



Fracture, Damage and Structural Health Monitoring

Progressive buckling of hydraulic actuators

Emanuele Vincenzo Arcieri^{a,*}, Sergio Baragetti^a

^a*Department of Management, Information and Production Engineering, University of Bergamo, Viale Marconi 5, Dalmine 24044, Italy*

Abstract

Hydraulic actuators are widely used in industrial and civil applications. Despite their compact size, they enable the movement of heavy loads. However, during service, they are often subjected to compressive stresses, which can lead to buckling. Accurately predicting the critical load that an actuator can withstand is essential to ensure performance and structural integrity. The progressive buckling behavior of an actuator could be influenced by several factors, such as the slenderness of the rod and cylinder, the boundary conditions, the geometric imperfections, the straightness errors, and the stiffness of the wear rings, which serve to reduce friction and minimize wear on the main assembly components. This study experimentally investigates the progressive buckling behavior of a slender hydraulic actuator under axial compression. Two boundary conditions – pinned-pinned and fixed-pinned – were analyzed, along with two different wear ring materials – PLA and nylon. For each configuration, the actuator was subjected to gradually increasing pressure until buckling occurred or material yielding was approached. Stresses were measured using strain gauges, and the resulting stress–pressure curves were analyzed to identify the critical pressure. Results indicate that the critical pressure increases under more restrictive boundary conditions and that wear ring material has negligible influence on the buckling behavior for the tested cases. The experimental data provide valuable information for improving hydraulic actuator design and reliability.

© 2025 The Authors. Published by ELSEVIER B.V.

This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0>)

Peer-review under responsibility of Ferri Aliabadi

Keywords: Hydraulic actuators; progressive buckling; stresses

* Corresponding author. Tel.: Tel.: +39-035-205-2382; fax: +39-035-205-2221.

E-mail address: emanuelevincenzo.arcieri@unibg.it

1. Introduction

Hydraulic actuators are widely used in both civil and industrial sectors to produce forces and displacements. Despite their relatively small size, they are capable of generating the high forces required to move large structures and machinery. A hydraulic actuator typically consists of two main components, the cylinder and the rod, and includes wear rings to reduce friction and ensure proper alignment between the parts. During operation, hydraulic actuators are often subjected to compressive loads. For this reason, in addition to preventing material yielding, it is crucial to analyze the progressive buckling behavior of actuators and determine the critical load. Several factors could influence the progressive buckling behavior of an actuator: the inertia and slenderness of its components, eventual eccentricity of the applied load, the stiffness of the wear rings, and the applied boundary conditions. Understanding the effect of these variables is fundamental for determining the service limits of an actuator.

In-depth investigation into the buckling behavior of hydraulic actuators began in the second half of the 20th century, when Euler formulas were first applied to calculate critical loads. Bleich (1952) proposed a simplified analytical model, consisting of a single beam with the circular cross-section of the rod extended along the full length of the system. However, this approach underestimates the actual load-bearing capacity of the actuator. Belluzzi (1961) modeled the system as a two-beam structure, made of a rod and a rigid cylinder, but this approach leads to an overestimation of load-bearing potential. Timoshenko and Gere (1961) proposed a model with two cross-sections, one for the rod and the other for the cylinder, to account for their different moments of inertia. However, the calculation of critical loads remained incomplete due to the existence of additional influencing parameters, which were addressed in other studies. Flugge (1973) and Hoblit (1950) demonstrated that internal fluid pressure does not significantly influence the critical load. Shenshai *et al.* (1975) examined the role of initial imperfections due to misalignment, which introduce eccentricity and bending moments. Baragetti and Terranova (1999, 2001) explored the influence of friction and clearance at the connection between the rod and the cylinder. They developed analytical models that were validated through experimental testing. Gamez-Montero *et al.* (2009a) developed similar models to include the load eccentricity, the actuator own weight and the internal fluid pressure. Their results confirmed that the effects of actuator weight and fluid pressure are negligible, supporting the findings of Flugge (1973) and Hoblit (1950). Friction effects in the supports were identified as critical for the load capacity of the actuators in Gamez-Montero *et al.* (2009b) and Zhou *et al.* (2020). The latter study emphasizes the need to account for large deflection, shear effects and bending stiffness of cylinder-rod junction in models developed to describe the buckling behaviour of a horizontally mounted hydraulic cylinder articulated at both ends. Ravinshankar (1981) employed a space-frame FEM approach, modeling the effects of seals and bearings with rotary springs. Yoo and Siegel (1986) estimated the critical column loads of telescopic power cylinders considering the initial misalignment at the cylinder-rod interface, the eccentricities of the applied load, the influence of support conditions and the lateral load resulting from the own weight of cylinders and oil. Baragetti and Villa (2016) studied the effects of rectilinear imperfections, wear ring stiffness and dimensions, and support friction on progressive buckling. The stiffness of the wear rings was assessed using finite element models based on material properties. The theoretical results were validated through experimental testing.

Based on the literature results, ISO/TS 13725 standard (2021) presents the methods for the evaluation of the buckling load of hydraulic cylinders, which are based on the elastic buckling theory and take into consideration possible eccentric loads and the weight of the whole assembly.

To advance the understanding of hydraulic actuators and accurately assess their actual load-bearing capacity, this work investigates the progressive buckling behavior of a slender hydraulic actuator under axial compression, following the study by Arcieri and Baragetti (2023), who presented a mathematical and finite element model for analyzing actuator buckling behavior. The main objective is to determine the critical buckling pressure while preventing material yielding. Experimental tests were carried out by varying the boundary conditions and the material of the wear rings (Costanzo, 2021). Buckling deformation was observed only under the pinned–pinned condition, allowing direct identification of the critical load, whereas the fixed–pinned configuration required an indirect estimation. The experimental data enabled the construction of bending stress versus pressure curves, with each tested configuration exhibiting an asymptote corresponding to the critical pressure. The results revealed no significant differences in performance based on the type of wear ring used.

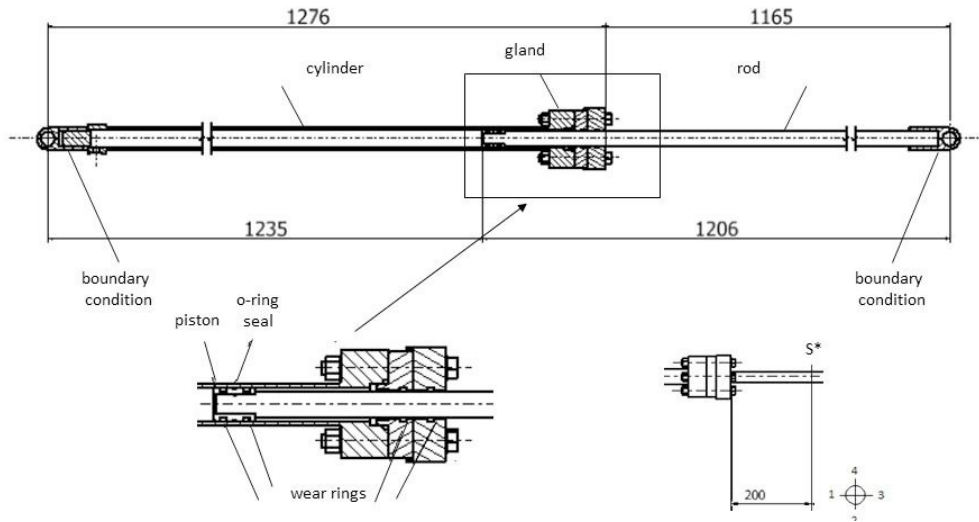


Fig. 1. Tested hydraulic actuator (Baragetti and Terranova, 1999, 2001).

2. Materials and methods

Generally, a comprehensive understanding of a phenomenon can be achieved by combining theoretical modeling, numerical simulations, and experimental testing (Baragetti, 2006; Baragetti and Tordini, 2007; Baragetti and Villa, 2015; Arcieri et al., 2021). Even simplified, theoretical models can offer valuable preliminary insights; numerical simulations provide more detailed and accurate results, though they may still be approximated. Experimental tests are essential to validate the created models and ensure their reliability.

In this work, experimental tests were conducted on the hydraulic actuator shown in Fig. 1 to determine its critical buckling pressure under two different boundary conditions and with two types of wear rings. The tested actuator was made of S235 steel, whose material properties are listed in Table 1, and its main geometric dimensions are reported in Table 2. The following boundary conditions were tested: pinned-pinned and fixed-pinned. The wear rings tested were a PLA molded ring and a nylon ring fabricated using fused deposition modeling. For each combination of boundary condition and wear ring type, three tests were conducted.

Table 1. Properties of S235 steel.

Property	Value
Yield stress (MPa)	235
Ultimate tensile strength (MPa)	360
Poisson's ratio	0.3
Young's modulus (MPa)	206,000
Density (kg/m ³)	7,850
Linear thermal expansion coefficient (m/°C)	12·10 ⁻⁶

Table 2. Main dimensions of the tested hydraulic actuator (Baragetti and Terranova, 1999, 2001).

Dimension	Value
Cylinder outer diameter (mm)	30
Cylinder inner diameter (mm)	25
Rod length (mm)	1,165
Cylinder length (mm)	1,276

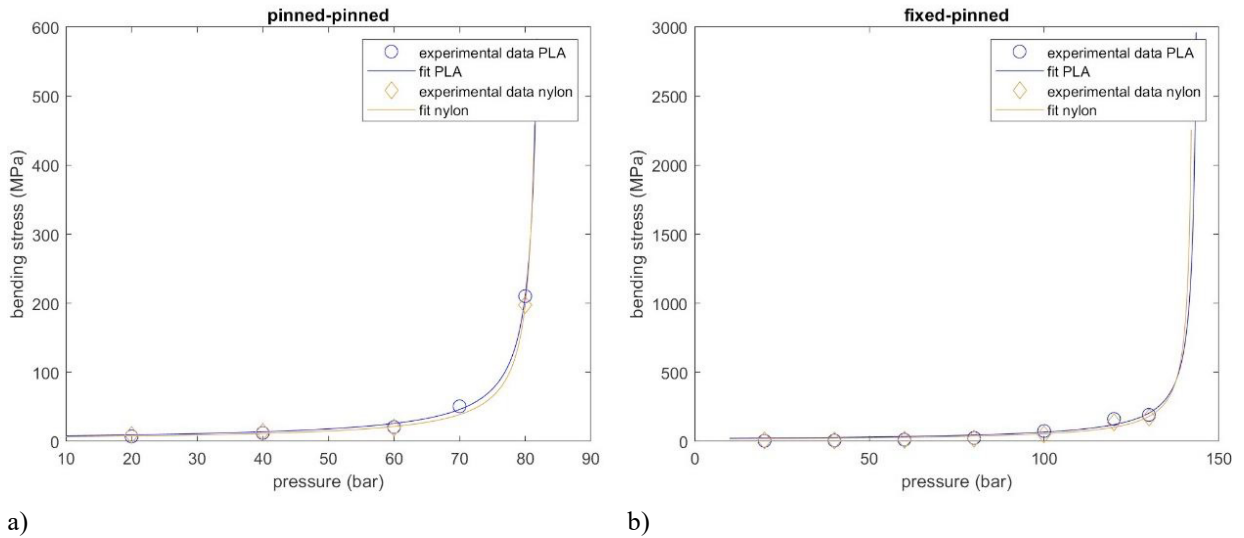


Fig. 2. Bending stress versus pressure: a) pinned-pinned; b) fixed-pinned.

During testing, the oil pressure in the actuator cylinder was gradually increased until buckling occurred or material yielding was approached. To monitor the stress–strain state of the actuator, four uniaxial strain gauges were placed at angular intervals of 90° at the axial position S^* shown in Fig. 1 (Baragetti and Terranova, 1999, 2001). A half-bridge Wheatstone configuration was implemented using active and dummy strain gauges to provide temperature compensation and minimize thermal effects on the measurements.

3. Results and discussion

For the pinned-pinned configuration, the buckling condition was experimentally achieved, as the measured stresses remained below the material's yield limit. In contrast, for the fixed-pinned configuration, it was not possible to reach the buckling state experimentally, and the critical pressure was therefore estimated.

The stress values obtained from the strain gauges were decomposed into an axial component (due to the applied axial load) and a bending component (resulting from structural deformation associated with buckling). The trends of bending stress versus applied pressure are shown in Fig. 2, for the both boundary conditions tested – pinned-pinned (Fig. 2a) and fixed-pinned (Fig. 2b) – and for both tested wear ring materials – PLA and nylon.

In all cases, the bending stress component exhibits a vertical asymptote, which can be associated with the critical pressure for buckling. As expected, the critical pressure is higher for the fixed-pinned configuration, due to the more restrictive boundary conditions.

The limit and critical pressures for the different tested configurations are reported in Table 3. A comparison of these values shows no significant differences between the two tested wear ring materials.

Table 3. Limit pressure and critical pressure.

Wear ring	Boundary condition	Limit pressure (bar)	Critical pressure (bar)
PLA	Pinned-pinned	80-85	80-85
	Fixed-pinned	120-130	140-150
Nylon	Pinned-pinned	80-85	80-85
	Fixed-pinned	120-130	140-150

4. Conclusions

This study investigated the progressive buckling behavior of a slender hydraulic actuator under axial compression, with the objective of determining the critical pressure while avoiding material yielding. Two boundary condition configurations – pinned-pinned and fixed-pinned – were experimentally tested, in combination with two types of wear rings – PLA and nylon. The following results were obtained:

- Buckling behavior is strongly influenced by boundary conditions. The pinned-pinned configuration led to observable buckling deformation, allowing direct identification of the critical pressure. In contrast, the fixed-pinned configuration, being more restrictive, prevented visible buckling, and the critical pressure had to be estimated indirectly from the bending stress-pressure curves.
- Bending stress trends revealed vertical asymptotes which correspond to the critical pressures for each configuration and wear ring material.
- The fixed-pinned configuration exhibited a higher critical pressure than the pinned-pinned case, as expected due to the greater constraint on lateral displacement.
- The type of wear ring had a negligible effect on both the limit and critical pressure values for the two tested materials – PLA and nylon. This suggests that within the tested conditions, both materials provide similar mechanical stiffness and alignment support.

Future research could explore the effects of alternative wear ring materials and varied boundary conditions through experimental testing.

References

- Arcieri, E.V., Baragetti, S., 2023. Influence of the wear rings on the buckling behaviour of hydraulic actuators. *IOP Conference Series: Materials Science and Engineering* 1275, 012029
- Arcieri, E.V., Baragetti, S., Božić, Ž., 2021. Application of Design of Experiments to Foreign Object Damage on 7075-T6. *Procedia Structural Integrity* 31, 22–27.
- Baragetti, S., 2006. A Theoretical Study on Nonlinear Bending of Wires. *Meccanica* 41, 443–458.
- Baragetti, S., Terranova, A., 1999. Limit load evaluation of hydraulic actuators. *International Journal of Materials and Product Technology* 14, 50–73.
- Baragetti, S., Terranova, A., 2001. Bending behavior of double-acting hydraulic actuators. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 215, 607–619.
- Baragetti, S., Tordini, F., 2007. Fatigue resistance of PECVD coated steel alloy. *International Journal of Fatigue* 29, 1832–1838.
- Baragetti, S., Villa, F., 2015. Corrosion Fatigue of High-Strength Titanium Alloys under Different Stress Gradients. *The Journal of The Minerals, Metals & Materials Society* 67, 1154–1161.
- Baragetti, S., Villa, F., 2016. Effects of Geometrical Clearances, Supports Friction, and Wear Ring on Hydraulic Actuators Bending Behavior. *Mathematical Problems in Engineering*, 2016, 3781397.
- Belluzzi, O., 1961. *Scienza delle Costruzioni*, vol. 4. Zanichelli, Bologna, Italy.
- Bleich, F., 1952. *Buckling Strength of Metal Structures*. McGraw-Hill, New York, NY.
- Costanzo, S., 2021. *Instabilità progressiva di attuatori idraulici: modelli teorici, numerici e risultati sperimentali* (master thesis).
- Flügge, W., 1973. *Stresses in Shells*, 2nd ed. Springer, Berlin, Germany.
- Gamez-Montero, P.J., Salazar, E., Castilla, R., Freire, J., Khamashta, M., Codina, E., 2009. Misalignment effects on the load capacity of a hydraulic cylinder. *International Journal of Mechanical Sciences* 51, 105–113.
- Gamez-Montero, P.J., Salazar, E., Castilla, R., Freire, J., Khamashta, M., Codina, E., 2009. Friction effects on the load capacity of a column and a hydraulic cylinder. *International Journal of Mechanical Sciences* 51, 145–151.
- Hoblit, F., 1950. Critical buckling for hydraulic actuating cylinders. In: *Stress Engineering, Product Engineering*. Lockheed Aircraft Corporation, Burbank, Calif, pp. 108–112.
- ISO/TS 13725, 2021. *Hydraulic fluid power — Method for evaluating the buckling load of a hydraulic cylinder*.
- Ravishankar, N., 1981. Finite Element Analysis of Hydraulic Cylinders. *ASME. Journal of Mechanical Design* 103, 239–243.
- Seshasai, K., Dawkins, W., Iyengar, S., 1975. Stress analysis of hydraulic cylinders. In: *Proceedings of the National Conference on Fluid Power*, Oklahoma State University.
- Timoshenko, S.P., Gere, J.M., 1961. *Theory of Elastic Stability*. McGraw-Hill, Tokyo, Japan.
- Yoo, C.H., Siegel, C. R., 1986. Column loadings on telescopic power cylinders. *Computers & Structures* 22, 245–251.
- Zhou, J., Shi, D., Di, C., Zhang, Y., Cheng, X., 2020. Buckling Behavior of Horizontal Hydraulic Cylinder Articulated at Both Supports. *International Journal of Structural Stability and Dynamics* 20, 2050033.