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Effect of Internal Clearance on Buckling of Multistage Hydraulic Cylinder

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ABSTRACT

Multistage cylinders are generally used to lift and tilt heavy loads under controlled speed. In defence applications multistage cylinders are used in missile tilt platform and antenna mast. Earth moving equipment's such as tippers, dumpers, cranes and compactors uses multistage cylinders for operations. In the present work multistage hydraulic cylinder (telescopic cylinder) with three stage has been analysed using strain energy method and verified with finite element analysis. The research work investigates the effect of internal clearances which reduces the critical buckling load of hydraulic cylinders. The results are validated by buckling load test. The clearances between the tube to piston guides, gland guide to piston rod, clearances due to tube expansion under pressure, initial curvature in the tube, eccentricity of cylinder components and tube ovality are considered in the buckling load test. Describes the comparative study of buckling load tests of three stage hydraulic cylinders having fixed free and hinged mounting with five different internal clearances.

Keywords: Buckling; Telescopic cylinder; Finite element analysis; Strain energy method; Hydraulic cylinder; Internal clearance

NOMENCLATURE

- P Critical buckling load, *(N)*
- E_i Young's modulus of section i (N/mm^2)
- I_i Moment of inertia of section i mm^4
- n Number of sections
- L_i Length of section i (mm)
- D_i Outer diameter of section i (mm)
- d_i Inner diameter of section i (mm)
- c Internal clearance (mm)
- y Deflection (mm)

1. INTRODUCTION

The hydraulic cylinders with more than one stage called as multistage cylinders are used to tilt and lift heavy loads under controlled speed with shorter closed length. Multistage cylinders with hinged mounting tilts heavy structures of missile tilt platform of length higher than 27 m as shown in Fig. 1. Fixed free mounting cylinders lifts antenna mast to a height of more than 30 m with closed length of less than 3 m. Multistage cylinders are used in variety of applications such as tippers, dumpers, dam gates, telescopic hoists, cranes, drill rigs, compactors, bascule bridges and many more applications.

The hydraulic cylinders critical buckling load are arrived using standards ANSI/(NFPA) T3.6.37[1], ISO/TS13725[2], DNVGL-CG-0194[3] and literatures[4-7]. These methods can be used for single stage hydraulic cylinders with initial deformation and cannot be used for the multistage hydraulic cylinders. Also it cannot be used for cylinders with fixed free mountings.

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The multistage cylinder buckling using FEM was discussed earlier in literature[8-12]. Multistage cylinder buckling load using classical and numerical methods explained by Chai[13] and Yoshihiko[14,15]. Gamez[16] and Baregetti[17] discusses the effect of misalignment and clearance in single stage hydraulic cylinder with hinged mounting.Baregetti[17] analysed the single stage cylinder with different wear rings and geometrical clearances and concludes the effect of internal clearance is significant in buckling of cylinders. The DNVGL-CG-0194[18] recommends

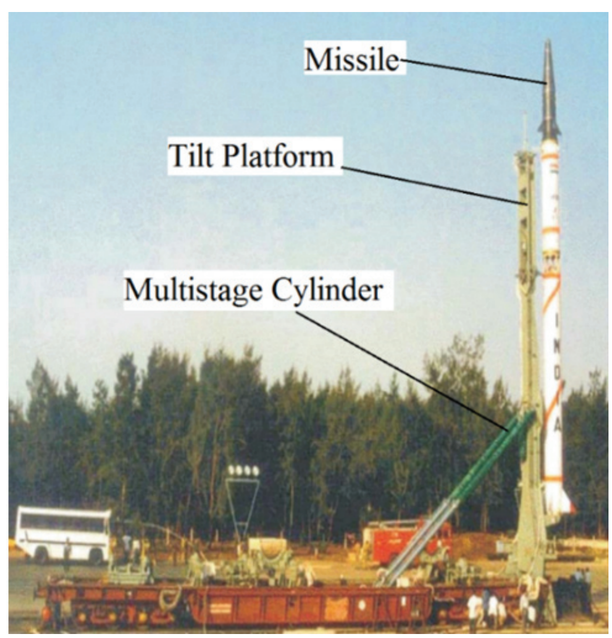

Figure 1. Missile tilt platform.

the guidelines for buckling analysis using finite element method. Muppavarapu[19] developed mathematical model for columns having varying cross sections to analyse the buckling load. Novoselac[20] analysed the bar having imperfections using Abaqus FEA software. The effects of internal clearance in the telescopic cylinder with different mounting conditions taken as a long slender stepped column are analysed in the present work.

It is important to limit the internal clearances to avoid buckling before reaching the critical load. The multistage cylinder with rear flange mounting and rod end flange mounting considered as fixed free mounting (cantilever mounting) for the buckling analysis as a case study 1 is described. The multistage cylinder with rear clevis mounting and rod eye mounting considered as hinged mounting for the buckling analysis of case study 2 is also explained. The case study 1 and case study 2 multistage cylinders are analysed using strain energy method[21] and FEM. The multistage cylinder having internal clearance ranging from 0.15 mm to 0.85 mm are subjected to buckling load test with hydraulic pressure to find the reduction in critical buckling load to validate the analysis.

2. CRITICAL BUCKLING LOAD

The critical buckling load (Euler load) of a long slender column taken as non-prismatic multistage hydraulic cylinder loaded axially defined as the compressive force required to keep the column in a slightly bent form. The critical buckling load marks the transition point from where the compressed column undergoes from stable to unstable equilibrium. In the present work the telescopic cylinder is taken as long slender stepped column for calculating the critical buckling load and not for short stroke cylinders.

2.1 Multistage Hydraulic Cylinder Construction

The multistage hydraulic cylinder having three stages consists of outer tube assembly, first stage piston rod assembly, second stage piston rod assembly, third stage piston rod assembly, gland assembly of first, second and third stages. Each stage piston rod assembly consists of piston rod made out of cold drawn structural steel tubes ground and hard chrome plated with welded piston having piston seal of material PTFE bronze with NBR ‘O-ring and wear ring. The gland of each stage assembled with wear ring and dust seal.

The piston and gland wear ring made out of gun metal for internal clearance of 0.15 mm and other cylinders with higher internal clearances made out of hard fabric. The cylinder bore of each stage honed to have surface finish of <0.4 Ra.

3. FIRST CASE STUDY

The multistage cylinder with rear flange mounting and rod end flange mounting considered as fixed free mounting (cantilever mounting) for the buckling analysis as a case study 1. The multistage cylinders are analysed using strain energy method and FEM. The multistage cylinder having internal clearance ranging from 0.15 mm to 0.85 mm are subjected to buckling load test with hydraulic pressure to find the reduction in critical buckling load to validate the analysis.

3.1 Buckling Analysis of Multistage Cylinder with Fixed Free Mounting by Energy Method

In the strain energy method, the critical buckling load for the telescopic cylinder is analysed considering the potential energy required to reduce the column length by a small amount x under the compressive force P. The critical buckling load calculated using strain energy method[22] for multi-stage hydraulic cylinder with one end fixed and other end free. The deflection curve of the nine section fixed free mounting hydraulic cylinder is given by the following Eqns. (1) - (3). The differential equation of the column is given by,

$$EI\frac{d^4y}{dx^4}+P\frac{d^2y}{dx^2}=0 \tag{1}$$

$$\frac{d^4y}{dx^4}+k^2\frac{d^2y}{dx^2}=0 \tag{2}$$

where $k^2=\dfrac{P}{EI}$ and I = Moment of inertia.

The general solution of the above equation is

$$y=A\sin(kx)+B\cos(kx)+Cx+D \tag{3}$$

Applying boundary conditions for cantilever mounting to the general equation we get the deflection equation of lowest critical load,

$$y=A\,(1-\cos\frac{\pi x}{2L_n}) \tag{4}$$

$$\Delta U=\sum_{i=1}^{n}\int_{L_{i-1}}^{Li}\frac{M^2dx}{2EI_i} \tag{5}$$

where bending moment $M = Py$ and n = number of stages

$$\Delta T=P\int_{L_0}^{L_n}\frac{1}{2}(\frac{dy}{dx})^2dx \tag{6}$$

Equating the strain energy of bending ΔU = work done by compressive forces ΔT, we get the critical buckling load of ideal hydraulic cylinder without any clearances as per below equation.

$$P=\frac{\pi^2E}{8L_n\left\{\sum_{i=1}^{n}\frac{Z_i}{I_i}\right\}} \tag{7}$$

$$Z_i=\frac{L_i-L_{i-1}}{2}-\frac{L_n\left(\sin\frac{\pi L_i}{L_n}-\sin\frac{\pi L_{i-1}}{L_n}\right)}{2\pi} \tag{8}$$

$$I_i=\frac{\pi}{64}\left[D_i^4-d_i^4\right] \tag{9}$$

Further the critical load of multistage hydraulic cylinder having fixed free mounting with initial deflection due to internal clearances can be obtained by modifying the Eqn. (4), we get deflection equation as

$$y=\delta+A\left(1-\cos\frac{\pi x}{2L_n}\right) \tag{10}$$

where δ = Initial deflection at distance x. The initial deflection due to internal clearance varies from zero at fixed end to maximum at free end. Solving Eqns. (5) and (6) by substituting y from Eqn. (10) will lead to complex equations which is not possible with analytical methods. Hence critical buckling load calculations by the strain energy is limited to ideal buckling analysis without clearance for the multistage hydraulic cylinder having fixed free mounting. The multistage cylinder with fixed free mounting has shut length or closed length of 665 mm. The stroke length of stage 1, stage 2, and stage 3 are 415 mm, 445 mm and 475 mm, respectively. The fully extended or open length of fixed free mounting cylinder is 2000 mm.

Using the above equation the critical buckling load of a three stage telescopic hydraulic cylinder having nine sections with fixed free mounting condition as shown in Fig. 2 is calculated for the cylinder specification given in Table 1. From Eqns. (7) - (9), we get the critical buckling load by energy method without initial deflection as P = 9181 N.

Table 1. Three stage nine section fixed free mounting cylinder dimensions

Section no.	Tube OD (mm)		Tube ID (mm)		Length (mm)	
1	D1	105	d1	0	L1	40
2	D2	55	d2	50	L2	455
3	D3	65	d3	40	L3	570
4	D4	45	d4	40	L4	930
5	D5	55	d5	30	L5	985
6	D6	35	d6	30	L6	1435
7	D7	45	d7	20	L7	1490
8	D8	25	d8	20	L8	1970
9	D9	105	d9	0	L9	2000

3.2 Buckling Analysis of Multistage Cylinder with Fixed Free Mounting using ANSYS FEM

The specified hydraulic cylinder without considering the initial deflection due to internal clearance as given in section 3.1 has been analysed by linear elastic static finite element analysis[3] as shown in Fig. 2 using ANSYS multiphysics release 13.0 software. Three node 3-D BEAM189 element having six degrees of freedom at each node has been used with an element size of 5. FEA model consists of 400 elements and 800 nodes with 11 sections. Each section is considered as a circular tube with dimensions as given in Table 1. The linear elastic isotropic element considered for cylinder material with Young's modulus E = $205000\frac{N}{mm^2}$. Poisson's ratio of 0.3 taken for cylinder material. The cylinder has been considered as a cantilever beam (fixed free) with zero degree of freedom at left end and six degrees of freedom at right end (rotation X,Y,Z and axial displacement X,Y,Z). The left end has linear displacement constraints in the directions X,Y,Z and rotational constraints at X,Y,Z. The right end has no linear displacement constraints and rotational constraints. Compressive load has been applied at top section in the analysis. The results of the finite element analysis are displayed in Table 2. The first mode shape of cylinder with fixed free mounting are as

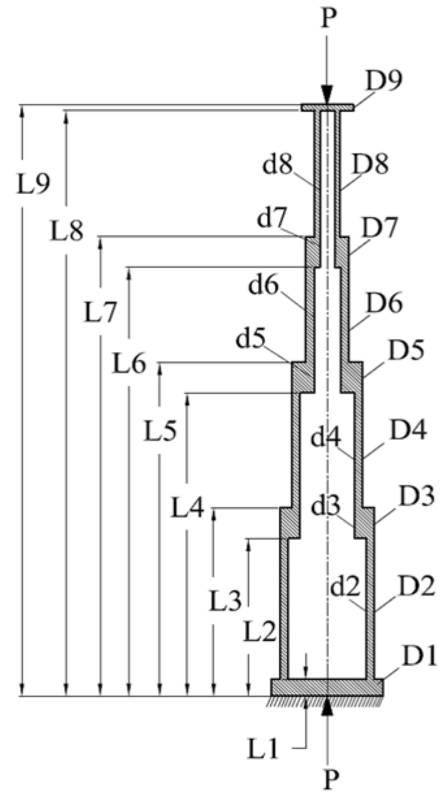

Figure 2. Three stage telescopic cylinder with nine sections fixed-free mounting.

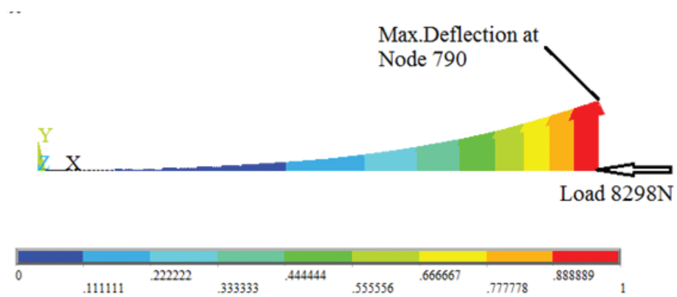

Figure 3. First mode shape of first case study.

shown in Fig. 3. The multistage hydraulic cylinder buckling analysis having fixed free mounting with initial deflection due to internal clearances can further be extended by non linear buckling analysis using ANSYS workbench and Abaqus FEA software.

Table 2. FEA results of first case study

Mode	Buckling load (N)
First mode	8298
Second mode	42863
Third mode	121266

3.3 Buckling Load Test of Multistage Cylinder Having Fixed Free Mounting with Internal Clearance

The hydraulic cylinder without clearance is practically not possible due to manufacturing tolerance and hence minimum clearance of 0.15 mm taken for comparative test.

The multistage cylinder with internal clearance of 0.15 mm to 0.85 mm and dimensions listed in Table 1 has been placed vertically with cylinder bottom flange mounted to the block on the ground. The Fig. 4 shows the three stage hydraulic cylinder with extended length of 2000 mm having internal clearance of 0.15 mm in buckled condition under the dead weight compressive load of 5514N including self weight and oil weight of hydraulic cylinder. Cylinder has been pressurised to hold the dead weight compressive load. The load is applied to the center of the last stage rod having flange at the top.

Test Conditions

Test fluid : Mineral oil -ISO VG 46
Cylinder mounting position : Vertical
Temperature : 32 °C
Pump : Radial piston pump with 3 LPM flow
Multistage cylinder mounting : Bottom flange bolted to fixed block and top rod end flange free to rotate and move in all directions (X,Y and Z)

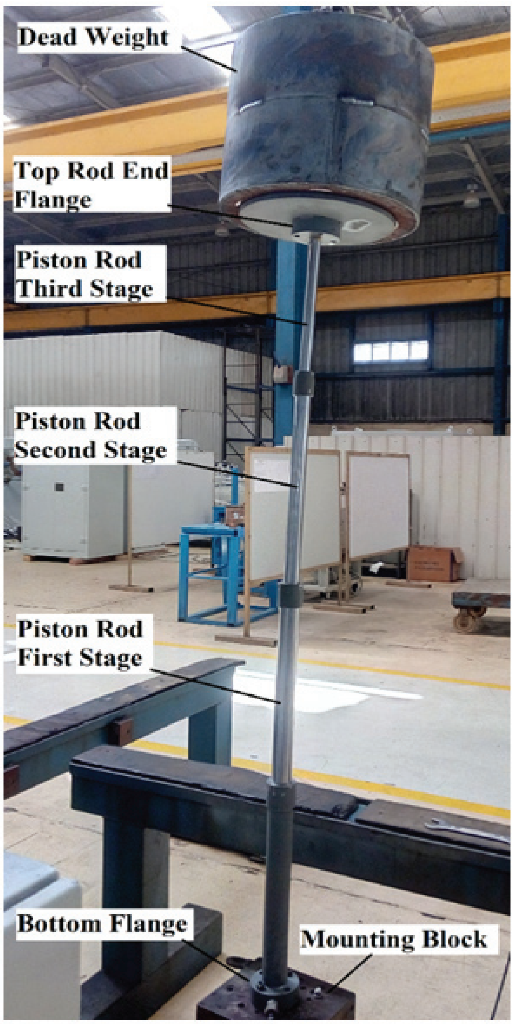

Figure 4. Buckling of three stage nine section fixed free mounting cylinder.

Five types of tests have been carried out with same hydraulic cylinder dimensions to find out the effect of cylinder internal clearance which reduces the critical buckling load[4]. The multistage cylinder each stage gland and rod are assembled together to have the internal clearance as listed in Table 3.

Table 3. Deflection of three stage nine section fixed free mounting cylinder

Clearance, **c** mm	0.15	0.325	0.5	0.675	0.85
Deflection, **y** mm	8.26	17.9	27.54	37.18	46.82

The deflection due to internal clearances between the tube to piston guide, gland to piston rod, initial curvature in the tube, eccentricity of cylinder components and tube ovality are measured on the surface table with height gauge is shown in Fig. 5 and recorded in Table 3.

The multistage cylinder with internal clearance of 0.15mm consists of gun metal wear rings at gland and piston. The multi-stage cylinder with internal clearance of 0.325 mm, 0.5 mm, 0.675 mm, and 0.85 mm consists of hard fabric wear rings at gland and piston. The gland and piston wear ring grooves as shown in Fig. 6 are oversised to have required internal clearances.

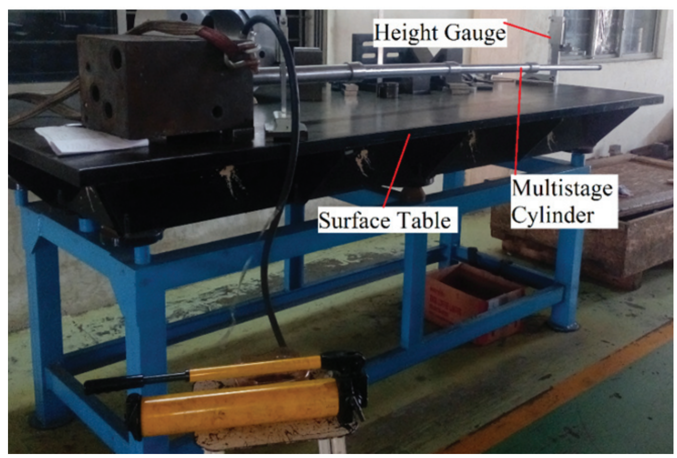

Figure 5. Deflection of three stage nine section fixed free mounting cylinder.

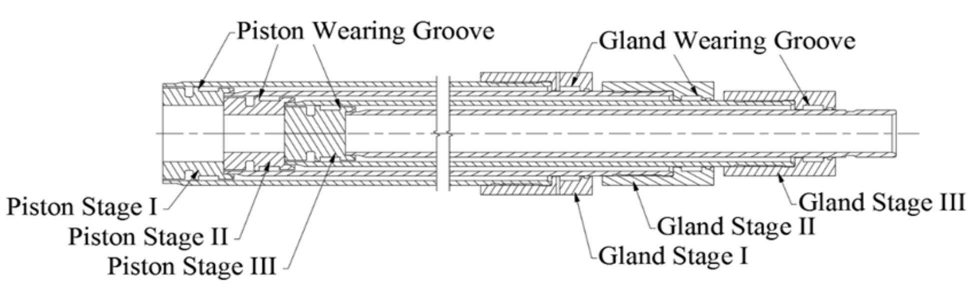

Figure 6. Wear rings of piston and gland.

The internal clearance verses buckling load is as shown in Fig. 7. Higher internal clearance with 0.85 mm causes the cylinder to buckle far below the buckling load as compared to internal clearance of 0.15 mm.

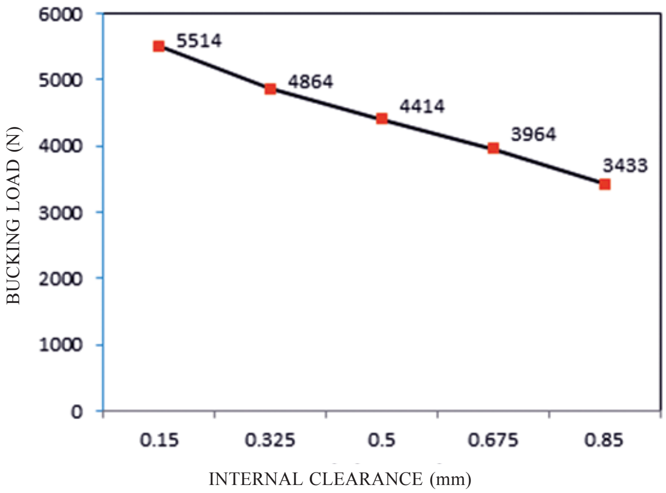

Figure 7. Internal clearance verses buckling load of case study 1.

4. SECOND CASE STUDY

The multistage cylinder with rear clevis mounting and rod eye mounting considered as hinged mounting for the buckling analysis of case study 2. The multistage cylinders are analysed using strain energy method[22] and FEM. The multistage cylinder having internal clearance ranging from 0.15 mm to 0.85 mm are subjected to buckling load test with hydraulic pressure to find the reduction in critical buckling load to validate the analysis.

4.1 Buckling Analysis of Multistage Cylinder with Hinged Mounting by Energy Method

The multistage hydraulic cylinder with hinged mounting is as shown in Fig. 8.

The critical buckling load is calculated using strain energy method[22] by the following Eqns. (11) - (14). Applying boundary conditions for both ends hinged to the general Eqns. (5) and (6) we get the deflection equation of lowest critical load,

$$y = A\sin\left(\pi x / L\right) \tag{11}$$

$$P = \frac{\pi^2 E}{2L_n\left\{\sum_{i=1}^{n}\frac{Z_i}{I_i}\right\}} \tag{12}$$

$$Z_i = \frac{L_i - L_{i-1}}{2} - \frac{L_n\left(\sin\frac{2\pi L_i}{L_n} - \sin\frac{2\pi L_{i-1}}{L_n}\right)}{4\pi} \tag{13}$$

$$I_i = \frac{\pi}{64}\left[D_i^4 - d_i^4\right] \tag{14}$$

Further the critical load of multistage hydraulic cylinder having pinned mounting with initial deflection due to internal clearances can be obtained by modifying the Eqn. (4), we get deflection equation as

$$y = \delta + A\sin\left(\pi x / L\right) \tag{15}$$

where δ = Initial deflection at distance x. The initial deflection due to internal clearance varies from zero at hinged ends to maximum at middle. Solving Eqns. (5) and (6) by substituting y from Eqn. (15) will lead to complex equations which is not possible with analytical methods. Hence critical buckling load calculations by the strain energy is limited to ideal buckling analysis without clearance for the multistage hydraulic cylinder having pinned mounting.

The multistage cylinder with hinged mounting has closed length of 855 mm and stroke length of stage 1, stage 2, and stage 3 are 400 mm, 425 mm and 420 mm, respectively. The fully extended or open length of fixed free mounting cylinder is 2100mm.Using Eqns. (12) - (14), the critical buckling load of a three stage hydraulic cylinder having eleven sections with hinged mounting condition as shown in Fig. 9 is calculated for the cylinder specification given in Table 4. From Eqns. (12) - (14), the critical buckling load by strain energy method is obtained as P = 18359 N.

4.2 Buckling Analysis of Multistage Cylinder with Hinged Mounting using ANSYS FEM

The specified hydraulic cylinder given in section 4.1 has been analysed by linear elastic static finite element analysis as shown in Fig. 9 using ANSYS multiphysics release 13.0 software. Three node 3-D BEAM189 element having six degrees of freedom at each node has been used with an element size of 5. FEA model consists of 420 elements and

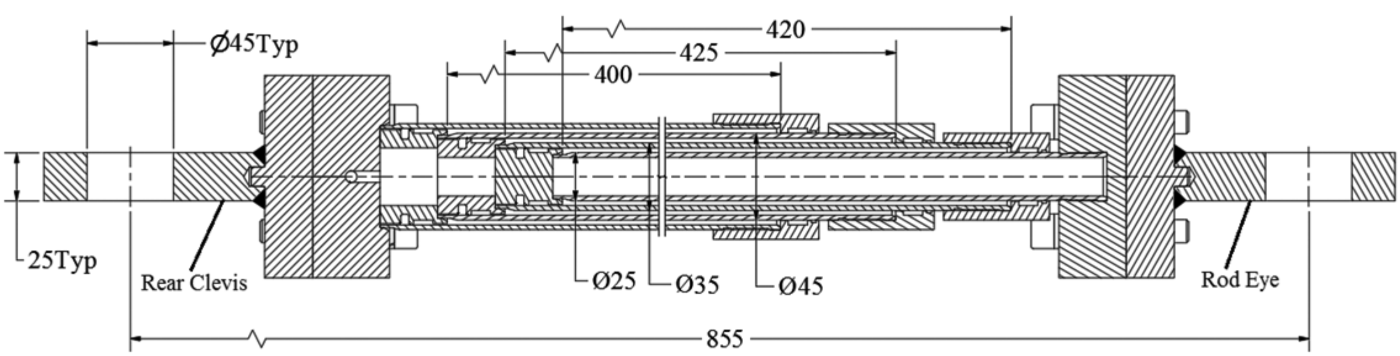

Figure 8. Construction of three stage telescopic cylinder with hinged mounting.

Table 4. Three stage eleven section hinged mounting cylinder dimensions

Section no.	Tube OD (mm)		Tube ID (mm)		Length (mm)	
1	D1	75	d1	0	L1	70
2	D2	105	d2	0	L2	135
3	D3	55	d3	50	L3	545
4	D4	65	d4	40	L4	600
5	D5	45	d5	40	L5	1005
6	D6	55	d6	30	L6	1060
7	D7	35	d7	30	L7	1490
8	D8	45	d8	20	L8	1545
9	D9	25	d9	20	L9	1970
10	D10	105	d10	0	L10	2030
11	D11	75	d11	0	L11	2100

840 nodes with 13 sections. Each section is considered as a circular tube with dimensions as given in Table 4. The linear elastic isotropic element considered for cylinder material with Young's modulus $E = 205000$ (N/mm^1). Poisson's ratio of 0.3 taken for cylinder material. The cylinder has been considered as a hinged beam with one degree of freedom at left end (rotation Z) and two degrees of freedom at right end (rotation Z and axial displacement X). The left end has linear displacement constraints in the directions X,Y,Z and rotational constraints at X,Y. The right end has linear displacement constraints in the directions Y,Z and rotational constraints at X,Y. Compressive load has been applied at right end in the analysis. The results of the finite element analysis are given in Table 5. The first mode shape of eleven section cylinder with hinged mounting are as shown in Fig. 10. The multistage hydraulic cylinder buckling analysis having fixed free mounting with initial deflection due to internal clearances can further be extended by non linear buckling analysis using ANSYS workbench and Abaqus FEA software.

Table 5. FEA results of second case study

Mode	Buckling load, N
First mode	15487
Second mode	66328
Third mode	965912

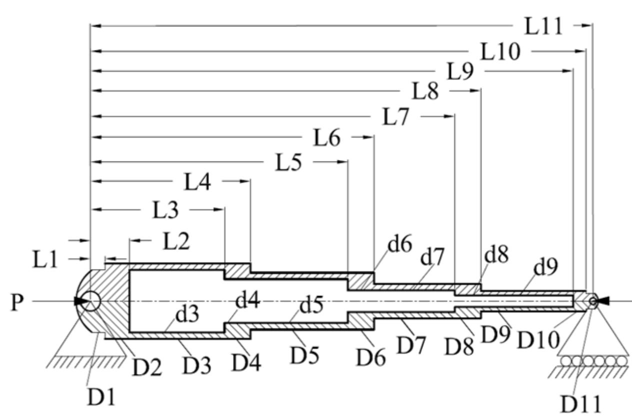

Figure 9. Three stage telescopic cylinder with eleven sections hinged mounting.

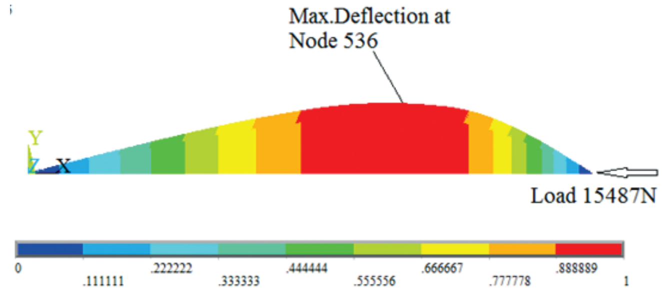

Figure 10. First mode shape of second case study.

4.3 Buckling Load Test of Multistage Cylinder having Hinged Mounting with Internal Clearance

The hydraulic cylinder without clearance is practically not possible due to manufacturing tolerance and hence minimum clearance of 0.15 mm taken for comparative test. The multistage cylinder with internal clearance of 0.15 mm to 0.85 mm and dimensions listed in Table 4 has been mounted with pins on the testing frame[23] in horizontal condition Fig. 11. The test cylinder having extended length of 2145 mm has been hinged at 2100 mm and pressurised to create compressive load. Fig. 11 shows the three stage hydraulic cylinder with internal clearance of 0.15 mm in buckled condition with compressive load of 16781N including self weight and oil weight of hydraulic cylinder. Higher internal clearance with 0.85 mm causes the cylinder to buckle far below the buckling load as compared to internal clearance of 0.15 mm. The internal clearance verses buckling load are shown in Fig. 12.

Test Conditions

Test fluid : Mineral oil -ISO VG 46
Cylinder mounting position : Horizontal
Temperature : 32 °C

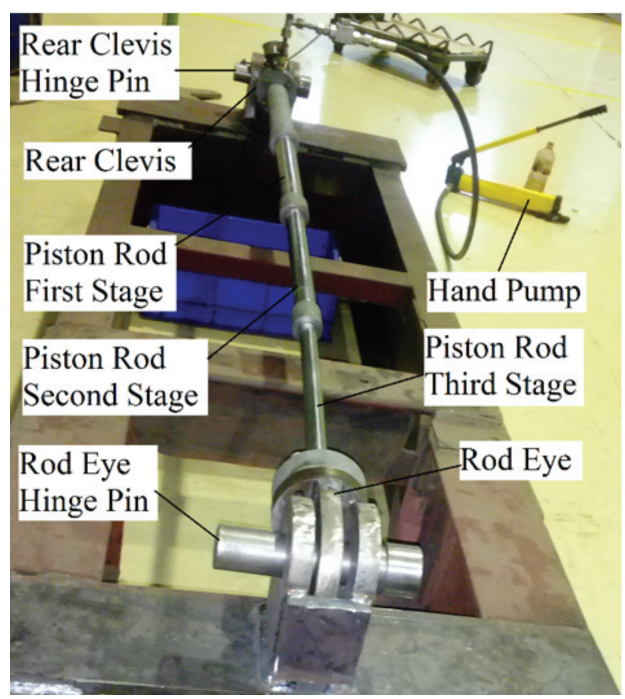

Figure 11. Buckling of three stage nine section hinged mounting cylinder.

Pump : Hand pump
Multistage cylinder mounting : Hinged mounting with Rear clevis and rod eye.

5. RESULTS AND DISCUSSION

The comparative buckling load test results are as shown in the Table 6. The hydraulic cylinder without clearance is practically not possible due to manufacturing tolerance and hence minimum clearance of 0.15 mm taken for comparative test. The variation in hinged cylinder test result between actual load test and strain energy method is 8.6 per cent lower due to the effect of 0.15 mm internal clearance and actual load test is higher by 7.7 per cent comparing to ANSYS FEA. The variation in fixed free cylinder test result between actual load test and strain energy method is 40 per cent lower and actual load test is lower by 34 per cent comparing to ANSYS FEA due to the effect of 0.15 mm internal clearance. The effect of internal clearance is higher in fixed free mounting comparing to hinged cylinder due to large deflections in fixed free cylinder leading to higher bending stress.

Load test results of hinged and fixed free cylinders are shown in Fig. 12 and Fig. 7. The hinged cylinder with 0.15 mm internal clearance buckles at 16781N in actual load test and cylinder with 0.85 mm clearance buckles at 24 per cent lower load than buckling load of 0.15 mm clearance. In the case of fixed free cylinder with 0.15 mm internal clearance buckles at 5514N in actual load test and cylinder with 0.85 mm clearance buckles at 38 per cent lower load than buckling load of 0.15 mm clearance. The results clearly indicates that the fixed free mounting cylinders buckles at far less than the actual load comparing to hinged cylinders due to internal clearance. The deflection due to self weight, oil weight and internal clearance for the fixed free mounting cylinder are indicated in Table 3.

Table 6. Cylinder buckling comparative test results

	Buckling Load (N)		
Cylinder mounting	Load test with 0.15 clearance	Energy method without clearance	FEA without clearance
Fixed Free	5514	9181	8298
Hinged	16781	18359	15487

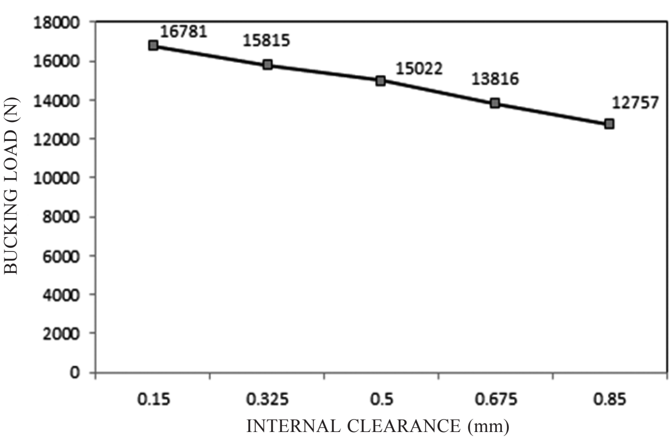

Figure 12. Internal clearance in mm verses buckling load in N second case study.

6. CONCLUSIONS

The actual load test results for the fixed free cylinder are much lower than calculated load due to instability in loading with internal clearance. This is caused by deflection of piston rod due to internal clearance, self weight, oil weight, tube ovality, wear ring compression, clearances due to tube expansion under pressure, initial curvature in the tube and eccentricity of cylinder components. Therefore proper design with appropriate minimum clearances have to be considered in case of multistage cylinders having fixed free mounting. The present work has been carried out initially to analyse the hydraulic cylinders with fixed free mounting using strain energy method and linear FEA to predict the actual buckling load. However, the present work can be extended to study the multistage hydraulic cylinder having fixed free mounting with clearances using strain energy method and nonlinear FEA. The hinged cylinder load test results with minimum clearance is closer to strain energy method and linear FEA. The present work can be useful for designers to obtain the critical buckling of multistage hydraulic cylinders with hinged mounting using strain energy method to reduce the dependency on costlier FEA packages.

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Contribution in the current study includes verification of the effect of internal clearance in the buckling load test.