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Comparison & Analysis of Residual Stress Impact Due to Autofrettage, in Hydraulic Cylinders.

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***Abstract*--In Autofrettage cylinder is subjected to internal pressure to cause plastic expansion of some or the entire tube wall. The stresses are created in the near-bore region while residual tensile hoop stresses are created in the outer-bore region. The resulting residual stress leads to a decrease in the value of maximum Von-Mises stress in the next loading stage. Abaqus FEA package is used for analysis & three different Models of Structural steel hydraulic cylinders are made to analyze the impact of Residual stresses in it. Same results are validated at working loading stage by using Lame's Equation. Considerable saving of maximum induced stress is observed & same is discussed in next few pages of this article.**

Key Words:Autofrettage, Von-Mises stress, Isotropic elastic model, Kinematic hardening model etc.

I. INTRODUCTION TO AUTOFRETTAGE

In this technique, the cylinder is subjected to internal pressure to cause plastic expansion of some or the entire tube wall. The stresses are created in the near-bore region while residual tensile hoop stresses are created in the outer-bore region. The resulting residual stress leads to a decrease in the value of maximum Von-Mises stress in the next loading stage. That means the increase in the pressure capacity of the cylinder in the next loading stage.[2]

The start point is a single steel tube of internal diameter slightly less than the desired caliber. The tube is subjected to internal pressure of sufficient magnitude to enlarge the bore and in the process the inner layers of the metal are stretched beyond their elastic limit. This means that the inner layers have been stretched to a point where the steel is no longer able to return to its original shape once the internal pressure in the bore has been removed.[4]

II. FEM ANALYSIS OF AUTOFRETTAGED CYLINDERS

FEA consists of a computer model of a continuum that is stressed and analyzed for specific results. A continuum has infinite particles with continuous variation of material properties. Therefore, it needs to simplify to a finite size and is made up of an assemblage of substructures, components and members. Discretisation process is necessary to convert whole structure to an assemblage of members/elements for determining its responses. As ANSYS is quite less precise & effective in non-linear stress zone, it is been observed that ABAQUS is quite suitable for non-linear stress analysis. Hence I selected ABAQUS as a FE tool which is been used in the analysis.

Preprocessing:

Here three hydraulic models of three different dimensions are selected & intentionally length along with bore diameter is kept constant, so that pressure acting area will be same. Details of models are as per table-1 shown below:

Cylinder Model	Model -I	Model -II	Model -III
Cylinder OD in mm	120.65	130.6	126.0
Cylinder ID in mm	101.60	101.60	101.60
Length of Cylinder in mm	57.15	57.15	57.15
Thickness of Cylinder wall in mm	9.52	14.5	12.20

Table-1: Cylinder Model Dimensional Specifications.

The material properties are defined as per elastic & plastic limits separately for Alloy structural steel. For elastic phase isotropic elastic model is been selected & properties are fed as per table-2.

Value of E in MPa	Value of µ
2 X 10^5	0.3

Table-2: Material Properties at Elastic Phase

Kinematic hardening model is been selected for plastic zone. Then material properties for plastic zone are defined as per table-3.

Yield Stress	Value of µ
200 MPa	0
480 MPa	0.18

Table-3: Material Properties at Plastic Phase

As meshing is also a important parameter in determining the nodes & sensitivity of the results. Mesh Size is been selected as 2 mm by greed independence. After sectioning & selecting proper instances analysis is performed.
Then yielding pressures for each cylinder are find out which is as per table-4.

Cylinder Model	**Model -I**	**Model -II**	**Model -III**
Yielding Pressure in MPa	29.08 MPa	39.47 MPa	34.97 MPa

Table-4: Yielding pressure values for respective cylinder model.

Now the working pressure should has lower values than the Yielding pressure, However Autofrettage pressure should has higher value than that of yielding pressure. Considering this stepwise loading was designed as under for autofrettage.Loading along with maximum Von-Mises stress result is shown in below table-5.

Model -I		**Model -II**		**Model -III**	
Internal Pressure in MPa	**Max. Stress in MPa**	**Internal Pressure in MPa**	**Max. Stress in MPa**	**Internal Pressure in MPa**	**Max. Stress in MPa**
27 [Before]	169.4	35 [Before]	158.5	30 [Before]	154.6
32	184.4	42	309.8	40	329.2
40	199.6	50	378.3	45	407.1
45	244.6	55	437.5	50	458.9
0 [Unloading]	2.17 Tens. 1.05 Comp.	0 [Unloading]	15.04 Ten. 10.06 comp.	0 [Unloading]	16.39 Ten. 10.59 Com.
27 [Working]	156.6	35 [Working]	143.9	30 [Working]	142.9

Table-5: Stepwise results for three Cylinder Models.

Average reduction in maximum stress for each model is shown in table-6.

Model	**Model-I**	**Model-II**	**Model-III**
Value of Maximum Stress for working pressure in MPa before Autofrettage.	169.4	158.5	154.6
Value of Maximum Stress for working pressure in MPa after Autofrettage.	156.6	143.9	142.9
% reduction of Stress due to Autofrettage	**7.6%**	**9.21%**	**7.56%**

Table-6: Stress Reduction due to Autofrettage

III. ANALYTICAL VERIFICATION OF FEM RESULTS

Above results can be verified in working phase, where stresses are below yielding stress. In elastic limit for Structural Steel Lame's equation is quite appropriate. Equation value of the Lame's equation is taken as below:

$$\sigma_r = a - \frac{b}{r^2} \quad \text{-------[1]}$$

$$\sigma_c = a + \frac{b}{r^2} \quad \text{--------[2]}$$

By putting conditions in above equations, after solving simultaneously following values can be obtained as per table-7.

Model	Model-I	Model-II	Model-III
Hydraulic Working Pressure considered in MPa. [Below yielding]	27	35	30
Value of 'a' as per final Equations.	66	53.70	55.76
Value of 'b' as per final Equations.	0.24	0.229	0.2213
Analytical value of Maximum Stress in MPa. [Value of σ_c]	**159.00**	**142.44**	**141.51**

Table-7: Analytical Values of Maximum Stress during working loading.

Sample Abaqus result for Model-I cylinder with 27 MPa working loading is shown in figure-1.

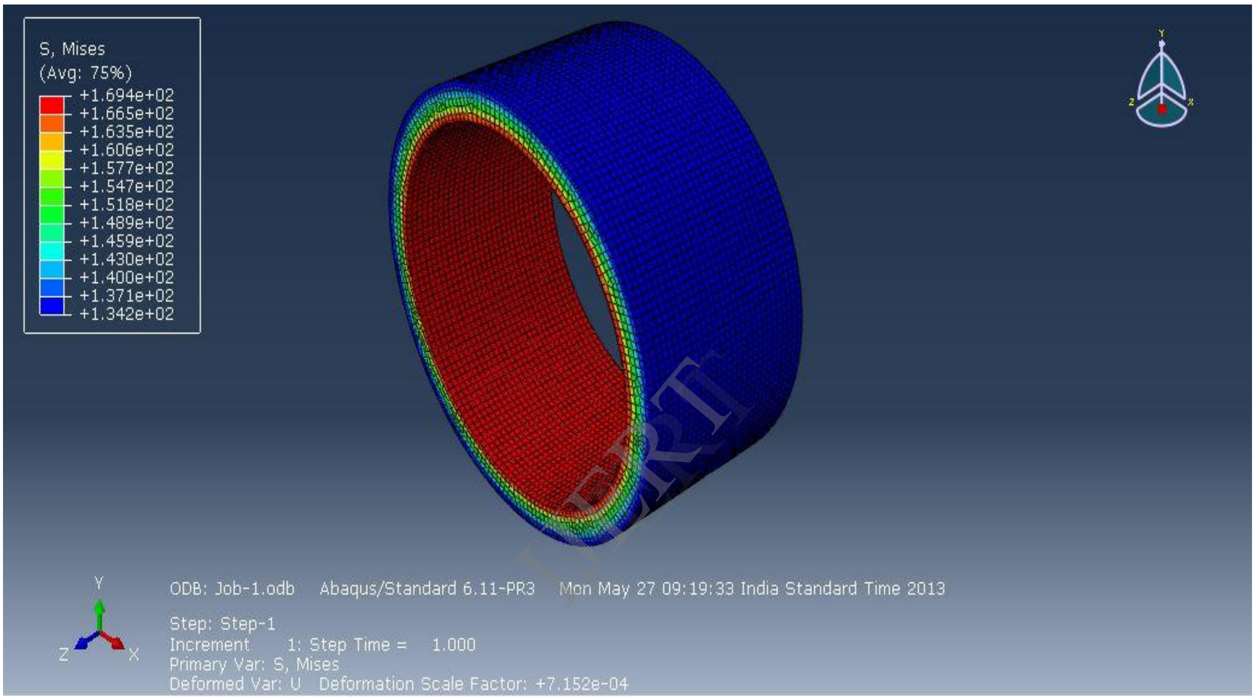

Figure-1: Stress analysis of Model-I Cylinder for working pressure of 27 MPa.[Maximum Stress is noted as 169.4 MPa]

Similarly for all three Models analytical & FEM results are compared as per table-8 which is shown below-

Cylinder Model	**Model-I**	**Model-II**	**Model-III**
Working Pressure considered in MPa.[Below yielding]	27	35	30
Analytical value of Maximum Stress in MPa.	159.00	142.44	141.51
Value of Maximum stress in MPa by FEM	169.40	158.5	154.6
% Variation between FEM results & Analytical results.	**6.14%**	**10.13%**	**8.47%**

Table-8: Comparison of FEM results & Analytical results during working pressure range.

IV. RESULTS & DISCUSSIONS

FEM analysis of three cylinder models of different dimensions is done. For Model-I, stress reduction in maximum stress due to Autofrettage is observed as 7.6%. For Model-II, stress reduction in maximum stress due to Autofrettage is observed as 9.21%.For Model-III, stress reduction in maximum stress due to Autofrettage is observed as 7.56%.

Same FEM results are compared with analytical results during working pressure range. Average variation between FEM results & Analytical results is 8 %.This may be due to properties variation, actual yielding, and porosity of material.

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