N curve for test rig Material

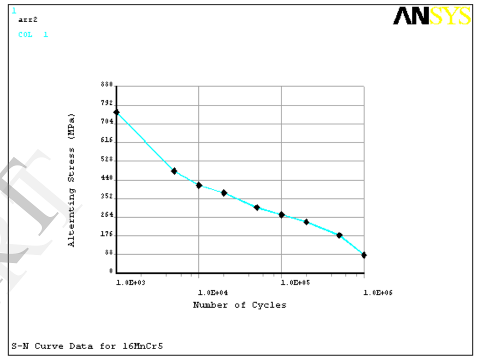
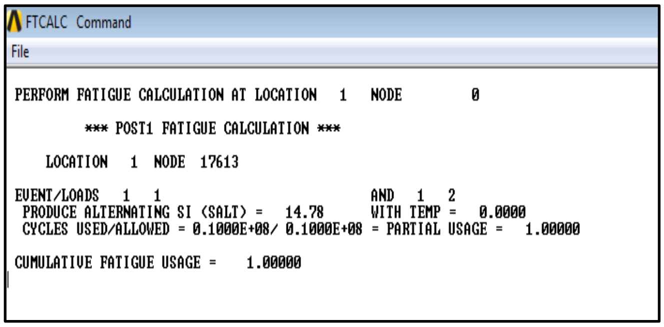


Figure shows the fatigue data which indicates the reduction of allowable fatigue stress as the number of cycles increases, 5N/mm^2 is the fatigue limit corresponding to one million or 10 lakh cycles.

Fatigue calculation from Ansys



```
PERFORM FATIGUE CALCULATION AT LOCATION   1   NODE       0

        *** POST1 FATIGUE CALCULATION ***

    LOCATION   1  NODE  17613

EVENT/LOADS   1    1                          AND   1   2
 PRODUCE ALTERNATING SI (SALT) =   14.78      WITH TEMP =   0.0000
 CYCLES USED/ALLOWED = 0.1000E+08/ 0.1000E+08 = PARTIAL USAGE =   1.00000

CUMULATIVE FATIGUE USAGE =    1.00000
```

The alternating stress induced in the fatigue analysis is 14.78 N/mm^2 which is less than the allowable fatigue limit stress of 85 N/mm^2.

So structure is safe for the fatigue design. Stresses are captured for maximum stressed node 17613. Cumulative usage factor shows the usage equal to 1. This indicates permanent life for the member for the given loading conditions.

6.0 CONCLUSIONS

The fixture designed for hydraulic cylinder testing is analysed for the given loads. The overall analysis summary of the problem is as follows.

- Initially the structure is built in three dimensional space with the given dimensions.
- Theoretical checks are carried out to check the safe limits of cross sections considered using basic strength of material formulations. A factor of safety of 6 is considered for theoretical checks. This factor of safety is required, as the structure is subjected to varying loads. Various references says, minimum 6 factor of safety should be considered for varying loads. .
- Meshing is carried out on the imported geometry in 'step' file format in hypermesh using both the shell and solid elements. The shell meshing is done to reduce the number of elements generated for the dynamic analysis. Dynamic analysis requires lot of computer resources with higher execution times.
- Cylinders are subjected to varying loads which are tested in the test rig.
- From the table 4.2 concluded that with increasing the pin diameter the stress developed in the pin region decreases that will increases the factor of safety of the pin material.
- 120mm pin diameter is recommended for running the test rig up to 10 lakh cycles without fail.
- For Promoting the cylinders 220mm pin diameter is recommended which gives a factor of safety of 6 for the safety of the test rig.
- For 220mm pin diameter the stresses developed on the pin region and test rig will be less hence it is recommended to use.
- Shell63 element for shell mesh and solid 45 element for three dimensional analysis is considered. Beam 188 element is used for representing the pins. RBE3 element is used for representing the connections between pin element to surrounding plate structures.
- The dynamic load is applied on the shell meshed structure using a function generator. The function results in the table format are applied on the pin structure using transient dynamic analysis. The results are captured for stress and deformation. The pin design is optimised until the required functionality is obtained. The final design with 220mm pin diameter is satisfying both stress and deflection requirement. This has given a maximum stress development of 90.8Mpa, frame stress of 31.5Mpa and displacement requirement of 0.32mm. So pin diameter can be considered as 220mm for further analysis. Various plots are represented to shows the effect of optimisation on stress, displacement on the structures. The stress on frame structure is also represented.
- The final fatigue analysis using three dimensional analysis shows the stress levels are within the limits of the materials. Fatigue estimation shows complete life for the structure.

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